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Effect of Complete Syndesmotic Disruption and Deltoid Injuries and Different Reduction Methods on Ankle Joint Contact Mechanics

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Abstract

Background: Syndesmotic injuries can be associated with poor patient outcomes and posttraumatic ankle arthritis, particularly in the case of malreduction. However, ankle joint contact mechanics following a syndesmotic injury and reduction remains poorly understood. The purpose of this study was to characterize the effects of a syndesmotic injury and reduction techniques on ankle joint contact mechanics in a biomechanical model.

Methods: Ten cadaveric whole lower leg specimens with undisturbed proximal tibiofibular joints were prepared and tested in this study. Contact area, contact force, and peak contact pressure were measured in the ankle joint during simulated standing in the intact, injured, and 3 reduction conditions: screw fixation with a clamp, screw fixation without a clamp (thumb technique), and a suture-button construct. Differences in these ankle contact parameters were detected between conditions using repeated-measures analysis of variance.

Results: Syndesmotic disruption decreased tibial plafond contact area and force. Syndesmotic reduction did not restore ankle loading mechanics to values measured in the intact condition. Reduction with the thumb technique was able to restore significantly more joint contact area and force than the reduction clamp or suture-button construct.

Conclusion: Syndesmotic disruption decreased joint contact area and force. Although the thumb technique performed significantly better than the reduction clamp and suture-button construct, syndesmotic reduction did not restore contact mechanics to intact levels.

Clinical Relevance: Decreased contact area and force with disruption imply that other structures are likely receiving more loads (eg, medial and lateral gutters), which may have clinical implications such as the development of posttraumatic arthritis.

Keywords: syndesmosis, syndesmotic injury, ankle contact stress, syndesmosis repair, suture-button construct

Rotational ankle injuries and fractures are the most common causes of ankle arthritis.[27] Posttraumatic arthritis likely arises from initial joint damage[28] or changes to joint loading mechanics.[18,33] Intra-articular tibiotalar fractures, such as posterior malleolar fractures, may have worse clinical outcomes than other ankle fractures.[11,13,17] Malreduced posterior malleolar fractures alter bony contact area[9,16] and congruence, which is critical in establishing normal contact mechanics.[32] However, anatomic reduction of bony congruence does not necessarily restore normal joint contact mechanics.[6,7,23] In addition to bony congruence, ankle ligaments influence tibiotalar contact mechanics.[5,19]

Strong ligaments connecting the fibula and tibia stabilize the syndesmotic and ankle joints. Therefore, fibular malunion[36] and untreated syndesmotic injuries[3] alter the local contact mechanics of the tibiotalar joint. Consistent with this, biomechanical analyses have demonstrated the effects of talar displacement on ankle loading mechanics. In a classic but mechanically flawed study, Ramsey and Hamilton[25] showed that a 1-mm lateral shift of the talus on

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the tibial plafond led to a 42% decrease in contact area. This has come to be the rationale for reducing and repairing syndesmotic injuries.

Syndesmotic reduction is critical for stabilizing the joint[22] and improving patient outcomes following an ankle injury, and malreduction of the syndesmosis has been linked to worse patient outcomes.[4,14,24,26,34] Several syndesmotic reduction techniques have been reported and may influence ankle contact mechanics differently. Using a clamp to reduce syndesmotic injuries may predispose to syndesmotic malreduction.[20] Other strategies to reduce syndesmotic injuries include open reduction[21] or arthroscopic assisted[29] reduction, and reduction can be held with a conventional screw construct or a suture-button construct,[30] the effect of which is poorly understood. Therefore, it is important to identify how different reduction and fixation techniques affect global tibial plafond contact mechanics.

The purpose of this study was to determine if syndesmotic reduction techniques restore global tibial plafond contact mechanics in an unstable syndesmotic injury model. We tested 3 reduction techniques: screw reduction without a clamp, screw reduction with a clamp, and reduction using a suture-button construct. We hypothesized that reducing the syndesmosis with a clamp would overconstrain the joint and increase contact pressure and decrease contact area while the other techniques would restore intact contact mechanics.

