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Minimum Distraction Gap: How Much Ankle Joint Space Is Enough in Ankle Distraction Arthroplasty?

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Abstract *Background:* The success of ankle distraction arthroplasty relies on the separation of the tibiotalar articular surfaces. *Question/Purpose:* The purpose of this study was to find the minimum distraction gap needed to ensure that the tibiotalar joint surfaces would not contact each other with full weight-bearing while under distraction. *Methods:* Circular external fixators were mounted to nine cadaver ankle specimens. Each specimen was then placed into a custom-designed load chamber. Loads of 0, 350, and 700N were applied to the specimen. Radiographic joint space was measured and joint contact pressure was monitored under each load. The external fixator was then sequentially distracted, and the radiographic joint space was measured under the three different loads. The experiment was stopped when there was no joint contact under 700N of load. The radiographic joint space was measured and the initial (undistracted) radiographic joint space was subtracted from it yielding the distraction gap. The minimum distraction gap (mDG) that would provide total unloading was calculated. *Results:* The average mDG was 2.4 mm (range, 1.6 to 4.0 mm) at 700N of load, 4.4 mm (range, 3.7 to 5.8 mm) at 350N of load, and 4.9 mm (range, 3.7 to 7.0 mm) at 0N of load. *Conclusion:* These results suggest that if the radiographic joint space of on a standing X-ray of an ankle undergoing distraction arthroplasty shows a *minimum* of 5.8 mm of DG, then there will be no contact between joint surfaces during full weight-bearing. Therefore, 5 mm of radiographic joint space, as recommended historically, may not be adequate to prevent contact of the articular surfaces during weight-bearing.

Keywords ankle distraction · arthrodiastasis · ankle arthritis · joint preservation · external fixation · Ilizarov · RAD

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Introduction

Ankle joint distraction arthroplasty has steadily gained popularity in Europe and the USA as an effective treatment for tibiotalar osteoarthritis with benefits including pain reduction and functional improvement [1, 3–5, 8, 9, 11, 12]. In this procedure, external fixation is used to place traction across the ankle joint separating or "distracting" the narrowed joint space. Unloading of the joint is hypothesized to create optimal conditions for cartilage repair [11–14]. When performing arthrodiastasis, it is believed that complete separation of the articular surfaces during weight-bearing is needed to obtain good clinical results with cartilage regeneration [1, 3, 11]. The stress shielding of the subchondral bone provided by unloading the joint surfaces has been shown to lead to decreased sclerosis of subchondral bone, subchondral cyst resorption, and pain relief [3, 6]. Weight-bearing is encouraged postoperatively while wearing the external fixator. This places full-body weight across the ankle and requires that the external fixator be distracted enough to prevent the articular surfaces from contacting. The distraction of the joint needs to be maintained for 3 months.

The terminology used to describe joint space needs clarification. "Joint space" refers to "radiographic joint space." This is the amount of space measured between the tibial plafond subchondral bone and the talar subchondral bone as

seen clearly on radiographs. This can be measured with the joint distracted or with the joint at rest or undistracted. At rest, the radiographic joint space measurement includes the height of any remaining articular cartilage. When the joint is distracted, then the joint space measurement includes both the height of the cartilage layer and the "distraction gap" between cartilage surfaces. The "distraction gap" is the space that is created iatrogenically in the joint by distracting the joint surfaces with an external fixator. This cannot be measured directly radiographically but can be calculated. The joint space measured on X-ray less the space occupied by the articular cartilage surfaces yields the distraction gap. The distraction gap is zero when the ankle is undistracted, and the radiographic joint space measurement will equal the cartilage height. In cases of severe arthritis, the undistracted radiographic joint space may be 0 mm indicating no articular cartilage. The ideal amount of distraction gap has not been studied. It has been shown that 5 mm of ankle joint space is associated with good clinical results [3, 5, 8–10] (Fig. 1).

