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Masticatory mechanics of a mandibular distraction osteogenesis site: Interfragmentary micromovement ☆

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Abstract

Micromovement at a fracture or distraction osteogenesis (DO) site may play a significant role in bone formation and healing. Mastication is an important physiological process that can cause substantial micromovement at a mandibular disjunction. The purpose of this study is to characterize and quantify the micromovement caused by mastication. Eighteen pigs, divided into three groups based on duration of consolidation, received a unilateral (right) mandibular angle distraction osteogenesis protocol. Differential variable reluctance transducers (DVRTs) and ultrasound crystals were used to measure the change of gap width as well as interfragmentary movement during mastication. Synchronized chewing video and interfragmentary movement recordings were used to determine the magnitude and direction of micromovement at different phases of the chewing cycle. The magnitude of micromovement did not increase significantly with distraction up to almost 5 mm, but did decrease gradually with consolidation. The average micromovement magnitude during the distraction phase was 0.2–0.3 mm, equaling 50,000–250,000 microstrain (με) on interfragmentary tissue. The dominant deformation pattern was bending in the sagittal plane. The most common direction of bending at the power stroke of chewing was concave dorsally, i.e., superior shortening and inferior lengthening. These findings elucidate how masticatory mechanics affect a mandibular distraction site, and the measurements may be useful for future simulation studies.

Keywords: Distraction osteogenesis; Mandible; Physiological loading; Mastication; Micromovement

Introduction

After over a decade of clinical application, mandibular distraction osteogenesis (DO) has become a commonplace treatment for severe mandibular retrognathia or mandibular hypoplasia [31,32,35]. As a mechanically manipulated process, bone regeneration at a DO site relies on the mechanics generated by the distraction through a so-called tension-stress effect [18]. Extensive research in the last decade has examined different aspects of the distraction force including magnitude, frequency and rate [1,11,24,25,36,41]. Little attention, however, has been given to local physiological mechanics. Under normal conditions, the mandible is heavily loaded during mastication [17,27]. In clinical practice, in order to avoid ankylosis of the temporomandibular joint, mastication (of a soft diet) is often encouraged early on after the DO surgery [5], but little is known about how masticatory loading, when superimposed on the distraction force, may affect bone regeneration in the DO gap.

On the other hand, investigation of long bones has suggested that physiological loading may play an important role in bone regeneration. Micromovement (<1 mm) across a tibial fracture stimulates the healing process in both animal and clinical studies [14,21–23], while excess mobility (≥2 mm) can inhibit healing [21]. Axial movements during walking 5 weeks after a tibial fracture are about 0.3 mm [8], suggesting that well-controlled early functional loading may actually help fracture healing [4]. Compared to a fracture, a distraction site has a gradually increasing gap. Larger gaps in fracture healing are associated with inferior mechanical and histological qualities of the regenerate [2,6], suggesting that distraction sites may be affected more adversely by functional loading than are fracture sites.

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Table 1
Animals and distraction osteogenesis (DO) protocol

Animals	DO protocol [a]	Measuring device	Ultimate sample size [b]
Group A: #A1–A5	5-Day distraction 1 mm/day [a], 1-day consolidation [b]	#A1–A4: ultrasound crystals #A5: DVRTs	2 Full and 1 partial recording
Group B: #B1–B8	5-Day distraction 1 mm/day 8-day consolidation	#B1–B5: ultrasound crystals #B6–8: DVRTs	4 Full and 2 partial recordings
Group C: #C1–C5	5-Day distraction 1 mm/day 15-day consolidation	#C1: ultrasound crystals #C2–C5: DVRTs	4 Full recordings

[a] #A1, A2, B1 were distracted at a rate of 1.5 mm/day, #A5 had 4 days of consolidation due to breakage of distractor, #B6 had 11 days of consolidation due to breakage of distractor.

[b] Full, both superior and inferior locations were recorded; partial, only one location was recorded.

Evidence from long bone distraction osteogenesis, however, implies that this is not necessarily true. Application of 0.2 mm of micromovement for 15 min daily to a rabbit tibia DO site actually enhances bone regeneration in the consolidation phase although not in the distraction phase [19,20]. In a goat distraction model, early weight bearing significantly improves bone formation relative to a control group [26].

In order to understand the effect of function on mandibular DO, it is indispensable to know how the DO site is deformed by mastication. However, no study has investigated micromovement at a mandibular DO site in vivo. Our previous study started to remedy this lack of data by measuring micromovement immediately after mandibular osteotomy and appliance placement [39], the baseline condition of a distraction site. In that study, we found that an average 0.3- to 0.4-mm micromovement was produced by mastication. In the current study, we proceed to investigate the micromovement of a mandibular DO site during the distraction and early consolidation phases of the procedure, and we ask two main questions. First, what is the pattern (lengthening vs. shortening) of the movement? Second, how much micromovement and tissue strain are generated by mastication during the course of DO?

Materials and methods

Animals

A total of 18 Hanford strain miniature pigs (*Sus scrofa*), obtained from Sinclair Research Farms (Columbia, MO), were used in this study. The animals were of both sexes, 3–6 months and 10–30 kg. As outlined in Table 1, pigs were divided into 3 groups based on the duration of consolidation (Group A, minimal consolidation; Group B, 1 week of consolidation; Group C, 2 weeks of consolidation). They were first acclimated to the laboratory environment for about 2 weeks and then received surgery, instrumentation and the DO protocol detailed below. All experimental procedures were approved by the University of Washington Institutional Animal Care and Use Committee.

