Review Article

Biomechanics of Craniofacial Sutures: Orthopedic Implications

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Abstract: Sutures are soft connective tissue articulations between craniofacial bones. Suture mechanics deals with patterns of mechanical stress experienced in sutures resulting from natural activities such as mastication and exogenous forces such as orthopedic loading. Patterns of sutural mechanical stress can be delineated readily as sutural strain using strain gages attached over the suture. In mastication, complex sutural strain patterns have been elucidated in a few species. Mechanical stresses are not transmitted in the skull as a continuing gradient, for different sutures are capable of redefining a propagating mechanical force as predominately tensile or compressive strain. Exogenous mechanical forces with engineering waveforms such as static and sine wave at different frequencies induce corresponding waveforms and rates of sutural strain, providing the basis for applying novel mechanical stimuli to engineer sutural growth. The available data on suture mechanics converge to a hypothetical theme that mechanical forces regulate sutural growth by inducing sutural mechanical strain. Various orthopedic therapies, including headgear, facemask, and functional appliances may induce sutural strain, leading to modification of otherwise natural suture growth. (*Angle Orthod* 2003;73:128–135.)

Key Words: Suture; Force; Bone; Headgear; Functional appliances

INTRODUCTION

Joints are meeting places of bones.[1] Because all bones are designed to withstand mechanical loading, all joints must transmit mechanical stresses. Cranial and facial sutures are connective tissue joints between skull bones. Sutures invariably experience and transmit mechanical stresses that are generated either endogenously by muscle contraction, or exogenously in trauma, during natural birth or by therapeutic mechanical devices. Suture mechanics deals with patterns of mechanical stresses experienced in craniofacial sutures. The present review was designed to accomplish two goals related to suture mechanics: (1) to summarize key knowledge about biomechanics of cranial and facial sutures upon mastication and orthopedic loading and (2) to identify the impact of suture mechanics research on orthopedic therapies such as distraction osteogenesis, headgear, facemask, and functional appliances. Mechanobiology of craniofacial sutures with a focus on biomechanical regulation of sutural growth has been subjected to a recent review.[2] The reader is also referred to several in-depth reviews on suture evolution, cell biology, and molecular genetics,[3–6] as well as advances in sutural synostosis.[7–10]

SUTURES EXPERIENCE AND TRANSMIT MECHANICAL STRESSES IN MASTICATION

Experimental evidence unequivocally indicates that cranial and facial sutures experience and transmit mechanical stresses generated in mastication. This kind of evidence usually is obtained by applying strain gages, engineering sensors used in structural mechanics, on the cortical surface of craniofacial bones either adjacent to or directly over sutures in animal models during mastication. Early attempts to understand stress patterns of facial bones were made by Endo.[11,12] Canvas sheets were attached to macerated human skulls to simulate the contraction of masseter and temporalis muscles while bone strain was measured adjacent to the nasofrontal, and frontozygomatic sutures. In general, simulated masseter contraction increased tensile strain, whereas simulated temporalis contraction increased compressive strain. Although Endo's experimental measurements of strain patterns of skull bones was pioneering, it has drawn criticism for its experimental model of macerated skulls. Inferences regarding masticatory bone strain drawn from macerated skull models are not as reliable as in vivo bone strain data obtainable from live animals. Nonetheless, Endo's experimental observations on bone strain patterns

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of the human craniofacial skeleton upon simulated masticatory loading remains valuable because in vivo bone strain measurements in the human craniofacial skeleton obviously are not an option.

Since Endo's experiments on macerated skulls, our knowledge of in vivo skull loading has been enriched by several investigators, most notably from the laboratories headed independently by Herring and Hylander. Their in vivo experimental data obtained in two species, Hylander's macaque model and Herring's pig model, have been the cornerstone of our current understanding of in vivo skull loading in mastication. These painstaking in vivo bone strain experiments are usually performed in several stages. First, strain gages and strain rosettes are placed on the cortical bone surface with animals under general anesthesia. Once awake, animals are fed while bone strain is continuously recorded. Finally, a large amount of biomechanical data are mathematically manipulated and further analyzed to obtain conclusions on complex sutural strain patterns.