Authors have reported that the tibiotalar joint space should be measured on a weight-bearing X-ray of the ankle and that 5 mm of space should be adequate to prevent joint surface contact during weight-bearing [11]. Most surgeons maintain that 5 mm is the desired end point for distraction, but some suggest that up to 10 mm of minimum distraction gap may be needed to ensure that there will be no contact between joint surfaces. Overdistraction may not be benign as it stretches neurovascular structures and the ankle ligaments. None of the prior studies call attention to the height of the remaining cartilage or do they distinguish between distraction gap (DG) and radiographic joint space (rJS).

The purpose of this study was to find the minimum DG needed while wearing the external fixator to ensure that the tibiotalar joint surfaces will not contact each other during full weight-bearing. Specifically, the study asks: What is the minimum distraction gap between the tibial and talar articular surfaces that will completely unload the ankle joint during weight-bearing while undergoing ankle arthrodiastasis, and, specifically, is 5 mm of radiographic joint space measured on a weight-bearing radiograph adequate to prevent articular contact during walking?

Materials and Methods

This was a cadaveric study performed with fresh frozen human specimens that included mid-tibia and the entire foot. Specimens that had previous ankle surgery or known arthritis were excluded. The average age of the specimens was 55 years old (range 39–60 years old) with average weight of 130lbs (56 kg) and BMI of 21 (range 17–28). Sixty percent of the specimens were female. These fresh frozen specimens were stored in a −20°C freezer. We included nine specimens for the study.

Each specimen was thawed at room temperature overnight for preparation the following morning. No specimen had previous incisions about the ankle or foot. The surgical preparations were performed by the same attending (ATF) and medical student (THM) in all cases. An anterior arthrotomy was made over the ankle utilizing the approach between the anterior tibial tendon and the extensor hallucis longus. The capsule was split longitudinally. ATFL, CFL, AITFL, and deltoid ligaments were preserved. The joint was visually inspected. No specimens were seen to have osteoarthritis. The capsule and periosteum were pealed medially and laterally. A 5-cm posterior ankle arthrotomy was made through an approach lateral to the Achilles tendon. The arthrotomies served to allow access to the tibiotalar joint

Fig. 1. **a** This is a case example of a patient that underwent ankle distraction arthroplasty included to illustrate the measurement techniques. This preoperative X-ray was used to measure an undistracted radiographic joint space (rJS) of 1.6mm. **b** This standing radiograph of the same patient undergoing ankle distraction arthroplasty was used to measure the rJS of the distracted ankle which was 5.7mm. The distraction gap (DG) can be calculated by subtracting the initial rJS 1.6mm from the distracted rJS 5.7mm. The difference is the DG 4.1mm.

for insertion of a pressure sensor (5033, Tekscan, South Boston, MA). This sensor would ultimately show the amount of contact that existed between the joint services. The sensor gave a real-time map of the magnitude and locations of tibiotalar joint contact pressures. This allowed us to visualize the tibiotalar contact area (Fig. 2). The external fixator was then applied in a standard fashion identical to the technique used on patients in the operating room [2]. The fixator used was the RAD frame (Rozbruch Ankle Distractor, Small Bone Innovations, Morrisville, PA). This external fixator consisted of one tibial ring attached to a foot ring with universal hinges. The tibial ring was mounted using two half pins. Each pin site was predrilled with a 4.8-mm drill bit and a 6-mm tapered, stainless steal pin was placed by hand into the tibial diaphysis through both cortices. C-arm fluoroscopy was used to ensure ideal pin placement. A guide wire was drilled through the talus along the axis of ankle rotation from the tip of the medial malleolous to the tip of the lateral malleolous. Universal hinges were placed along the wire medially and laterally and attached to the tibial ring. The foot ring was then attached to the two hinges and then was connected to the foot. Foot fixation included three, 2.0-mm tensioned wires. There were two crossed calcaneal wires tensioned to 130 kg and one talus wire tensioned to 90 kg. The talus wire helped prevent inadvertent distraction of the subtalar joint. No joint distraction was applied at this stage of the experiment. The rods connecting the rings were loosened to release any tension in the system and then re-tightened in the resting position. The frames were locked with the foot in a plantargrade position. Specimens were then potted in cement (Bondo, 3M, Altanta, GA) at both ends to aide in testing (Fig. 3). Multiple specimens were prepared in this way and then frozen again until testing day.

