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Advances in Patellofemoral Disorders

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Numerous advances continue to be made and have contributed to the improvement of the diagnosis and treatment of patellofemoral (PF) disorders. These include technological advances in imaging and computational modeling, devices for implantation, and developments in the field of orthobiologics. Developments in dynamic/three-dimensional computed tomography (CT) imaging as well as utilization of the Porto Patellofemoral Testing Device (PPTD) have the potential to serve as enhanced tools to improve diagnosis of PF disease. Similarly, investigation into finite element analysis of the PF joint has encouraged a greater appreciation of the implications that anatomical variants can have on PF mechanics. Finally, advances in internal bracing have emerged as a potentially useful augment in the treatment of patellar instability.

28.1 Instrumented Laxity Evaluation

Physical examination plays a critical role in the accurate diagnosis of PF disorders, however it is limited by its qualitative nature and variability among examiners [1–3]. Standard imaging modalities currently fail to incorporate a dynamic assessment of the injury [4]. Although there have been previous attempts at instrumented quantita-

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J. L. Koh et al. (eds.), *The Patellofemoral Joint*, https://doi.org/10.1007/978-3-030-81545-5_28

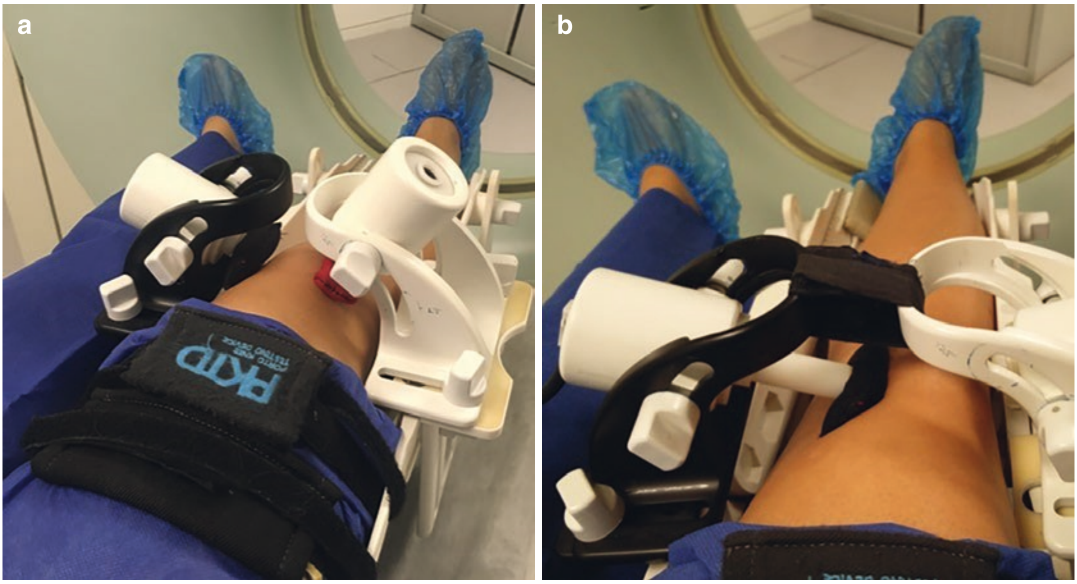

Fig. 28.1 Porto Patella Testing Device (PPTD) setup for stress-testing within imaging equipment (**a**) initial setup without any stress to obtain the position of the patella at rest, and (**b**) 30° of lateral translation stress with medial actuator

tive assessments [5–12], their outcomes and measurement methods demonstrated a significant amount of heterogeneity [13].

To address this need, the Porto Patellofemoral Testing Device (PPTD) has emerged to provide a standardized tool to quantify patellar position and displacement [14] (Figs. 28.1 and 28.2). This device has the advantage to combine stress-testing system simultaneously during an MRI or CT scan. Leal et al. have demonstrated that the PPTD offers excellent reliability, accuracy, precision, and low variability as compared to manual physical exam [14, 15]. In addition, it provides a better understanding of the pathophysiology of the various PF disorders.