Hylander et al made systematic observations on strain patterns not only across facial sutures but also in the mandibular condyle and the circumorbital region in a macaque model. The mandibular condyle experiences large mechanical strain in mastication,[13–15] thus providing experimental evidence that the temporomandibular joint, like other synovial articulations, sustains mechanical stresses. In contrast, the macaque circumorbital region experiences little bone strain despite a large amount of bone mass.[16–18] Bone strain differs across the zygomaticotemporal suture of the zygomatic arch: high strain anterior to the suture, likely attributable to the attachment of the contracting masseter muscle, but low strain posterior to the suture.[19,20] Loading of the zygomatic arch is more complex, and is likely to be composed of bending in multiple planes, with shearing and twisting.[20] Herring's laboratory conducted a series of investigations of bone strain patterns of the pig zygomatic arch, which is characterized by a short vertical zygomatic segment and a long horizontal squamosal segment.[21] Bone strain patterns differ between these two segments and across the zygomaticotemporal suture: compressive in the vertical segment, but tensile in the horizontal segment.[21] The pig squamosal bone experiences higher strain (mean, 349 $\mu\epsilon$ strain) than the zygomatic bone (mean, 174 $\mu\epsilon$ strain).[22] These strain measurements on the lateral (outer) surface of the squamosal bone have been complemented by strain recordings from the medial (inner) surface of the zygomatic arch.[23] The outer squamosal bone experiences higher strain than the inner squamosal bone.[23] Another valuable contribution by Herring et al. is the strain patterns of cranial vault sutures. The pig nasofrontal, interfrontal, and internasal sutures in an adjacent area were measured with a uniaxial strain gage attached directly over each suture, half on each side of the suture.[24] This technique to directly measure sutural strain, also used by Mao et al,[25] represents an important departure from previous attempts to measure sutural strain with two strain gages on each side of the suture. Mastication induces large tensile strain (mean, $\sim$1036 $\mu\epsilon$ strain) in the interfrontal suture but compressive strain (means, -440 $\mu\epsilon$ strain and -1583 $\mu\epsilon$ strain, respectively) in the internasal and nasofrontal sutures. Sutural strain is consistently higher than cortical bone strain adjacent to the suture.[26]

Additional important investigations have further contributed to our understanding of in vivo skull loading. Deformation of facial bones indicates that sutures withstand mechanical stresses without overstressing facial bones.[27] There is consistent tensile strain across the zygomaticofrontal suture during mastication in both macaques and chimpanzees.[28,29] The macaque sagittal suture experiences tensile strain upon temporalis contraction.[30] An exhaustive search has, unfortunately, revealed few additional sutural strain investigations during mastication.

On the basis of the knowledge gained from a limited number of species, patterns of sutural mechanical stresses in mastication can be summarized as follows:

- Cranial and facial sutures experience and transmit mechanical stresses generated during mastication.
- Sutural mechanical stresses during mastication are complex because of momentary changes in force direction, muscle function, complex sutural forms, and the irregular shape of craniofacial bones.
- Strain patterns vary between sutures. Adjacent sutures can experience tensile or compressive stresses.
- Although our understanding of suture mechanics has gained solid ground, much additional work is needed to study unexplored sutures, and in many species.

SUTURES TRANSMIT MECHANICAL STRESSES UPON EXOGENOUS FORCES SUCH AS ORTHOPEDIC LOADING

Given the aforementioned evidence that sutures experience and transmit mechanical stresses in mastication, it is not difficult to understand that mechanical stresses elicited by exogenous forces also are experienced and transmitted by sutures. Simulated masticatory forces applied to macerated skulls by canvas sheets[11,12] can also be regarded as exogenous forces. Subsequent investigations have provided further insights of simulated orthopedic loading in macerated human skulls, for the same data cannot be obtained in human beings in vivo, and orthopedic loading such as headgear is applied in the absence of muscle contraction. Thus, although the dry human skull model is inappropriate for studying stress patterns of craniofacial bones during natural activities such as mastication, it may be the best alternative experimental approach for studying bone strain responses to orthopedic loading.