Surgery and instrumentation

On the surgery day, the pig was pre-medicated with IM ketamine and buprenorphine injections, followed by endotracheal intubation and anesthesia maintenance with isoflurane and oxygen. The pig was transferred to the operating room, where standard aseptic surgical procedures were followed. An incision was made on the lower border of the right mandible and the anterior–inferior 1/3 of the right masseter muscle was reflected supra-periosteally to expose the ramal–body junction. A corticotomy, about 60° to the occlusal plane, was then made laterally using a Stryker® Command2 Recip saw (Kalamazoo, MI), followed by the placement of a Synthes® distractor (Monument, CO) approximately perpendicular to the corticotomy (Fig. 1). The custom-elongated handle (activator) of the distractor was brought out of the skin just posterior to

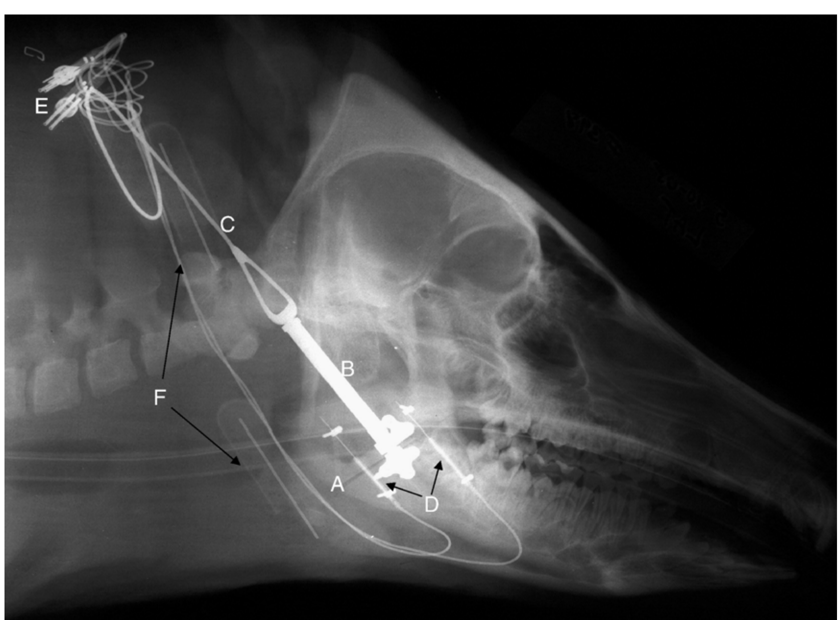

Fig. 1. DO surgery and device placement. Post-operative lateral view X-ray showing an osteotomy (A) at the mandibular angle. A distractor (B) was placed perpendicular to the osteotomy with an elongated handle (C) exiting posterior to the condylar neck. Measuring devices (D, DVRTs) were placed parallel to the distractor at superior and inferior locations. (E) The DVRT leads exited at the back of the neck. Antibiotic osmotic pumps (F) were inserted near the distractor handle and device wires for infection control.

the condylar neck via a sub-masseteric tunnel. Five bicortical self-tapping screws (diameter 2.4 mm, length 8–14 mm) were placed to fix the distractor plates to the bone after pilot drilling. The corticotomy was then extended to the medial cortex followed by fracture of the middle trabecular bone, resulting in a complete osteotomy with an intact neurovascular bundle in most cases. Copious warm sterile saline irrigation was applied for all cutting and drilling procedures.

The width of the distraction gap and the interfragmentary micromovement were measured at two locations on the lateral surface, one above (superior) and the other below (inferior) the distractor (Fig. 1). For the first 10 experimental pigs (Table 1, #A1–A4, B1–B5, C1), ultrasound crystals (Sonometrics, London, Ontario) were used for these measurements. These crystals record distance as ultrasound time-lapse signals with a claimed resolution of 0.02 mm. However, due to breakage problems, only 3 full recordings (#A3, B2, B4) and 2 partial recordings (#A4, B1) were obtained for these pigs (Table 2). A second type of device, differential variable reluctance transducers (DVRTs, Microstrain, Williston, VT), was therefore used for the next 8 pigs (#A5, B6–8, C2–C4), from which 7 full and 1 partial recordings were obtained (Table 2). The DVRT has a company-claimed resolution of 0.001 mm and it records distance as voltage. Both crystals and DVRTs were secured through long pegs (crystals 7 mm, DVRTs 12 mm) inserted into predrilled holes at desired locations on the bone. The ultrasound crystal pairs and the DVRT axes were aligned parallel to the long axis of the distractor. The lead wires were pulled through a subcutaneous tunnel and brought out of the skin via a small incision on the back of the neck, where the connectors were sutured to subcutaneous tissue and skin.

For infection control at the exit sites, two Alzet® osmotic pumps (Durect Corporation, Cupertino, CA) loaded with antibiotic (Amikacin 250 mg/ml, 2 ml, Bedford Laboratories™, Bedford, OH) were placed in the two tunnels (Fig. 1). These pumps release antibiotic to adjacent tissues at a continuous rate of 5 μl/h for 14 days.