Patients with idiopathic unilateral acute knee pain (AKP) with morphologically equivalent knees demonstrate increased patellar lateral displacement after stressed lateral force with the PPTD in their painful knee [15]. Patients with objective patellar instability (OPI; patients that had a patellar dislocation event with or without the presence of anatomical risk factors) and potential patellar instability (PPI; patients with risk factors but that did not have a patellar dislocation event) display the same curve pattern (steep increase close to the final displacement), but with patients with PPI showing higher stiffness than patients with OPI, as would be expected if their medial soft tissue stabilizers function better than the OPI group where the medial restraints have presumably been injured. For maximum lateral displacement, values for patients with PPI are closer to the values for patients with patellofemoral pain (PFP; patients with PF pain without anatomical risk factors) because both presumably have intact medial soft tissue stabilizers and therefore can tolerate greater force application than the patients with OPI. These results suggest that the force–displacement curve pattern is directed by the anatomy and the presence of risk factors while the amount of displacement is related to the integrity of the medial patellar restraints [16].

More research utilizing this device is needed, but data incorporating objective PF laxity and stiffness may be used to better define surgical indications in the setting of instability and to evaluate the surgical outcomes of patellar stabilization techniques. This device also offers new insights into the origin of unilateral anterior knee pain, admittedly still in an investigative mode.