Sutures absorb considerable energy generated by impact mechanical forces on goat skulls,[31,32] suggesting the possibility that sutural cells and the extracellular matrix components may store strain energy. Sutures also have a range of mobility and certainly are not immovable joints when they are patent.[4] Even visually closed sutures of macerated human skulls demonstrate sutural edge displacement upon moderate orthopedic forces.[33,34] Relative movement of sutural bony edges, even of minute magnitude, provides a potential mechanism for mechanical stimuli to activate biological responses of sutural cells. Sutural strain varies upon changing directions of orthopedic forces as shown in a computer model and later experimental bone strain experiments.[25,35–39] Sutural strain patterns are similar between dry skull models and the same structures in vivo.[27,40] For example, sutural strain patterns upon in vivo headgear loading in *Macaca irus* are substantially similar to sutural strain patterns in the same locations of dry skulls of the same animals obtained thereafter,[27,40] validating the approach of using dry skulls to study orthopedic loading with the caveat that the magnitude of bone strain is several fold less in dry skulls because of its higher stiffness than in vivo.[27,40] Upon the same orthopedic load, equivalent sutures of juvenile skulls experience significantly higher bone strain than adult skulls, suggesting that the same mechanical force may have different biological effects on immature and mature facial skeletons.[25,39] Contrasting bone strain patterns are present in the zygomatic arch across the zygomaticotemporal suture: tensile on its lateral surface, but compressive on its medial surface,[25] suggesting potentially differential growth responses of the zygomatic arch upon headgear therapy.

One of the influential theories of skull loading was based on presumed stress patterns and trajectories on dry human skulls. The ‘‘beam hypothesis’’ proposed by Benninghoff and Sicher states that compressive mechanical stresses generated from bite forces upon the whole dentition are transmitted by the superior, intermediate, and inferior routes.[41–43] All three routes have the common origin of mechanical stress generated on the maxilla. The superior route represents strain dissipation from the maxilla through the nasal and frontal bones; the intermediate route represents strain dissipation through the zygomatic and temporal bones; and the inferior route represents strain dissipation through the palatal and sphenoid bones.[43] Although the above experimental evidence obtained during natural activities such as mastication provides limited support to stress transmission through the superior and intermediate routes, these bone strain data vividly dispute the beam hypothesis in recognizing either a continuous gradient of stresses transmission from the origin of loading to the rest of the skull bones or the nature of stresses being entirely compressive, upon both mastication[18,20,24,26] and simulated orthopedic loading.[25,39] In many instances, tensile stresses have been observed across several cranial and facial sutures.[22,24,25,29,39] There was a lack of experimental evidence in support of the inferior route of stress transmission through the pterygoid buttress to the cranial base until our recent experimental data demonstrating compressive bone strain posterior to the sphenooccipital synchondrosis in response to headgear loading on the maxillary first molars.[25] Another deficiency of the beam hypothesis is that only mechanical stresses resulting from bite forces on the dentition are considered. In many instances, mechanical stresses resulting from muscle contraction produce large bending moments and therefore large bone strain adjacent to several cranial and facial sutures such as the zygomaticotemporal[19,20,22,24] and reaction forces from the temporomandibular joint.[23,44] In hindsight, the ‘beam hypothesis’ was a much needed step forward from the notion that craniofacial bones are incapable of stress bearing and was proposed before the availability of experimental bone strain data mostly collected in the past two decades. Recent experimental data demonstrate rather complex bone strain patterns, both tensile and compressive, during mastication in a pig model (Figure 1 from Herring et al[45] with permission).

An important subject in suture mechanics that has not received due attention is characterization of in vivo sutural strain in response to delivery of precise doses and magnitudes of exogenous forces. Besides the default genetic plan, sutural growth is likely a function of certain parameters of mechanical stimulus.[2] The precise characteristics of anabolic mechanical stimuli for sutural bone growth are not known. Bone strain or its derivative, interstitial fluid flow, inducible by exogenous forces are both candidate anabolic stimuli in the appendicular skeleton.[46–50] To determine whether exogenous forces with various engineering waveforms and frequencies induce corresponding waveforms and rates of sutural bone strain, we have recently quantified in vivo sutural strain patterns in response to both tensile and compressive mechanical forces in a rabbit model (Figure 2 modified from Mao et al[51]). Different waveforms of macroscale, exogenous forces, such as static and sine-wave cyclic forces, were applied to the maxillary incisors and measured as sutural strain with strain gages and strain rosettes placed over the premaxillomaxillary suture (Figure 3 from J. A. Nudera et al, personal communication; see also Kopher and Mao[52]; Mao et al[51]). Indeed, the waveforms of static force (Figure 3A) and sine-wave cyclic forces at various frequencies (Figure 3B through F) were expressed as corresponding sutural strain waveforms and strain rates in the premaxillomaxillary suture (Figure 4A through F from J. A. Nudera et al, personal communication). These data reveal that sutural cells and extracellular matrix components likely experience different waveforms and rates of mechanical stimuli, providing the basis for applying novel mechanical stimuli to modulate sutural growth.[2] If different waveforms and frequencies of exogenous forces had induced a uniform sutural strain waveform and rate, there would have been no basis for assuming that different characteristics of exogenous forces could engineer different amounts of sutural growth.[2] These studies were motivated by the finding that functional bone strain such as during