The incisions were then closed in two layers. A fentanyl patch (50 μg/ml) was attached to the back skin for pain control (removed 3 days after surgery). Baseline X-rays (Fig. 1) were taken in lateral and dorsal–ventral projections. The endotracheal tube was then removed and the pig was brought back to its pen, where it awakened.

Post-operative care, distraction and data acquisition

To simulate the soft diet regimen adopted by clinical DO patients, the pig chow was softened by soaking with water. Post-operative pain control was managed by the fentanyl patch and buprenorphine hydrochloride (Reckit and Colman, Richmond, VA) 0.01 mg/kg intramuscular injection as needed. Infection control was managed by daily debridement and topical application of a powder containing neomycin sulfate and tetracaine hydrochloride (Neo-Predef®, Pharmacia and Upjohn Company, Kalamazoo, MI), together with antibiotics given twice daily in the food, (a) trimethoprim and sulfadiazine (Tucoprim®, Pharmacia and Upjohn) at 50 mg/kg and (b) cephalexin oral suspension (Teva Pharmaceuticals, Sellersville, PA) at 22 mg/kg.

As shown in Table 1, distraction at 1 mm/day started the second day after osteotomy surgery (1-day latency) except for the first three pigs (#A1, A2 and B1). These 3 pigs had a 2-day latency period and were distracted at 1.5 mm/day. The change in protocol was prompted by the desire to more closely mimic clinical usage [34] and the observation that the slower rate did not lead to premature consolidation, as originally feared. The minimal latency is based on other reports [13,34] that such short latency periods do not endanger the osteogenesis process. Distraction continued for 5 days. During the daily activation of the appliance, the actual opening of the distraction gap was monitored by ultrasound or DVRT readings as detailed below. In general, 1 mm of gap opening was achieved by approximately 2 full turns of the distractor but the first 1 mm often required additional turns, probably due to settling of the distractor at the initial phase of distraction [40]. After the distraction phase, the distractor was kept in place for consolidation on periods of 0, 1 and 2 weeks as shown in Table 1.

The lead wires of the ultrasound or DVRT devices were connected to their respective external receiving boxes to measure gap size and micromovement. The ultrasound signals were collected by a computer running Sonometric software (Sonometrics, London, Ontario); analog DVRT signals were collected by a computer running Acqknowledge III (Biopac Systems, Santa Barbara, CA) and converted to linear distance changes using pre-determined calibration equations. After the distractor was turned, micromovements were recorded for about 10 min on each post-operative day. These daily functional recordings were continued during the consolidation phase.

In addition, for those pigs in which DVRTs were used, several brief recordings (5 s) of synchronized video (Canon ZR50 digital camercorder) and micromovement signals were collected by a PeakMotus® system (Vicon, Centennial, CO).

X-rays were taken at post-operative days 6 (all groups), 13 (groups B and C) and 20 (group C). X-ray films were used to measure the opening of the distractor

Table 2
Distraction gap width (mm) during DO

Animal ID	Week 1 (post-operative day 6)			Week 2 (post-operative day 14)			Week 3 (post-operative day 20)		
	Distractor (X-ray)	Superior gap (device)	Inferior gap (device)	Distractor (X-ray)	Superior gap (device)	Inferior gap (device)	Distractor (X-ray)	Superior gap (device)	Inferior gap (device)
Group A									
A1	7.8	ND	ND						
A2	7.6	ND	ND						
A3	5.6	5.0	4.7						
A4	3.6	ND	2.9						
A5	0.6	0.2	0.2						
Group B									
B1	8.6	6.8	ND	8.1	ND	ND			
B2	5.0	4.8	5.1	4.0	2.1	ND			
B3	1.1	ND	ND	0.7	ND	ND			
B4	6.1	5.5	4.4	6.7	4.8	3.4			
B5	3.1	ND	ND	1.0	ND	ND			
B6	1.5	0.1	0.1	1.5	0	0.1			
B7	5.0	5.5	5.1	4.0	3.8	2.3			
B8	4.6	4.5	ND	3.9	ND	ND			
Group C									
C1	3.2	ND	ND	3.4	ND	ND	3.6	ND	ND
C2	4.0	3.5	2.4	3.0	2.1	1.2	2.2	2.1	ND
C3	5.9	5.1	4.7	5.9	5.4	4.9	5.9	ND	4.2
C4	5.1	6.5	5.3	4.8	6.1	6.8	4.8	6.2	6.4
C5	5.8	5.0	5.4	5.3	5.3	ND	5.2	5.2	ND

ND, no data available.