The previously prepared specimens were thawed overnight for testing the following day. Testing was performed with all authors present. The joint was temporarily distracted using the external fixator to allow insertion of the sensor. The pressure sensor was inserted into the ankle joint. The distraction was released as soon as the sensor was seen to be well positioned. This would define the undistracted or resting position of the ankle.
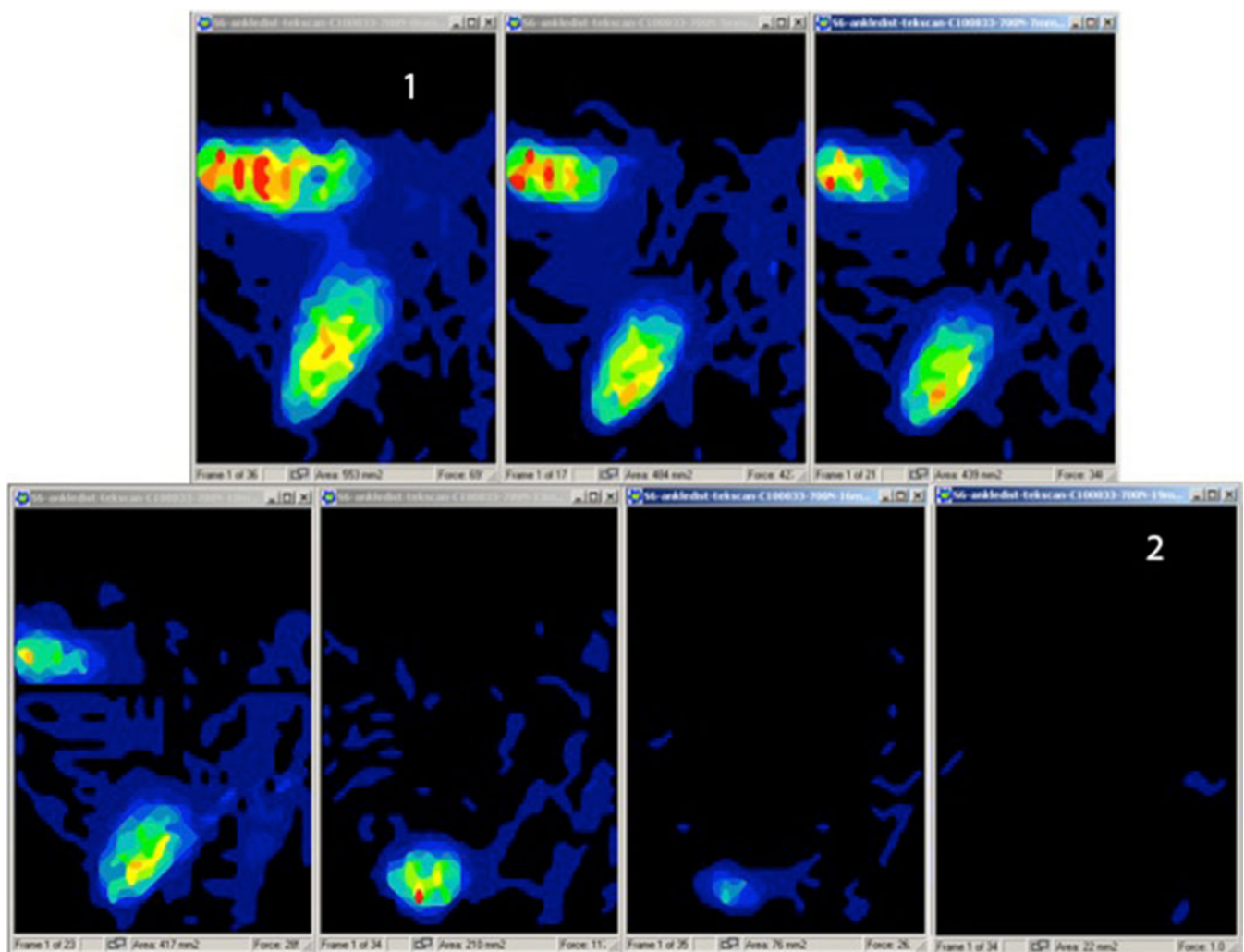