Materials and Methods

Ten skeletally mature lower leg specimens (mean age, 64 ± 7 years) with intact proximal tibiofibular joints were used. The sample size was chosen based on the reported difference in contact area with syndesmotic and deltoid disruption, using a power of 0.8 and $\alpha = .05$.[3] This resulted in a sample size of 5 based on the conditions of maximum difference (intact vs completely disrupted). We chose to double the sample size to test for the smaller difference in mean values likely present with the different conditions of reduction. Skin, muscles, and tendons were removed from the ankle joint from 10 cm proximal to the ankle joint to the midfoot while preserving the Achilles tendon. The plantar aspect of the foot as well as all ligaments and joint capsules were left intact. All specimens were free of any lower extremity malalignment or trauma. Proximal tibiae were dissected free of soft tissue to the level of the fibular head, preserving the proximal tibiofibular articulation. The proximal tibia was secured in epoxy cement (Bondo; 3M, Atlanta, GA, USA) with the mechanical axis of the tibia vertical in no varus/valgus or flexion/extension. The specimen was then placed in a mechanical testing device, and the foot was placed on a low friction plastic surface and allowed unconstrained accommodative motion.

Using a cadaveric loading model,[1] we examined the effects of syndesmotic reduction techniques on ankle joint contact mechanics. We applied a ground reaction force of 400 N and Achilles tension of 350 N to test 5 conditions: intact, syndesmotic injury, screw reduction without a clamp, screw reduction with a clamp, and suture-button reduction. Prior to creating the syndesmotic injury, a fellowship-trained foot and ankle trauma surgeon prepared a screw hole for a best-case scenario of syndesmotic reduction: a 2.9-mm drill hole was placed along the transmalleolar axis at the proximal aspect of the physeal scar. A drill hole was placed in the intact situation to exclude gross malreduction from the analyses. Next, we created a syndesmotic injury by sectioning the syndesmotic ligaments (anteroinferior tibiofibular ligament, posteroinferior tibiofibular ligament, transverse ligament, and distal 10 cm of interosseous ligament) and the deltoid ligament. This injury model was chosen as it represents the most unstable ankle syndesmotic injury.[12] The syndesmosis was then reduced using 3 techniques and tested in a randomized order.

Syndesmotic injuries were reduced using 3 techniques: a thumb technique (no clamp), a reduction clamp, and a suture-button construct. The thumb technique used the surgeon's thumb to palpate congruence of the anterior distal tibiofibular incisura. No additional compression was used with the thumb, and the thumb was only used to palpate congruence of the reduction. When the fibula was manipulated with the thumb so that there was no palpable step or gap between the tibia and fibula, this was defined as reduced, and a 0.045-inch K-wire was used to provisionally secure the fibula to the tibia. A tetracortical 4.0-mm screw was then placed through the predrilled 2.9-mm drill hole, and the K-wire was then removed. The clamp reduction technique used a large Weber reduction clamp placed along the transmalleolar axis with the ankle in neutral dorsiflexion. The transmalleolar axis was visualized perfectly on the bones, and this is where the tines were placed. The clamp was squeezed firmly to a point that estimated intraoperative pressure. Standardized measures were not possible due to the difference between cadaveric specimens. All clamping was performed by a trauma and foot and ankle fellowship-trained surgeon in a similar fashion. There was no noted difference in anterior or posterior fibular translation with clamping. The clamp was firmly squeezed to allow the syndesmosis to be firmly held in place. Following clamping, the syndesmosis was secured with a tetracortical 4.0-mm screw through the previously placed 2.9-mm drill hole. The screw was tightened until the screw head was seated flush with the lateral fibular cortex. A torque screwdriver was not used given the variability in the material properties of the different cadaveric specimens. If the ankle was clamped in plantarflexion, there was visible medial and lateral ankle joint gutter impingement that prevented normal articulation at the plafond. Care was taken to ensure that this was avoided with the reduction clamp and thumb technique by keeping the ankle at 90 degrees for reduction. The suture-button reduction technique used a commercially available suture-button construct (TightRope; Arthrex, Naples, FL, USA) placed through the previously drilled 2.9-mm hole. The suture button was firmly tightened to the amount representative of the usual intraoperative amount, thereby reducing distal tibiofibular diastasis. The syndesmosis was held reduced with a thumb, similar to the thumb reduction technique. Tightness was gauged by pulling until both the medial and lateral buttons were firmly seated on the bones and had no mobility when probed with a forceps.