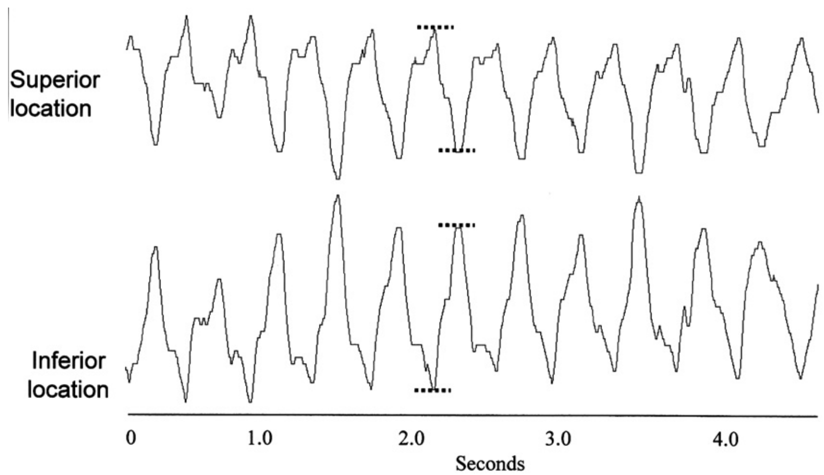

Fig. 2. Micromovement magnitude measurement. A typical crystal recording showing 12 chewing cycles in about 4.5 s was selected for analysis. The magnitude of micromovement was measured as the inter-peak distance (between broken lines). All cycles were measured and averaged. Calibration bar, 0.2 mm.

and check the consistency of device locations. Terminal experiments were performed on the day that the pig was sacrificed, during which strain gages were implanted on the condylar regions, as will be reported in detail elsewhere. No invasive procedures were performed at the distraction site at the terminal experiment. Micromovement during mastication was recorded as usual along with strain at the condyle. After data collection, the pig was placed under deep anesthesia and perfused with fixative. Specimens were collected for future analysis of histology.

Data analysis

The distraction gap is defined as the space between two original (old) bone fronts. Its width was measured directly by the implanted devices. The opening of the distractor, defined as the distance between the two appliance plates, was measured from X-ray films.

The following criteria were used to reject ultrasound crystals or DVRT recordings: (1) absence of waveform traces, (2) unreasonable readings, e.g., gap width measurement much wider or narrower than the X-ray measurements, (3) unreasonable changes, e.g., decrease or increase of gap width by more than 2 mm when the appliance had not been activated. These findings were taken as indications that the devices were broken or dislodged.

The direction of micromovement was deduced from crystal or DVRT recordings. Usually, the baseline was defined at a time when no mastication was taking place, and masticatory micromovement direction (shortening or lengthening) was established by comparison to the baseline. For the video-synchronized recordings, the chewing cycle was divided into three phases, closing stroke, power stroke and opening stoke [15,16]. The beginning of each chewing cycle was considered to be maximum opening and as a result, a chewing cycle consisted of the closing, power and opening strokes in that order.

As shown in Fig. 2, out of the 10-min recording each day, 2–3 sequences (each 10–20 chewing cycles long) were selected using the criterion of continuous chewing without nibbling or ingestion behaviors. Micromovement magnitude for each chewing cycle was defined as the difference between the longest and the shortest gap widths. Chewing cycle measurements were then averaged to gain the magnitude for each chewing sequence. Because of the relatively large number of cycles analyzed, the magnitude was usually similar (<10% different) between sequences. The overall magnitude for each day was then calculated by averaging all sequences measured.

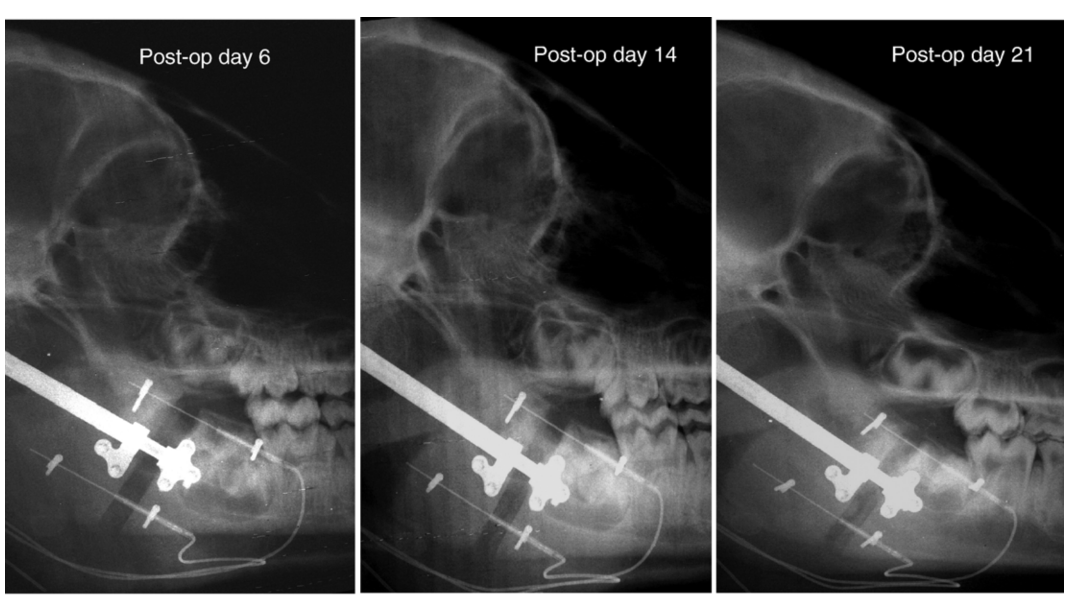

Fig. 3. Serial X-rays of a distracted mandible (#C4). Note the uneven opening of the gap at the end of distraction. Pronounced new bone formation was seen after one week of consolidation (post-operative day 14) and continued at 2 weeks of consolidation (post-operative day 21), leading to decreased distraction space.