Fig. 2. This is a series of Tekscan images showing pressure on the sensor as a visual graphic. All of the images were taken under 700N of load. The image in the *upper left corner* (*1*) shows the least distraction and the greatest compression of joint surfaces. This progresses to the *lower right corner* (*2*) where there is maximal distraction and unloading of the sensor.
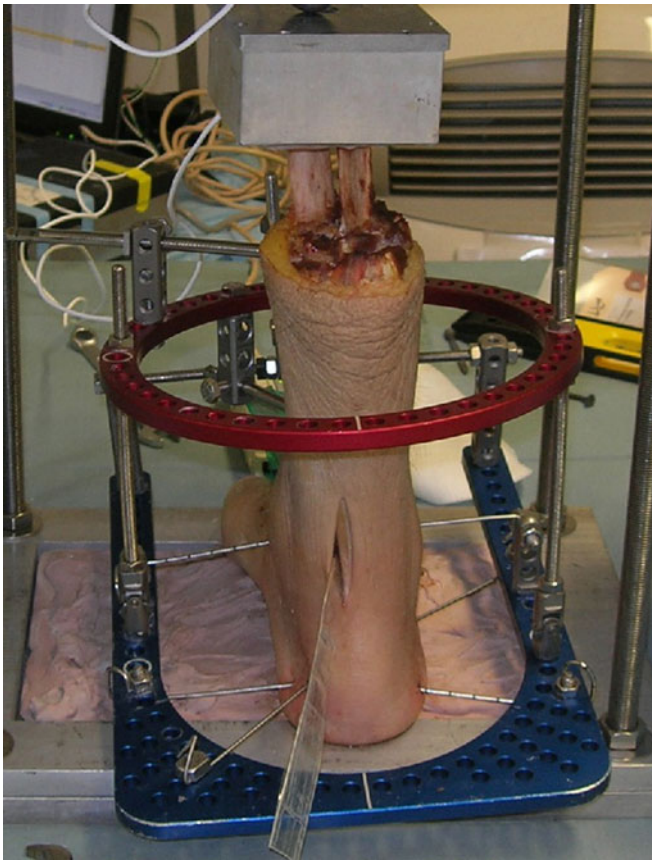
Fig. 3. The specimen is seen from the posterior view. The two-ring external fixator is positioned, and the specimen is potted in resin and fastened to customized aluminum fixtures.

Fig. 4. The C-arm fluoroscopy (*1*) is positioned for lateral ankle imaging. The ankle specimen is seen with attached external fixator inside the load chamber (*2*). Load is delivered by screwing the load cell (*3*) down into the specimen. The pressure sensor (*4*) enters the anterior ankle joint and measures intraarticular contact pressure.

The specimen was then placed into a custom-designed load chamber (Fig. 4). This chamber was capable of applying axial loads over 1,000N. The apparatus had a 300-lb (1,334N) load-cell in line with a screw actuator that placed axial load through the long axis of the tibia. The load cell measured the applied load with accuracy to the 0.1N. A 2-mm wire was drilled into the tibial metaphysis, from anterior to posterior, close to the subchondral bone and served to calibrate our fluoroscopic measurements (Fig. 5 measurements). The wire was positioned at the center of the joint. C-arm fluoroscopy was used to measure the ankle rJS. An OEC fluoroscopy machine was used for testing. The specimen was placed a uniform distance from the image intensifier for each series. The foot was positioned perpendicular to the beam. The specimen position was slightly adjusted until an ideal lateral image of the ankle joint was seen. The tibiotalar joint space was measured directly off of the screen with a digital caliper. Two separate investigators measured joint space, and interobserver reliability was calculated using the Pearson correlation. The 2-mm reference wire was also measured with the caliper after each image. The magnified wire measurement was standardized against 2 mm. This ratio was then used to convert the magnified fluoroscopic joint space measurements into millimeters.