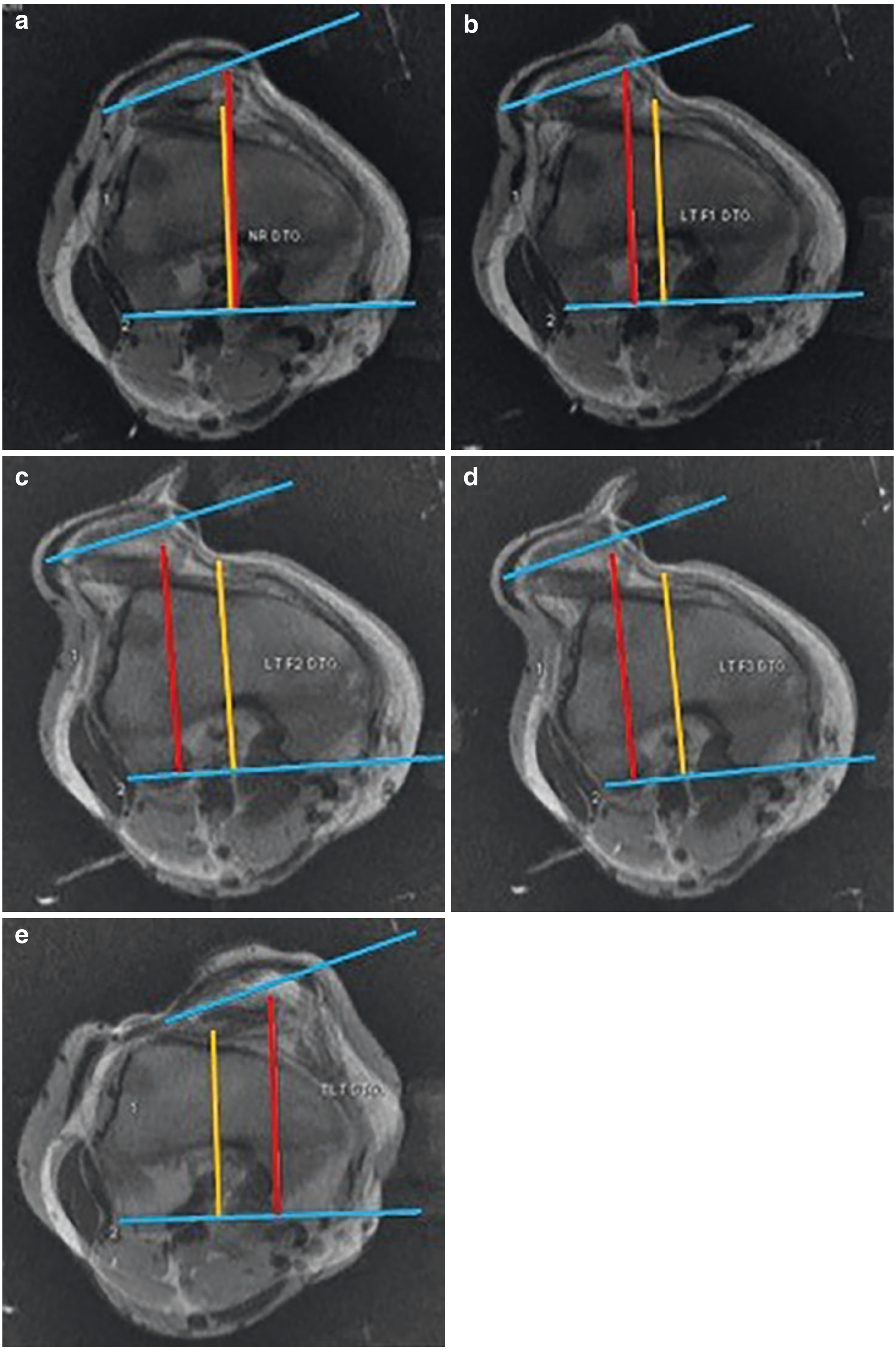

Fig. 28.2 Porto Patellofemoral Testing Device (PPTD) sequential stress testing of the right knee with a medial patellofemoral ligament tear. (**a**) Rest position (−1 mm, 18°); (**b**) Lateral transition of 0.2 bar, the patella moved 10 mm and −1° (9 mm, 17°); (**c**) Lateral transition of 0.4 bar, the patella moved 15 mm and −2° (14 mm, 16°); (**d**) Lateral transition of 0.6 bar, the patella moved 15 mm and −1° (14 mm, 17°); (**e**) Lateral tilt up to pain threshold, the patella moved 18 mm medially and increased 1° of tilt (−19 mm, 19°). From A (rest) to B (0.2 bar) to C (0.4 bar) there is low stiffness and high stiffness from C to D (0.6 bar)

28.2 Dynamic Computed Tomography (CT)

The use of dynamic CT has begun to improve our ability to quantify the contribution of each pathoanatomic variant on patellar tracking throughout knee range of motion (ROM) and provides a better understanding of the biomechanical effects that corrective surgical techniques have on patellar tracking. The images can be directly evaluated or a 3D computational model can be reconstructed based on the images acquired (Fig. 28.3).

Tanaka et al. found that knee flexion angle during imaging is a critical factor when measuring tibial tuberosity-trochlear groove distance (TTTG) to evaluate patellofemoral instability. The mean TTTG distance, which is often utilized to indicate osteotomy, varied by a mean 5.7 mm between 5 and 30° of flexion in each knee with symptomatic instability although this relationship was not completely linear. Measurements of patellar lateralization and tilt mirrored this pattern, suggesting that TTTG distance influences patellar tracking throughout knee range of motion [17].

In regard to abnormal tracking with patellar lateralization, higher grades of J-sign (>2 quadrants, or when the entire patella is lateral to the trochlear groove) have been found to be predictive of symptomatic patellar instability while