Ankle joint contact stress was measured during each test condition with a thin pressure sensor (model 5033; Tekscan, South Boston, MA, USA) that was inserted into the joint through anterior arthrotomy and centered under the tibial plafond. The sensor was specifically designed for ankle testing[2] with a sensor matrix of 26.7 mm × 38.4 mm and a resolution of 144.1 sensels/cm^2. Sensor contact was only on the tibial plafond, and it did not extend into the medial and lateral ankle gutters. Test conditions were loaded for 1 single 30-second period to account for the history dependency of the sensor, and measurements were recorded after 30 seconds. A custom-written MATLAB routine (MathWorks, Natick, MA, USA) calculated the global contact mechanics: contact area, contact force, and peak contact pressure.[10] In addition, contact pressure maps were generated for visual comparison.

Repeated-measures analyses of variance were performed to detect differences between the 5 test conditions for the 3 dependent variables: contact area, contact force, and peak contact pressure. Tukey post hoc tests were performed to control for multiple comparisons, and statistical significance was set to $\alpha = .05$.

Results

Syndesmotic disruption significantly reduced tibial plafond contact area compared to the intact situation by approximately 17% (503 mm^2 ± 106 mm^2 vs 604 mm^2 ± 77 mm^2, respectively) (Figure 1). Similarly, there was a significant reduction in total joint force in the disrupted condition (412 N ± 83 N) relative to the intact situation (494 N ± 104 N) (Figure 2). Despite these differences, there were no significant differences in the magnitude of peak contact pressure between the intact (4.5 MPa ± 1.2 MPa) and disrupted conditions (5.3 MPa ± 1.8 MPa) (Figure 3).

Tibial plafond contact area with syndesmotic disruption was not significantly different between the disrupted (503 mm^2 ± 106 mm^2) and clamp (483 mm^2 ± 89 mm^2) or suture-button conditions (496 mm^2 ± 104 mm^2) (Figure 1).

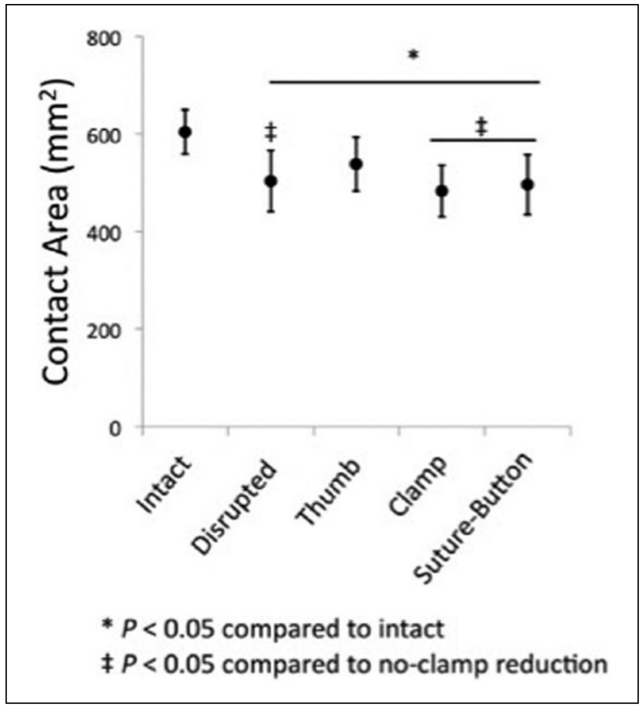

Figure 1. Tibial plafond contact area with an intact and disrupted syndesmosis, with the 3 conditions of reduction.