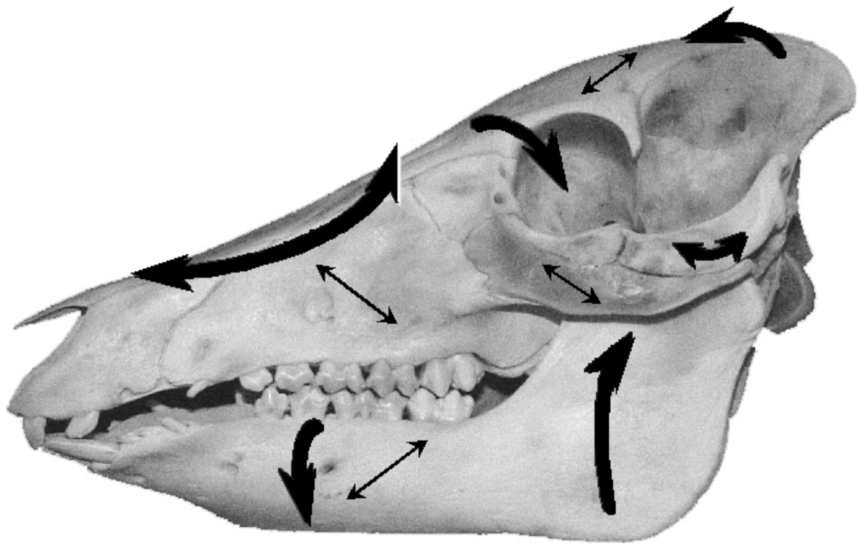

FIGURE 1. Schematic diagram illustrating overall loading patterns of the pig skull during mastication based on experimental bone strain evidence (cf, Herring et al[45]). Bending (squamosal bone and snout) is indicated by curved double-headed arrows. Torsion (braincase and mandible) is represented by pairs of curved single-headed arrows. Straight double-headed arrows show the orientation of principal tensile strain in selected regions. The direction of torsion and tension in the braincase is associated with contraction of the left masseter and right temporalis. Reprinted from Comp Biochem Physiol A Mol Integr Physiol. Vol. 131, Herring SW, Rafferty KL, Liu ZJ, Marshall CD. Jaw muscles and the skull in mammals: the biomechanics of mastication. 207–209, © 2001, with permission from Elsevier Science.

gait is remarkably uniform across species, ie, approximately 2500 $\mu\epsilon$ strain whether in the rat or horse tibia.[46–50] Accordingly, certain sutural strain parameters determined in the rabbit model[51,52] may be applicable to other species if they are determined to be a function of sutural osteogenesis.[2]

Patterns of orthopedically induced sutural mechanical strain are summarized as follows:

- Orthopedic loading on the dentition produces mechanical stresses experienced in facial and cranial sutures. Upon simplified loading such as headgear, different sutures experience characteristic tensile or compressive strains.
- Engineering waveforms of exogenous forces, such as static and sine wave at various frequencies are expressed as corresponding strain waveforms and strain rates in sutures, providing the basis for applying novel mechanical stimuli to engineer sutural growth.
- Sutures absorb large mechanical stresses upon exogenous loading, with bony edges displaced either in tension or compression, suggesting that sutural cells and extracellular matrix molecules experience these mechanical perturbations.
- Mechanical stresses are not transmitted in the skull as a continuing gradient, for different sutures are capable of redefining a propagating mechanical force into predominantly tensile or compressive strain.