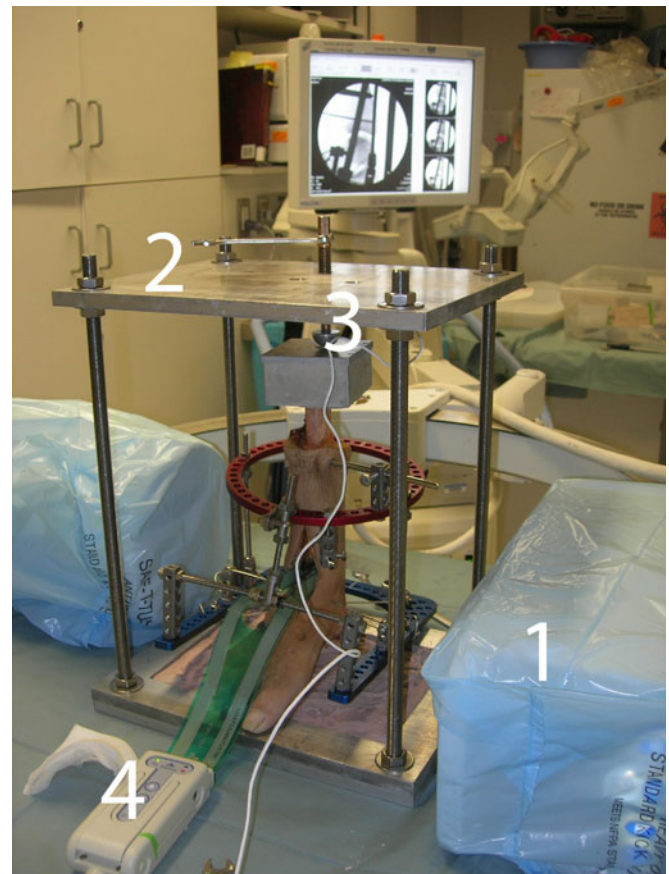The testing began with the specimen under no distraction. The rJS was measured on fluoroscopy, and a joint pressure map was recorded with the pressure sensor. This was the undistracted rJS and represented the space occupied by the articular cartilage and the sensor. The undistracted rJS was a baseline measurement that would later be subtracted from the distracted rJS measurements to calculate the DG. Load was then applied to the joint to simulate weight-bearing. A load of 350N was applied to mimic 50% weight-bearing for the average person. The rJS was measured under this load, and the joint surface pressure graphic was recorded. A load of 700N was then applied to simulate ambulation with 100% bodyweight, and again, the rJS and pressure were measured. The applied load was then returned to zero. The external fixator was then distracted in 1.0 mm increments. The rJS was measured and pressure recorded with no load, 350N load, and 700N load for each 1.0 mm increment. The external fixator distraction was stopped when the Tekscan sensor showed 0 MPa and no visual pressure under 700N of load. This was called the "unloaded frame." The rJS was measured. This was the "minimum rJS" that would ensure no loading of the articular surfaces under 700N.

Since each specimen had a slightly different initial undistracted rJS, the DG was calculated to standardize the space between articular surfaces. The undistracted rJS was then subtracted from the minimum rJS to provide the DG of
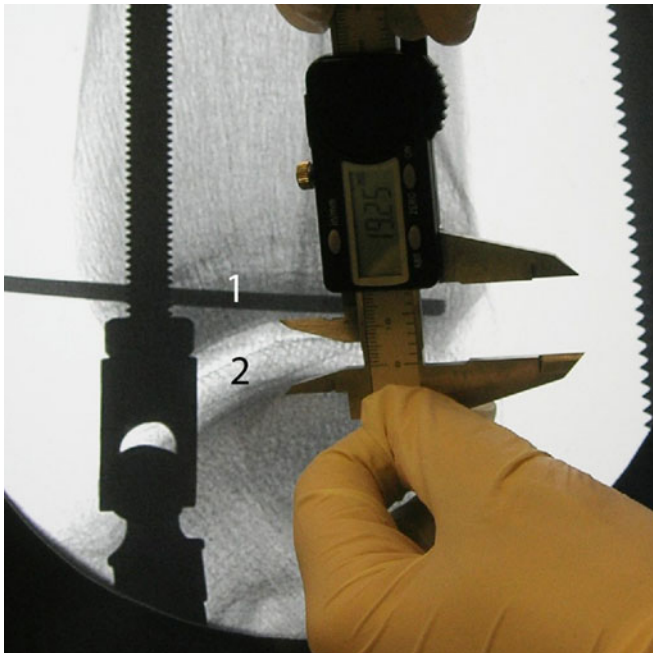
Fig. 5. The mini fluoroscopy was used to obtain a lateral image of the specimen. The 2-mm reference (*1*) wire is seen. The joint was distracted, and the rJS was measured with calipers. The shadow of the pressure sensor (*2*) is seen in the joint.