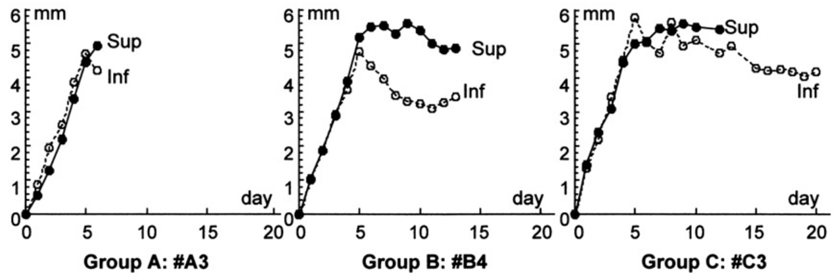

Fig. 4. Examples of daily measurements of gap width change with time as measured by crystals or DVRTs. In successfully distracted animals, gap width increases linearly during the distraction phase (post-operative days 1–6). During the consolidation phase, gap width tends to decrease at the inferior location.

Strain of interfragmentary tissue during mastication was calculated by dividing micromovement by gap width.

Results

As might be expected for a first attempt to characterize the masticatory mechanics of a mandibular distraction site, this study encountered several technical difficulties. First, three distractors failed to activate due to breakage of the distractor handle (pig # A5, B3, B6). Second, as mentioned earlier, the ultrasound crystals used in the first 10 animals failed at a high rate. Third, like many chronic recordings from animals, there was some deterioration of measuring device performance starting at post-operative week 2, resulting in incomplete data for the consolidation phase. In spite of these problems, we were able to record the masticatory mechanics for most animals.

Distraction gap width

Gap width measurements are presented in Table 2. An example of serial lateral X-rays and examples of gap width recordings using ultrasound crystals and DVRTs are illustrated in Figs. 3 and 4, respectively.

At the end of the distraction phase, measurement from the X-ray films showed that all pigs were successfully distracted except those with broken appliances. Pigs #A1, A2, B1, 2, 6 had over 7 mm of distractor activation because a 1.5 mm/day rate was used in these pigs. On the other hand, although we followed the distraction protocol strictly by ensuring 1 mm of distraction was gained every day using the measuring devices, 4 pigs (#A4, B5, C1, C2) showed under-distraction of 1 mm or more (compared to the expected amount of 5 mm).

As shown in Table 2, compared to the opening of the distractor appliance measured on X-rays, widening of the bony distraction gap measured by ultrasound crystals or DVRTs tended to be less. Based on all available data (Table 2), after the distraction the superior and inferior bony locations were less separated than the appliance by an average of 0.4 mm and 0.7 mm, respectively, although neither difference reached statistical significance (paired *t*-tests, superior $p = 0.09$; inferior $p = 0.07$). Another tendency was the uneven opening of the distraction gap (superior slightly more open than inferior, average 0.4 mm), which is also shown in Fig. 3. However, the difference was again below statistical significance (paired *t*-test, $p = 0.07$).

After 1 week of consolidation, most pigs showed slight decreases (≤ 1.0 mm) in the distractor activation (X-rays) and gap width (devices). During the second week of consolidation, measurements were generally stable.

Pattern of micromovement

Significant micromovement at the DO site was only seen when the pig was chewing. During the distraction and early consolidation (3–4 days after distraction) phases, micromovement showed clear directionality. During the late consolidation phase, micromovement direction was less regular, in part because reduced magnitude made measurement difficult. Typical recordings from the distraction phase are presented in Fig. 5. The ultrasound crystals (Fig. 5A) and DVRTs (Fig. 5B) gave similar results, although they indicated the movement direction differently. During chewing, both the superior and inferior locations of the distraction site moved in a cyclic sinusoidal fashion. At any given time, however, the two locations were moving in opposite directions to each other. Thus, a shortening peak at the superior location always

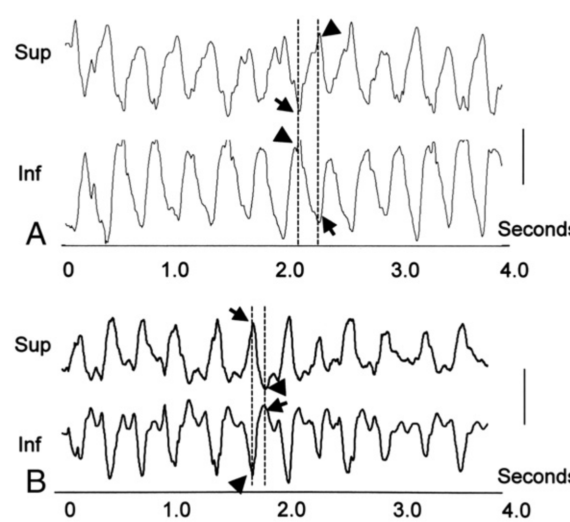

Fig. 5. Micromovement directionality during mastication. Typical recordings from ultrasound crystals (A, pig #B4) and DVRTs (B, pig #C5), both exhibiting cyclic features. DVRT analog signals show the opposite direction of the true movement, i.e., a downward peak is lengthening while an upward peak is shortening. Two major peaks (broken lines) are present for each chewing cycle. The peak values (shortening, arrow; lengthening, arrow head) are opposite between the superior (Sup) and inferior (Inf) locations. Calibration bar, 0.2 mm.