ORTHOPEDIC IMPLICATIONS OF SUTURE MECHANICS

About a century ago, Kingsley and Angle independently applied various types of mechanical appliances such as headgear and fixed orthodontic appliances in patients with perceived dentofacial deformities and malocclusion.[53,54] Without the benefit of past experimental animal data in support of these therapies, Kingsley's and Angle's attempts to correct facial and dental disfigurations worked, and laid the foundation for contemporary orthodontics and dentofacial orthopedics.[55,56] Subsequently, several orthopedic devices have been applied clinically with a common goal of modifying the growth of cranial and facial bones. These orthopedic devices include, but are not limited to, headgear, facemask, palatal expanders, and several functional appliances such as Herbst, Frankel's, activators, twin blocks, and bionators. Although some of these devices have similar therapeutic goals, no two devices are the same from a clinical standpoint. Despite extensive clinical literature describing their efficacies in patient populations,[57–61] the mechanisms of action of these orthopedic devices are not well understood.[55,56] A synopsis of this subject is perhaps more challenging than the aforementioned topics, primarily because of the paucity of experimental work that elucidates the mechanisms of action of these orthopedic devices.

All craniofacial orthopedic devices have one thing in common—delivery of mechanical forces in attempts to modify the form of craniofacial bones. Thus, the biological effects of these orthopedic devices, regardless of their clinical distinctness, may be similar in that macroscale mechanical forces produced by these appliances cause microscale sutural bone strain, which in turn induces cellular growth responses in sutures.[2] Exogenous forces do not directly induce sutural growth because they do not directly ''communicate'' with cells.[2] Any exogenous force applied