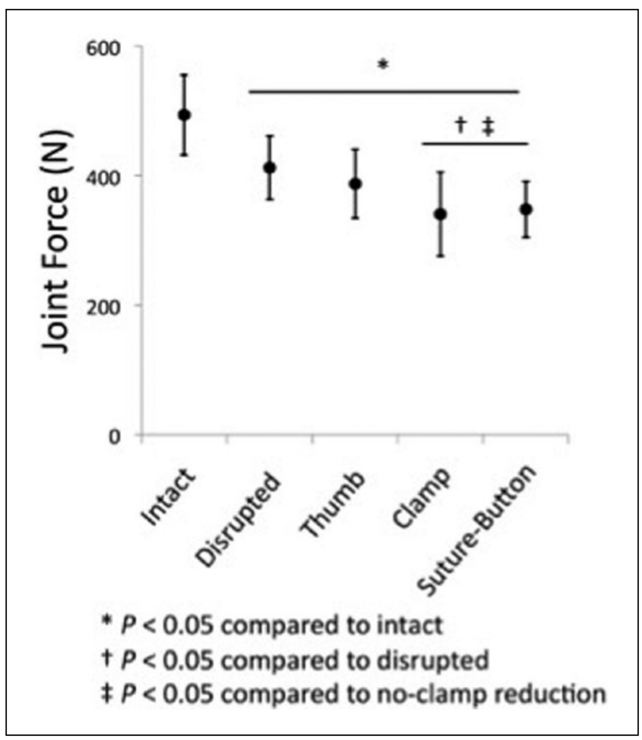

Figure 2. Tibial plafond joint force with an intact and disrupted syndesmosis, with the 3 conditions of reduction.

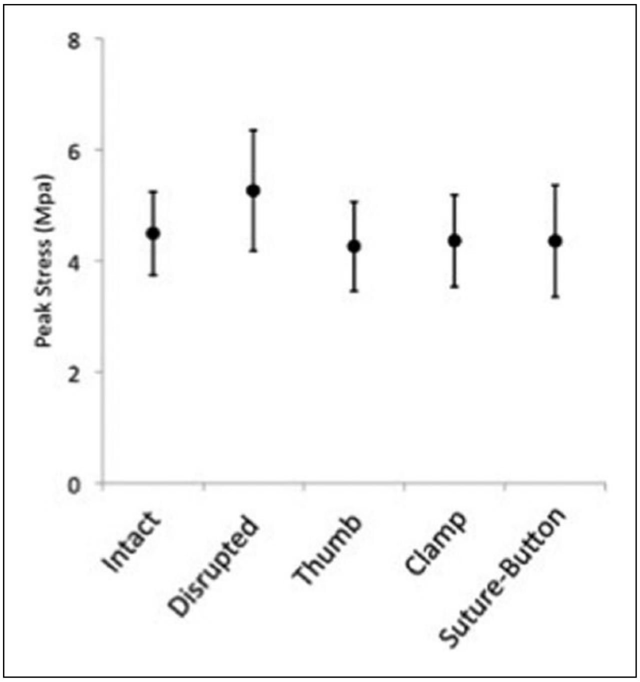

Figure 3. Tibial plafond peak pressure with an intact and disrupted syndesmosis, with the 3 conditions of reduction.

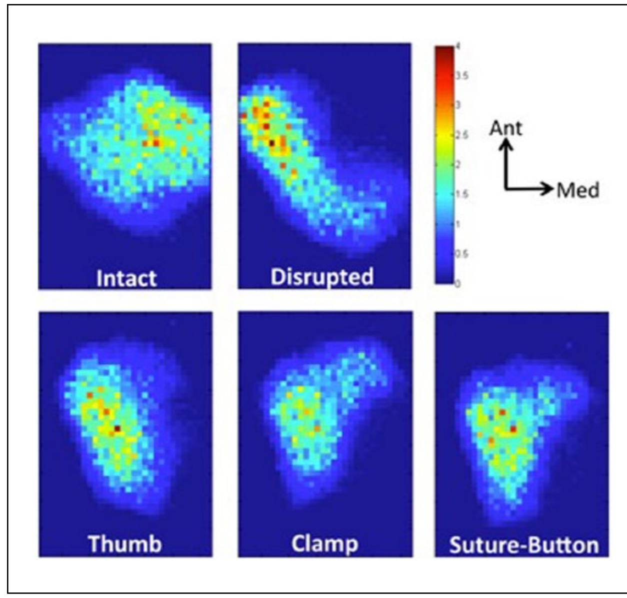

Figure 4. Pressure sensor recording images for each loading condition. Pressure is represented in MPa. Total contact area and total joint force were significantly decreased with disruption, and no reduction technique was able to restore the normal joint contact mechanics.