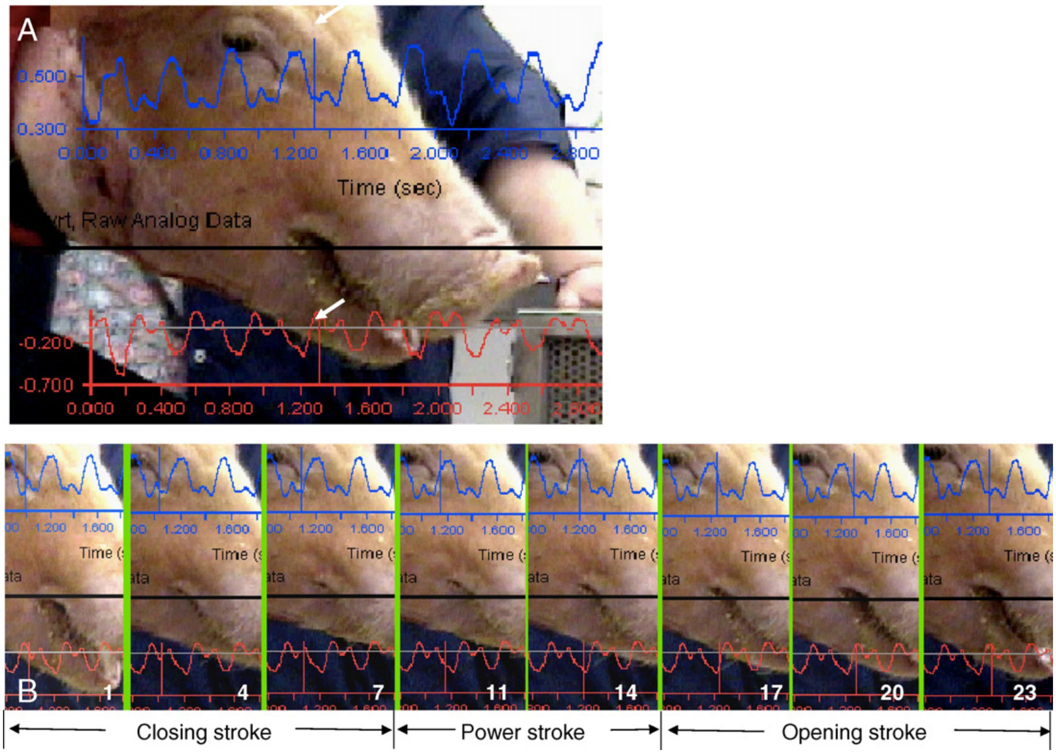

Fig. 6. (A) Overview of a masticatory sequence showing micromovement (recorded by DVRTs) at superior (blue) and inferior (red) locations superimposed on the video. The vertical scanning lines (arrows) show the moment recorded. (B) A single chewing cycle consisting of 23 frames (1/60 s each). The selected frames (numbered) indicate the closing stroke (frames 1–7), the power stroke (frames 8–14) and the opening stroke (frames 15–23). During the power stroke, the superior location shortened, while the inferior location lengthened. During opening, these changes were reversed.

coincided with a lengthening peak at the inferior location, and vice versa.

A synchronized video-micromovement recording illustrating a typical pattern is shown in Fig. 6. During the closing stroke, the DO gap exhibited only minimal micromovement. During the power stroke, significant micromovement was present. Specifically, the gap shortened superiorly and lengthened inferiorly, both of which peaked right before the start of the opening stroke. During the opening stroke, the DO site returned to the previous level, i.e., lengthened superiorly and shortened inferiorly. An opposite pattern was observed in two animals (pigs #C1, C2).

In summary, the DO site micromovement is initiated at the power stroke, and the most common, but not only, pattern is superior shortening and inferior lengthening.

Magnitude of micromovement

The average magnitude of micromovement as a function of time is illustrated in Fig. 7. The 3 pigs with broken distractors were treated as a separate group, referred to as “undistracted”.

During the distraction phase (post-operative days 1–6), both the superior and the inferior locations had interfragmentary

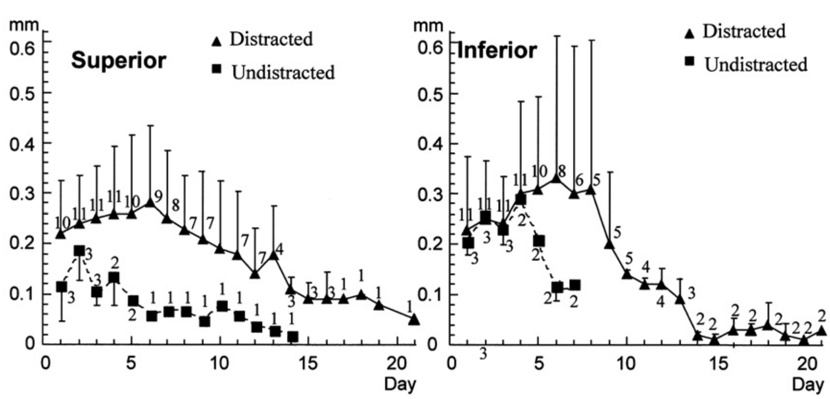

Fig. 7. Masticatory micromovement magnitude over time (average and standard deviation). The “distracted” are those with at least 3 mm of distraction ($n=15$), while the “undistracted” group consists of 3 pigs with broken appliances and maximum distraction of 1.5 mm. Numbers beside each average value indicate the sample size that had available data. Vertical bars indicate standard deviations (upward, distracted group; downward, undistracted group). Note both superior and inferior locations showed a minor gradual increase during the distraction phase (days 1–6) and a more substantial decrease during the consolidation phase (days 7–21).