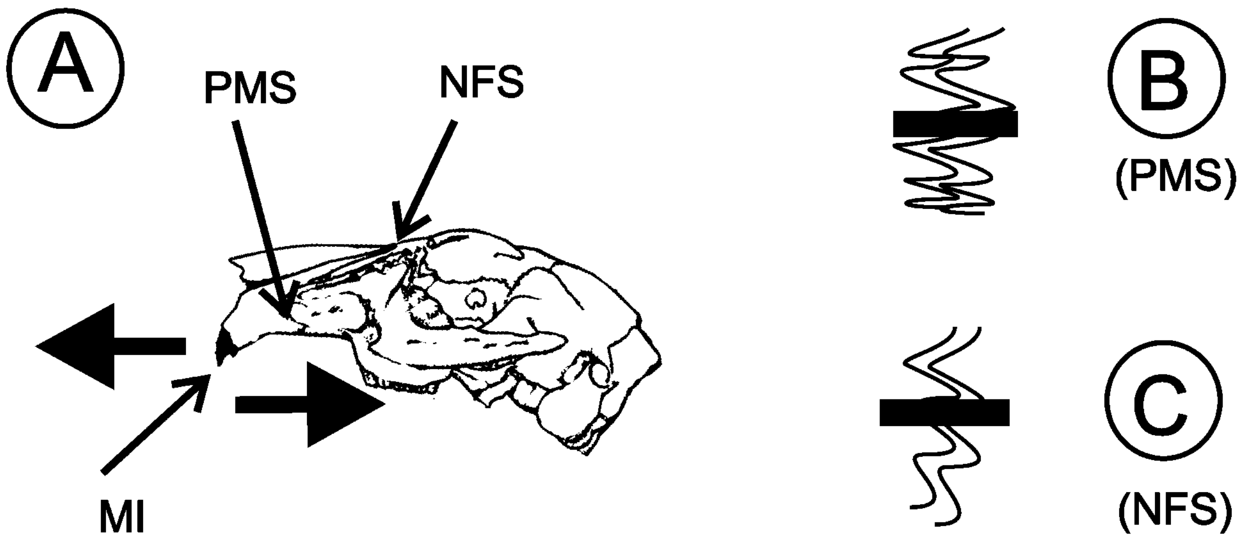

FIGURE 2. (A) Schematic diagram illustrating the rabbit skull in the sagittal plane and a segment of the premaxillomaxillary suture (PMS) and the location of the nasofrontal suture (NFS). The anteriorly directed horizontal arrow indicates the direction of tensile forces applied to the maxillary incisors (MI) and the premaxilla. The posteriorly directed horizontal arrow indicates the direction of compressive forces applied to the maxillary incisors (MI) and the premaxilla. (B) The PMS has a wavy, complex course, extending from the oral cavity between the premaxilla and maxilla rostrally toward the nasal bone. The strain gage/rosette was placed in the intraoral portion of the PMS. The PMS has a high degree of sutural interdigitation at its inferior end. The dark rectangle indicates the location of the strain gauge parallel to the direction of exogenous loading. The strain gauge was reduced in size to illustrate the sutural course. (C) The NFS has an intermediate degree of sutural interdigitation among all craniofacial sutures. The dark rectangle indicates the location of the strain gauge perpendicular to the suture's longitudinal course. The strain gage was reduced in size to illustrate the sutural course.

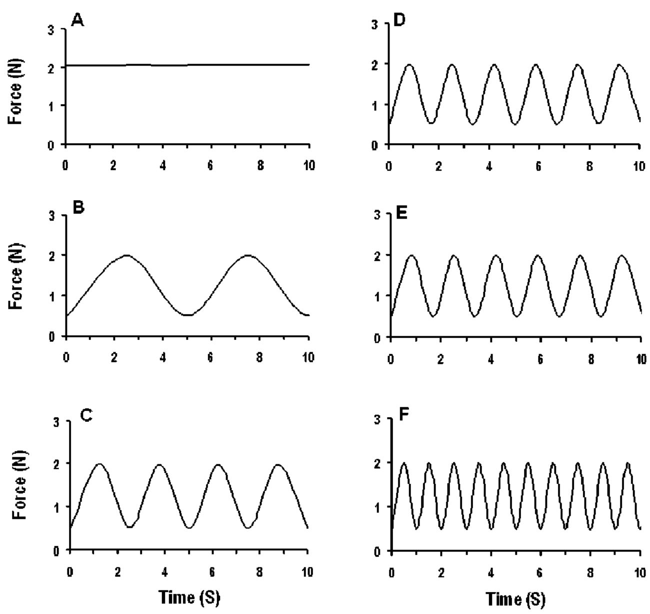

FIGURE 3. Waveforms of static force (A) and sine-wave cyclic forces (B)–(F) at 2 N applied to the maxillary incisors. In (B) through (F), forces were preprogrammed to oscillate from 0.2 Hz (B) to 1 Hz (F) in 0.2 Hz increments. Despite the same 2-N peak magnitude, static force lacked appreciable oscillation in force magnitude.

to bone is transmitted as mechanical stresses in bone, measurable as bone strain on the cortical surface or over craniofacial sutures. Although functional appliances may exert skeletal effects by inducing the action of muscles of mastication, their effects are likely expressed by multiple lines of stresses exerted by various muscles of mastication directly on the zygomatic, sphenoid, and temporal bones (because of attachments of the masseter, temporalis, medial, and lateral pterygoid muscles), which are articulated by various sutures.

About half a century ago, a Russian physician named Ilizarov who worked largely in isolation used orthopedic devices to lengthen limb bones in a process later called distraction osteogenesis. This technique was introduced to the West about two decades ago.[62] Inherited from the Ilizarov technique, distraction osteogenesis usually involves an osteotomy and subsequent separation of the osteotomy site by either external or internal distractors. Bone ends are literally pulled apart, leaving it to nature to fill the gap with bone regeneration over time. Distraction osteogenesis provides an interesting model of in vivo mechanical interactions with sutural growth. Forces generated by distraction devices in the maxilla or other cranial bones are likely transmitted as sutural strain, which in turn may induce sutural osteogenic responses.[2] For instance, distraction forces applied to coronal sutures with delayed-onset synostosis induce significantly more sutural growth than coronal sutures with delayed-onset synostosis without distraction.[63] Similarly, sutural growth measured with marker separation and histologically identified newly formed bone is observed in both zygomaticomaxillary and coronal sutures upon sutural distraction without osteotomy.[64,65] It is anticipated that research on distraction osteogenesis of the craniofacial skel-