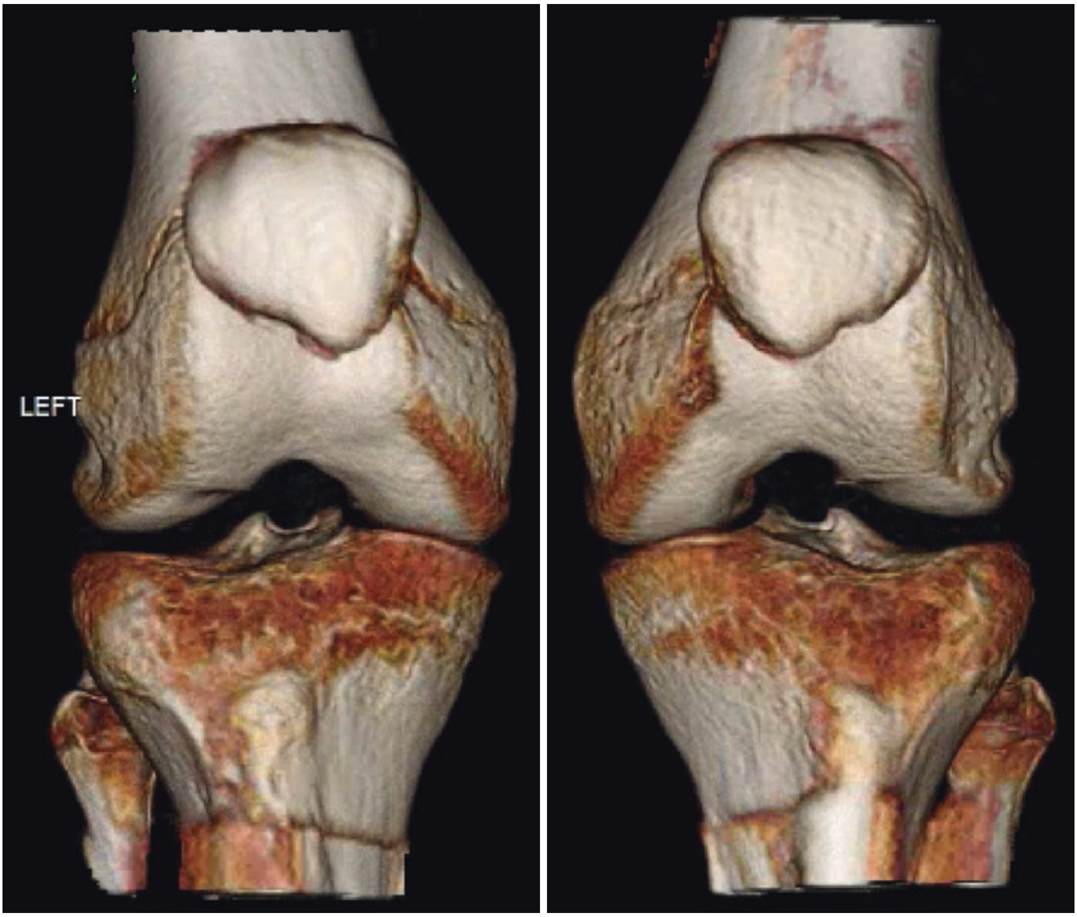

Fig. 28.3 3D reconstruction of dynamic CT imaging in bilateral knees demonstrates one image obtained during a sequence of knee flexion and extension. Visualization throughout range of motion allows for qualitative assessment of patellar tracking, while measurements performed in corresponding 2D axial or sagittal cuts allow for quantitative measurements of patellar position and morphology

milder lateralization (<2 quadrants) are not [18]. That suggests that the degree of patellar lateralization during ROM is related to symptoms, which may have utility during physical examination assessment such as the J-sign. Dynamic CT can improve patellar tracking assessments since intra- and inter-observer reliability of the visual assessment of the J-sign is inadequate ($k < 0.60$) and the agreement between visual and dynamic CT is between 53 and 68% [19]. The causes of a J-sign can also be better understood with the use of dynamic CT. At low flexion angles, both trochlear dysplasia (represented by the lateral trochlear inclination (LTI)) and lateral quadriceps vector (represented by the tibial tuberosity to posterior cruciate ligament (TT–PCL) distance) are correlated with the bisect offset index, a sign of patellar lateralization. However, only lateral trochlear inclination has been shown to be correlated with lateral tilt, another sign of maltracking. At high flexion angles, bisect offset index and lateral tilt are correlated with only lateral TT–PCL distance [20]. Such findings help us to better understanding and evaluate the validity of the current definition of abnormal tracking; dynamic CT studies of larger populations of asymptomatic patients may better distinguish abnormal tracking from normal tracking evaluation with dynamic CT imaging modalities.

Dynamic CT can also be applied postoperatively to assess and evaluate the alterations in anatomic parameters of various PF instability correction techniques (isolated MPFL reconstruction [21] vs MPFL reconstruction with tibial tuberosity osteotomy [22]) to determine if the underlying anatomic abnormalities had been correctly addressed. Gobbi et al. demonstrated a lack of correction of patellar tracking parameters in patients that underwent indicated isolated MPFL reconstruction [21]. Though an interesting finding, clinically none of the patients had recurrence of dislocations. On the other hand, Elias et al. reported that MPFL reconstruction with tibial tuberosity realignment reduces patellar lateral shift and tilt at low flexion angles [22], suggesting that further investigation into the roles of each procedure at different flexion angles will continue to improve our understanding of maltracking and its (potential) role in patellar instability, patellofemoral pain, and patellofemoral load/chondrosis.