However, contact area was significantly greater with the thumb technique (538 mm^2 ± 94 mm^2) relative to the disrupted condition (503 mm^2 ± 106 mm^2) (Figure 1). The disrupted condition had significantly greater joint force relative to the clamp or suture-button conditions (412 N ± 83 N vs 341 N ± 109 N and 348 N ± 73 N, respectively) but not the thumb technique (387 N ± 89 N) (Figure 2). Peak contact pressure did not differ between the disrupted and 3 repair conditions (Figure 3).

Repair with the thumb technique increased contact area compared to the clamp and suture-button conditions (538 mm^2 ± 94 mm^2 vs 483 mm^2 ± 89 mm^2 and 496 mm^2 ± 104 mm^2, respectively) (Figure 1). The thumb technique also had significantly greater joint force relative to the clamp and suture-button conditions (387 N ± 89 N vs 341 N ± 109 N and 348 N ± 73 N, respectively) (Figure 2). Peak contact pressure did not differ between the 3 reduction techniques (Figure 3).

Discussion

Syndesmotic injuries remain a challenge to treat among surgeons. Furthermore, poorly treated injuries have significant long-term consequences. Multiple reduction techniques limit the current body of literature to determine the optimal reduction maneuvers to avoid long-term damage to the ankle joint. The purpose of this study was to establish the effects of syndesmotic reduction techniques on global tibial plafond contact mechanics in a syndesmotic injury model. Specifically, contact mechanics was assessed in a cadaveric model of simulated standing for the intact condition, syndesmotic injury condition, and 3 syndesmotic reduction techniques: screw fixation without a clamp, screw fixation with a clamp, and suture-button fixation. Syndesmotic disruption significantly changed plafond contact mechanics. Although the thumb technique performed better than the clamp and suture-button techniques, no reduction technique restored contact mechanics back to the intact condition.

Disruption of the syndesmosis caused significant reductions in contact area and total contact force across the tibial plafond, but increases in the magnitude of peak contact pressure were not detected. Given that the loads imparted to the specimen through the hydraulic testing frame and Achilles tendon were the same in the intact and disrupted conditions and that peak contact pressure did not change, it was implied that tissues outside of the sensor's footprint experienced higher loads.[10] Tissues experiencing higher loads could include the fibula or medial gutter. Alternatively, although the sensor used in the current study was specifically designed for use in ankles,[2] there could have been some areas on the talar dome outside of the sensor footprint that were experiencing more loads. This is less likely the case because our measurements did not appear to expand past the sensor's immediate footprint (Figure 4), and contact area and total joint force were similar to those reported in the literature.[5] Additionally, the sensor was centered for each trial to keep this effect to a minimum. Similar to the current study, Burns et al[3] reported a significant reduction in contact area with complete syndesmotic and deltoid disruption. A measured reduction in contact area with syndesmotic disruption suggests that the tibiotalar joint does not fully autocentralize into normal articular congruity with a simple axial loading protocol in an unconstrained hindfoot.

Despite reduction using 3 different techniques, no technique was able to restore normal contact area or total plafond joint force. Using a clamp or a suture button to reduce the injury caused a significant reduction in contact area and a reduction in joint force, which imply that the syndesmosis may have been overreduced with these techniques and structures other than the tibial plafond were carrying more loads (eg, medial and lateral gutters). The fact that contact area was reduced with a complete injury and with a clamp or a suture-button construct, but to a lesser degree with the thumb technique, suggests that contact mechanics was very sensitive to small perturbations in tibiofibular relationships. These differences were significant, despite the syndesmotic screw pilot hole being drilled in the reduced condition prior to testing. Additionally, the relationship between the ankle ligaments, bones, and interosseous membrane may be critical in influencing tibial plafond contact mechanics.[15]