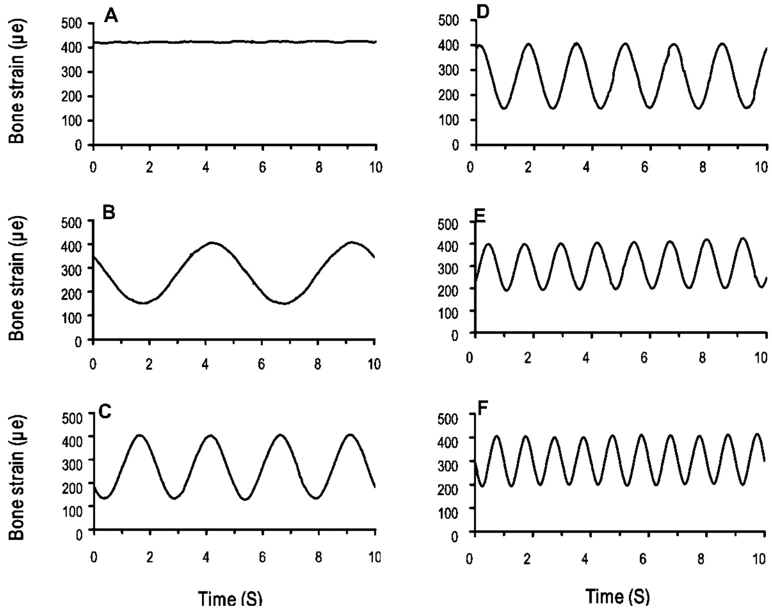

FIGURE 4. Strain rates and patterns of the premaxillomaxillary suture (PMS) closely mimic the frequencies and waveforms of exogenous forces (cf, Figure 3). Static sutural strain (A) in response to static force without appreciable oscillation. Sine-wave cyclic bone strain (B–F) has corresponding oscillatory patterns and rates between 0.2 Hz (B) and 1 Hz (F) in response to sine-wave cyclic forces from 0.2 to 1 Hz (cf, Figure 3). The rates and patterns of PMS strain were modulated by frequencies and waveforms of exogenous forces.

eton would continue to flourish and enrich our understanding of not only distraction osteogenesis but also sutural osteogenesis. Thus, it is probable that craniofacial sutures can be ''distracted'' to grow by optimal mechanical stimuli in actively growing individuals, instead of the constant necessity of an osteotomy in association with distraction osteogenesis. An in-depth review of distraction osteogenesis is beyond the scope of the present article but can be found elsewhere.[66,67]

Thus, the common threads of craniofacial orthopedic devices can be summarized as follows:

- All craniofacial orthopedic devices generate forces that are likely transmitted as bone strain and sutural strain. Sutural growth likely is a function of certain optimal parameters of mechanical stimuli that remain to be determined instead of a particular type of orthopedic appliance.
- New concepts in suture mechanics and suture mechanobiology likely will facilitate innovative design of new devices, improvement of current orthopedic appliances, and new concepts in clinical craniofacial orthopedics including orthodontics.

CONCLUDING REMARKS

Experimental evidence unequivocally indicates that sutures experience, absorb, and transmit mechanical stresses generated from either functional activities such as mastication or exogenous forces such as orthopedic loading. Certainly true in mechanics and may be also true in connective tissue biology, to connect means to withstand forces.[2] Mechanical stresses experienced in sutures, given the ''right'' characteristics, are capable of modulating sutural growth.[2] Because mechanical stresses transmit through bone, their effects are experienced in a hierarchical manner sequentially as tissue-level bone strain, interstitial fluid flow that in turn induces cell-level strain on bone cells,[2] and subsequent anabolic or catabolic responses. What optimal stimuli induce anabolic and catabolic sutural responses, both of which contribute directly to separate craniofacial orthopedic goals, is presently unknown. Current clinical orthopedic devices exert static forces on craniofacial sutures for sustained periods of time. Recent experimental evidence indicates that repeated application of cyclic forces for as short as 10 minutes per day for 12 days was sufficient to induce significantly more sutural growth than static forces of matching peak magnitude and duration.[2,52] From the experimental bone strain data, it is clear that at least some of the current orthopedic devices such as headgear exert sutural bone strain, whereas other devices are untested. It is probable though that any mechanical force capable of modulating craniofacial growth exerts its therapeutic effects by generating mechanical strain in craniofacial sutures.

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