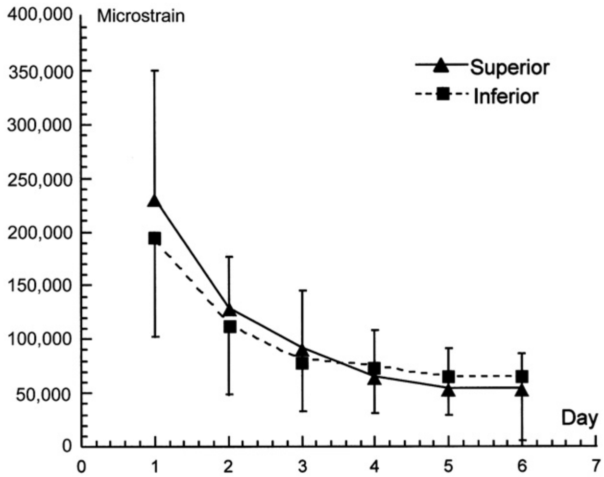

Fig. 8. Interfragmentary tissue strain during the distraction phase. Note in both superior and inferior locations, the strain during mastication decreased from 200,000–250,000 με to 50,000–100,000 με with the progress of distraction. Vertical bars indicate the standard deviation (upward, superior location; downward, inferior location).

micromovement in the range of 0.2–0.3 mm, and a paired *t*-test did not find a significant difference between the two locations. Compared to the distracted animals, the undistracted animals had about 0.1 mm less micromovement at the superior location but a similar level at the inferior location. During the distraction phase, there was a slight increase in magnitude with distraction, but only in the distracted pigs. However, the daily increase was only several hundredths of a millimeter.

During the consolidation phase, fewer data were available. Nevertheless, superior and inferior locations both demonstrated decreasing magnitudes of masticatory micromovement as consolidation progressed. Towards the second week of consolidation, less than 0.1-mm movement was observed at either location.

Masticatory strain of the interfragmentary tissue

Masticatory strain across the DO site during the distraction phase is charted in Fig. 8. On the first day of distraction, an average strain in the range of 200,000–250,000 με was applied to both superior and inferior interfragmentary tissue by mastication. Although distraction enlarged the gap, the strain level dropped gradually because the increase in micromovement was so small. At the end of the distraction, the strain had dropped to a level in the range of 50,000–100,000 με.

No calculation was made for the consolidation phase, because gap width during this phase was changed by new bone deposition and this could not be measured accurately on the X-rays. However, based on the decreasing interfragmentary movement, the strain caused by mastication was probably no greater than that at the end of the distraction.

Discussion

Although we experienced device failures, those instruments that remained unbroken and in place, both ultrasound crystals and DVRTs, gave consistent and precise measurements.

The possibility exists that the two types of measuring devices used were not fully comparable. Only 3 full and 2 partial recordings were obtained from the ultrasound crystals, which makes meaningful comparison impossible. However, in our previous acute study [40], we found that the crystals tended to generate slightly larger readings, but by less than 0.1 mm. Therefore, the potential bias due to changing devices was small.

We were also concerned that the formation of callus adjacent to the distraction site would change the alignment of the devices, thus resulting in a false finding of increased gap width. This phenomenon may be responsible for the anomalous post-distraction increases in pigs #C4 and C5. However, interfragmentary micromovement would not be affected since it depends on the relative motion of the two fragments. Therefore, for the consolidation phase, the measurement of micromovement is valid, but caution is necessary for gap width measurement.

Gap width

As reported above, two tendencies were observed regarding the DO gap opening during the distraction phase. First, the gap tended to open unevenly with slightly more opening superiorly. Uneven opening of the distraction gap and uneven formation of regenerate have been reported in other animal mandibular DO models [3,7,25] and patients [10], as well as in our acute osteotomy study [40]. In that study, we activated the distractor when the pig was under anesthesia and in a prone position with teeth in occlusion, and we found that the inferior location tended to open more than the superior location. In contrast, the current study found that during actual distraction the superior location tended to open more. This uneven opening of the distraction gap may arise from unbalanced muscle force exerted on the fragments. Specifically, the downward pull of jaw openers on the distal fragment together with the backward and upward pull of intact jaw closers on the proximal fragment would lead to more opening at the superior location.

Second, the bony gap width tended to be less than the opening of the distractor appliances. Similar findings have been reported in a rat mandibular DO study [28]. This phenomenon could result from (1) migration of the devices through the bone (i.e., via resorption or physical fracture) and or (2), tissue resistance to the distraction, causing bending of screws or deformation of the screw/plate junction as suggested by Gateno et al. [12]. Similar phenomena may have caused the reduction of distractor opening and gap width during the early consolidation phase compared to the distraction phase.