Fig. 6. The bar graph shows an average of the mDG needed to unload the joint for all nine specimens for the three different loads. The *error bars* represent the range of DG values (not the standard deviation).

the unloaded frame. This would be the "minimum DG" at 700N (mDG700) needed to ensure that the joint was unloaded for that specimen. The mDG of the unloaded frame was then calculated for 0N (mDG0) and 350N (mDG350) of load as well. Please keep in mind that the goal was to find the least amount of distraction that would unload the ankle joint under 700N of external loading pressure. We then needed to review the rJS measured under 0 and 350N of load with the same amount of external fixation distraction. Under the lesser loads, the rJS increased and the DG increased. The question, again, was when a patient undergoing ankle distraction is seen in the office and a standing (350N) ankle X-ray is obtained: How much DG (mDG350) is needed to ensure that the joint surfaces do not contact each other during walking? This experiment was repeated for eight other specimens, and an average mDG was calculated.

Results

The mDG required to unload the pressure sensor while applying 700N of force to the specimen (mDG700) was calculated for each specimen and averaged 2.4 mm (range, 1.6 to 4.0 mm). The average mDG350 was 4.4 mm (range, 3.7 to 5.8 mm), and the mDG0 was 4.9 mm (range, 3.7 to 7.0 mm) at 0N. Under 350N of load (a standing X-ray), an average of 4.4 mm of DG prevented contact between joint surfaces at all loads up to 700N; however, a 5.8-mm DG was needed to ensure no contact between joint surfaces in all specimens. A DG of 7 mm calculated at 0N of loading (a non-weight-bearing X-ray) was required to ensure no contact at 700N (full weight-bearing) of load (Fig. 6 bar graph). The interobserver reliability for measuring rJS off of the
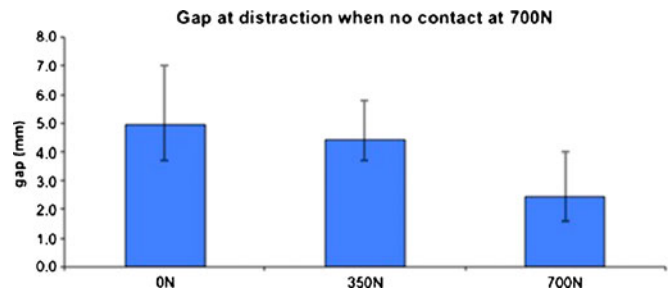
fluoro screen had a Pearson correlation coefficient of 0.995 with $p<0.001$.

Discussion

This study aimed to approximate clinical practice and determine what mDG was needed in ankle distraction to ensure that the tibial and talar articular surfaces did not contact one another during full weight-bearing during the period of treatment. This mDG700 may be a crucial quantity for foot and ankle surgeons strive to achieve. In current practice, it is presumed that 5 mm of rJS measured from a weight-bearing X-ray is adequate to ensure no contact during ambulation. However, the undistracted rJS is not accounted for, and surgeons have no idea how much the rJS seen on X-ray will compress during full weight-bearing.

There are several limitations of this study. This was a cadaveric study and has inherent limitations. The dynamic load that the tendons, including ankle dorsiflexors and plantar flexors, place on the ankle joint was not present. In vivo, these leg muscles may increase load and require greater distraction to unload the joint. The specimens had normal articular cartilage. In vivo, the arthritic, articular cartilage is thinned or absent. This normal cartilage made the undistracted joint space measurement greater than would be seen in vivo. Thought was given to removing the articular cartilage from the specimens, but we decided against that. The concern was that acutely removing the articular surfaces would leave the joint lax and less resistant to distraction thereby decreasing the tension needed to achieve the mDG700 thus altering the mechanical environment that is seen clinically. Maintaining the tension from the surrounding ligaments was thought to be very important in our simulation. We were also concerned that removal of the articular cartilage may not be uniform which would make the Tekscan pressure measurements unreliable. Viscoelasticity of the surrounding ligaments was not accounted for. In vivo, a rJS of 4 mm is acutely applied in the operating room. Additional frame distraction is applied postoperatively until 5 mm of rJS is achieved on a standing X-ray. In vivo, we have the benefit of applying distraction over time. Sustained distraction as seen in clinical practice may also lengthen the ligaments making them more receptive to additional distraction. In vitro, the specimens were distracted for testing and then the tension was immediately released. The joint space was not measured over weeks of sustained distraction. We