28.3 Finite Element Analysis

Recent investigations applying finite element analyses have aimed to address factors that contribute to PF disorders and treatments. Utilizing finite element modeling (FEM) [23–25], researchers have been able to evaluate the kinematic behavior of PF articulation in various disease settings and simulate morphological changes using patient-specific models.

Because of the complexity of patellofemoral joint kinematics, which include the static soft tissue, static osseous, dynamic and alignment-related factors that contribute to stability, the application of FEM has allowed for a greater understanding of the individual factors, as well as the interaction between those factors and their roles in PF mechanics. Studies of articular geometry [26, 27], orientation of the patellar tendon [28], rotational alignment of the femur/tibia [27, 29], vastus medialis obliquus (VMO) functionality [30] have increased our understanding of PF reaction forces, contact mechanics, and kinematics (including patellar tracking).

Using a geometric statistical model, Fitzpatrick et al. demonstrated that the shape of the articular surface in the patellofemoral joint had the greatest influence in PF contact variations with larger PF size having increased contact and lower contact pressure. This was followed by patellar height (5 mm of patellar alta results in a 25% increase in contact pressure in midflexion) and then the contributions of trochlear morphology (more conformity confers lower peak contact pressures) [26]. Elias et al. demonstrated that an increase in PF contact pressures occurs with a lateralized patellar tendon through a computational analysis of external rotation of the tibia [28]. A similar computational analysis by Besier et al. revealed that a 15° increase in external rotation of the femur resulted in a 10% increase in PF contract pressures (shifting the pressure from the lateral patellar facet to the medial facet). In this study, patellar cartilage was shown to be more sensitive to these changes in femoral rotation with a greater increase in shear stresses in the patellar cartilage than in the femoral cartilage [29]. A subsequent computational analysis performed by Elias et al., looking PF contact force variations with VMO functionality revealed that with decreasing VMO force there is an analogous increase in lateral patellar contact forces [30]. Rezvanifar et al. evaluated the influence of trochlear dysplasia (represented by the lateral trochlear inclination), patella alta (represented by the Caton-Deschamps index; CD), and lateral tuberosity position (represented by the TT-PCL) on tracking (represented by the bisect offset Index and lateral patellar tilt) during knee squatting. Modifying the LTI, CD, and TT-PCL to represent mild to severe abnormalities, the authors demonstrated that a shallow trochlear groove increases lateral patellar maltracking. They also found that a lateralized tibial tuberosity in combination with trochlear dysplasia increases lateral patellar tracking and the risk of patellar instability. In this study, patella alta had relatively little influence on patellar tracking when in combination with trochlear dysplasia due to the limited articular constraint provided by the trochlear groove [27].

Patient-specific models can be used to perform simulated TTO [22, 31] and MPFL reconstruction [32–34] with analysis of the resultant effects on PF kinematics, contact pressures, and reaction forces. Application of this technique has also improved our understanding of the influence of tuberosity lateralization on the MPFL graft function and subsequent maltracking patterns [35, 36]. Through this method, simulated anteriorization TTO of 1.25 cm and 2.5 cm has shown to be effective in reducing patellofemoral contact forces, especially at smaller knee flexion angles. The total resultant PF contact force substantially increased with flexion but decreased as the tibial tubercle was moved anteriorly by 78% at 0° and 12% at 90° of flexion. In accordance, the maximum compressive stress substantially decreased at full extension; however, it increased at 90° of flexion. Substantial effects of tuberosity elevation on tibial kinematics, cruciate ligament forces, tibiofemoral contact forces, and extensor lever arm were found. As TTO anteriorization increased posterior translation of the tibia, the posterior cruciate ligament and tibiofemoral contact forces at larger flexion angles considerably increased, whereas the anterior cruciate ligament and tibiofemoral contact forces at near full extension angles decreased. Overall, the extent of changes depends on the magnitude of anteriorization, joint flexion angle, and loading.