Pattern of micromovement

Masticatory loading is clearly the cause of micromovement of the distraction gap, as no significant movement was seen during other activities. In order to understand the overall deformation pattern of the DO site, it is necessary to measure interfragmentary movement at multiple locations. In our previous acute study, three measuring devices were placed, allowing both sagittal and transverse plane movements to be measured [39]. However, only sagittal plane deformation was seen. In the current study, the medial side was not instrumented due to the difficulty of surgical access and the probability that little important information would be gained. Indeed, the movement pattern observed was consistent with sagittal plane bending in that the superior and inferior locations were always moving in opposite directions. Other patterns, such as shear or transverse bending, would have caused the same movement direction in both locations. However, we cannot eliminate the possibility that the fragments were rotating around the long axis of the mandible, which also would produce such a pattern.

The cyclic nature of masticatory micromovement, together with the changing baseline, made it necessary to deduce directionality from the synchronized video and micromovement recordings. The most common deformation pattern at the power stroke was found to be superior shortening and inferior lengthening. Mechanically, this deformation must have been caused by a combination of jaw closer contraction and occlusal force, with the latter being the dominant element, since little deformation occurred during closing, which also requires muscle contraction. It is known that occlusal contact and muscle contraction set up twisting forces in the mandible [9,27]. After osteotomy, establishment of occlusal contact may have permitted the intact opposite side muscles to set up a rotation of the larger jaw fragment, thus separating the osteotomy inferiorly. However, this scenario does not explain why an opposite pattern was seen in two pigs; we could not identify any feature of these two distractions that would account for the difference.

Adding more to the puzzle, our previous study [39] found that the main deformation pattern immediately after DO osteotomy was superior lengthening and inferior shortening, just as in the 2 anomalous pigs. However, in the previous study we did not have synchronized data, and so the findings are less secure than the present study. Additional differences between the previous and present studies are that the previous pigs had distraction surgery but were not actually distracted and that they avoided chewing on the osteotomy side [37]. In the present study, pigs were observed alternating sides during chewing (the normal pattern) [15,38] by post-operative day 3.

Magnitude of masticatory micromovement and strain

Intuitively, opening a distraction site should increase its instability, causing increased micromovement under the same level of loading. In the current study, however, only a very slight increase was observed over 5 mm of the opening. We conclude that magnitude of micromovement reflects primarily the limited compliance of the appliance–bone interface. Furthermore, 5 mm is a relatively small distraction; conceivably, greater micromovement might be seen with greater distraction.

The average masticatory micromovement during the distraction phase was in the range of 0.2–0.3 mm. This is very similar to the physiological (walking) axial movements at tibial fractures 5 weeks after injury [8]. This is also the magnitude of micromotion applied in vitro and found to enhance bone formation during the consolidation phase of DO [19,20]. It is also in the range of movement considered to stimulate fracture healing [14,21–23].

The force system at the distraction site is very complex, involving masticatory and bite force, compliance of the appliance, and stabilization of hard and soft tissues around and inside the distraction site. At this time, meaningful estimates of the magnitudes of each factor are not possible. What is clear, however, is that because muscle force and hardware compliance are relatively constant, the decreasing magnitude during consolidation must have resulted from bone and soft tissue regeneration at the distraction site.

To the best of our knowledge, this is the first study to quantify in vivo micromovement in mandibular DO, thus no comparison is possible. However, the level of 0.2–0.3 mm is somewhat lower than the 0.3–0.4 mm found immediately after DO osteotomy [39], suggesting that the chronic DO sites are less mobile. A reasonable explanation is that even 1 day after surgery, there is already some repair of soft tissue around the DO site and formation of granulation tissue inside the gap, both of which could potentially help with the stabilization.

The strain level was found to decrease gradually from 200,000–250,000 $\mu\varepsilon$ to 50,000–100,000 $\mu\varepsilon$ during the distraction due to increasing gap size and relatively constant micromovement. Compared to the "physiological" strain (2000 $\mu\varepsilon$) discussed by Meyer et al. [33], the strain of masticatory micromovement is certainly much higher. According to Meyer et al. [33], high strain (200,000–300,000 $\mu\varepsilon$) caused by distraction promotes fibrous tissue rather than bone formation. On the other hand, an experimental [30] and finite element analysis [29] of rat mandibular DO found the ideal strain for bone formation was 100,000–125,000 $\mu\varepsilon$. Therefore, the masticatory strain observed in our study may actually be beneficial for bone formation. Furthermore, a dramatic decrease of interfragmentary movement was observed during the consolidation phase, suggesting bone formation in the distraction gap was indeed active. The X-ray films also demonstrated rapid deposition of new bone.

Overall, this study characterized and quantified micromovement across a mandibular distraction site in the pig. These findings should be useful for future simulation studies to model the relationship between mechanics and mandibular distraction osteogenesis, although of course data from other locations and other species are still needed. In addition, the experimental pigs in this study had normal occlusion and masticatory activity, and were made abnormal by the procedure. This differs from clinical DO patients with mandibular retrognathia or hypoplasia. Theoretically for these patients, mandibular distraction could bring masticatory mechanics to a more normal status.

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