tried to minimize the number of times each specimen was thawed as each thaw cycle weakens the specimen. The applied loads assumed average body weight of the patient. A heavier person would need a larger DG and a lighter person would be able to reduce the DG. For a 70-kg person, standing should place half of bodyweight on the ankle or 350N. Ambulation loads the ankle with 110% of bodyweight [7] which would require loading to 770N. However, the average bodyweight for our specimens was 56 kg making 110% bodyweight 616N. We felt that this was too low a load to extrapolate to the general population. We had to choose between 616 and 770N and decided on 700N load to simulate normal walking. The statement that 4.4 mm of DG is enough to ensure no contact at the articular surface may not be true for a 100-kg individual. This heavier patient may benefit from additional distraction or from adding additional fixation to the rings. A 70-kg patient that walks briskly and places 2× bodyweight across the ankle may similarly benefit from more joint distraction. The average mDG350 of 4.4 mm assumes the patient is placing equal weight on both feet during the weight-bearing X-ray. If the patient is unloading the operated leg because of pain, then this number is invalid. To compensate for this, we calculated the average mDG0 of 4.9 mm for a non-weight-bearing X-ray. Measuring the joint space using a C-arm image is not very accurate, but it is clinically relevant. Joint space is measured off of ankle X-rays in the physician's office using a ruler or PACS system. By using a real-time intraarticlular sensor, we were able to correlate the less accurate fluoroscopic measurement with a highly accurate joint pressure measurement. In this way, we were able to confirm when the joint was unloaded. Interestingly, when the sensor showed that the joint was unloaded under a 700-N load, the average mDG700 was 2.4 mm. One would have expected the DG to be closer to 0 mm. This further confirms the inaccuracy of measuring directly off an X-ray. Our findings and subsequent recommendations may not apply to different external fixators as frame rigidity varies with the numbers of rings and pins used.

This study showed that the *average* mDG350 needed was 4.4 mm with the RAD frame, but to ensure no contact under 700N, simulating ambulation, a 5.8-mm DG was needed. This experiment can be extrapolated into clinical practice to state the following: if the patient is of average weight (70 kg) and can stand for a weight-bearing X-ray then the RAD frame will prevent articular surface contact while ambulating provided the mDG350 is 5.8 mm. If the patient is not weight-bearing during the X-ray, then an mDG0 of 7.0 mm would be needed. Van Valburg et al. [11] have recommended that the ankle joint space (rJS) measurement be 5 mm as seen on weight-bearing X-rays. The same authors report that ambulation is important to provide the intermittent piston-like action in the joint. This piston-like action then creates intermittent joint fluid pressure that in turn stimulates the regenerating articular cartilage [14]. The consensus is that the joint must be unloaded during weight-bearing for this regenerative process to occur and to obtain the good reported results. It is not clear how the authors arrived at the value of 5 mm, and it has not been shown that 5 mm is adequate to ensure no contact. The dogmatic 5 mm of rJS may be adequate to prevent joint

surface contact during ambulation provided that the mDG350 is greater than 4.4 mm and the patient does not weigh more that 70 kg. However, our recommendation is to obtain a DG of 5.8 mm when possible. A clinical trial needs to be performed to assess whether complete separation of the surfaces is beneficial clinically. Our results suggest that it is likely that the articular surfaces were in contact during ankle distraction in many cases. It may be that the success realized in arthrodiastasis can be attributed to articular surface contact at low loads. Conversely, these patients may represent the clinical failures. There are many future studies that could be done to help answer how much distraction is ideal clinically.

Disclosures

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