Our results demonstrate that native syndesmotic ligaments are necessary to maintain the ankle mortise, thus facilitating appropriate ankle congruity and loading mechanics. Syndesmotic reduction under ideal conditions did not restore native ankle loading mechanics.[25,31] However, despite reducing the syndesmosis with conventional intraoperative techniques, the fact that contact area remained significantly decreased suggests that other soft tissues play critical roles in establishing normal ankle contact mechanics.[5,6,15] Liu et al[15] developed a finite element model to assess the pressure distribution around the ankle with a syndesmotic injury and with screw fixation. Their model showed that with a syndesmotic injury, ankle ligaments experience different loads than in the intact situation. In particular, with loads commensurate with standing, the anterior talofibular ligament experienced less loads, and the medial posterior tibiotalar band experienced greater loads. This has been supported with a cadaveric study demonstrating that with syndesmotic disruption, the deltoid ligament experiences greater strain than with an intact lateral syndesmosis.[3] This suggests that collateral ligaments, the deltoid in particular, may play a key role in ankle contact mechanics. In keeping with this, 2 studies have reported decreased ankle contact area between 20% to 43% with deltoid sectioning.[5,6] The current model had a complete deltoid injury, and this could explain why ankle contact area remained lower in the reduced and repaired situations.

Treatment of the deltoid remains a controversial issue as well. Many authors will not repair the deltoid after a syndesmotic injury. Instead, syndesmotic fixation is used to obtain an anatomic ankle mortise, and the deltoid is left to heal without operative intervention. While deltoid instability may be infrequently encountered after a syndesmotic injury, the current study does have several implications with regard to deltoid repair. Clinically, if early weightbearing is allowed after isolated syndesmotic fixation regardless of the reduction technique, the contact mechanics of the joint is abnormal. This may predispose the ankle joint to early wear. If early weightbearing is desired, it may be advantageous to address the soft tissues acutely to minimize abnormal contact stress. Specifically, acute repair of the deltoid may be beneficial to patients in whom early weightbearing is desired. Clearly, future biomechanical and clinical studies will be needed to further investigate this.

The current study used 3 reduction techniques. Recent data suggest that syndesmotic malreduction is common[8] and that syndesmotic malreduction may portend a worse patient outcome.[26,34] Performing reduction with a clamp may malreduce the syndemosis.[18] A suture-button construct may be used to reduce the syndesmosis.[22] Based on the rationale that clamps may malreduce the syndesmosis, the current study also used a technique in which the syndesmosis was palpated with a thumb, and when the anterior distal tibiofibular incisura was congruent and lacking any steps or gaps, the syndesmosis was secured with a screw. Although this technique performed better than the other reduction techniques, the differences were small, and no technique was able to return contact area or total joint force back to the intact situation. This could be due to the concomitant deltoid injury or the presence of the fixation itself. Placing a rigid screw across the syndesmosis altered the pressure distribution of tissues around the ankle in a finite element model.[15] However, this is less likely to be the cause in the current study as there were no differences in contact mechanics between the rigid screw and the flexible suture-button construct.

The current study has several limitations. Although the sensor was designed specifically for use in ankles and is very thin (0.1 mm),[2] the sensor itself may have altered the articular cartilage contact mechanics.[35] While these pressure-sensitive sensors do deteriorate following multiple loading cycles, previous work demonstrated no change in measurements when loaded regularly over 8 hours.[18] The sensor was also limited in that it was not designed to simultaneously measure gutter and plafond contact mechanics. Hence, tissues experiencing loads other than the tibial plafond were not directly measured. The loading protocol used was a simple axial load with an Achilles load. This loading protocol was not able to demonstrate dynamic instability of the ankle, which may significantly alter contact mechanics.[31] Since the primary outcome of the study was global contact mechanics, the sensor was moved to ensure capture of the entire contact footprint in each condition. However, movement of the sensor precluded the correlation of centers of high pressure with the anatomic location on the talus.

In conclusion, syndesmotic disruption altered global ankle contact mechanics. Despite performing 3 different syndesmotic reduction techniques, contact mechanics was not restored to the intact situation. Reducing the syndesmosis with pressure generated by a surgeon's thumb performed slightly better than the reduction clamp or suture-button construct; however, no reduction technique restored contact mechanics to the intact situation. Taken together with the published literature, these data suggest that factors in addition to tibiotalar alignment are important in determining the contact mechanics of the tibial plafond in syndesmotic injuries, and further studies are needed to determine what these factors are.

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Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Mark C. Drakos, MD, is a paid consultant for Extremity Medical and FastForm Medical, neither of whose products are involved in the current study.

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