Similar modeling studies have advanced our understanding of MPFL reconstruction by reinforcing anatomic placement of the femoral tunnel, as small deviations have been shown to result in increased PF contact pressures [32–34]. In a study performed by Oka et al., they sought to determine the optimal femoral insertion site based on three criteria for the MPFL reconstruction: the graft should remain isometric from 0 to 60° of knee flexion, be taut in full extension, and slacken at >60° of knee flexion. They showed that using simulated models their "optimal insertion sites" were analogous to that of the anatomic insertion site, which was just distal to the adductor tubercle [32]. Such a model to determine femoral insertion site was further reinforced by Sanchis et al. comparing parametric models of anatomic, non-anatomic/physiometric, and non-anatomic/non-physiometric MPFL reconstructions. In reconstructions that were anatomic/physiometric, the contact pressures in the PF articulation were increased from 0 to 30° but then decreased from 60 to 120° of knee flexion as the MPFL reconstruction slackened. They showed that if the insertion site was moved anteriorly (non-anatomic) it would be non-physiometric in behavior by having no tension from 0–30° but with increased tension and PF contact from 60 to 120° [33]. This is similar to previous findings based on FEM studies that showing increased graft tension/restraint with anteriorization of the femoral insertion site; however, these findings were performed at a static 30° knee flexion [34]. Anatomic reconstruction is of utmost importance as it can have a dramatic influence on the tensioning of the graft throughout ROM and the resultant PF contact pressures. The goal is to create a reconstruction that remains functional during the first 30° of knee flexion until the trochlear groove captures the patella and then subsequently slackens as the two attachment points converge towards each other.

Collectively, these FEM models hold great potential in uncovering important factors that affect our ability to diagnose and treat for PF instability, and to tailor treatments based on individual pathoanatomy. With advances in technology and the validation of these models, there will be continued insight into each PF disease process and their respective ideal treatments.

28.4 Suture Tape Augmentation of MPFL Stabilization Surgery

The primary surgical treatment of patellofemoral instability consists of an MPFL reconstruction. Most commonly, tendon autograft/allograft tissue is utilized to reconstruct the MPFL. Harvesting hamstring autograft can lead to deleterious changes in joint mechanics and gait patterns [37, 38]. Similarly, due to cost and availability of allograft, surgeons may be limited in their options. MPFL repair has been shown to have inferior results when compared to MPFL reconstruction [39]. As a result, suture tape augmentation of an MPFL repair has recently been explored to determine if it may serve as an equivalent treatment option for graft-based reconstruction [40]. Mehl et al. performed a biomechanical study comparing suture tape-augmented MPFL repair to MPFL reconstruction with allograft in ten fresh frozen cadaveric knees. They determined that suture tape-augmented repair displayed equivalent PF contact pressures and joint kinematics throughout all knee ROM at a preload of 2 N. While there are known higher failure rate with isolated MPFL repair, it is not yet known whether the suture tape augmentation may negate this risk [40]. A recent cadaveric study performed by Skamoto et al. demonstrated equivalent maximal patellofemoral contact pressures when comparing knees with suture tape MPFL reconstruction fixed at 60–90° of flexion with native knees. Fixation of the suture tape at lower degrees of flexion was found to result in abnormally increased PF maximal contact pressures [41]. At this time, no clinical studies have been conducted to investigate this novel technique. In addition, similarly to the concept of its use along with anterior cruciate ligament reconstruction [42]; suture tape augmentation may be used along with MPFL reconstruction to increase load to failure and decrease elongation of the construct in the early post-operative period. While further studies are needed to better understand the role of such a technique, this serves as preliminary evidence that MPFL repair with suture tape augmentation may be a future alternative for reconstruction techniques with the benefit of not requiring a soft tissue graft.

28.5 Conclusion

In summary, application of these advances to growing areas of inquiry studying PF disease have led to avenues of tremendous potential to improve our ability to accurately diagnose and treat patellofemoral disorders. From dynamic/3D-CT to PPTD testing, individualized diagnoses and quantitative assessments may be made as to the reason for a patient's PF symptoms. FEM analyses may then be applied to understanding these diagnoses, identifying individual alterations of pathoanatomy and potentially resultant changes with patient-specific treatments. And lastly, we are breaking into a new era of biologic treatments and implantable materials that will undoubtedly have a significant impact on future surgical techniques in the management of PF instability.

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