Assessing the Biomechanical Impact of Dentition Types and Craniofacial Forms on Intact and Fractured Mandibles

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An essay submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfilment of the requirements of the degree of

Master of Dentistry (MDent) in Oral and Maxillofacial Surgery

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Table of Contents

LIST OF FIGURES:

1.0 INTRODUCTION

Currency, Oral and maxillofacial surgeon globally dealing with some challenges in Management of Mandibular fracture. It is imperative for clinician to have in depth understanding of biomechanic of the intact and fractured mandible to be able to improve the quality care and prevent further complications associated with the effectiveness of the open reduction and internal fixation of mandibular fracture. It is also important for clinician to have a thorough understanding of bone biology and the healing process, and how it is directly affected by mechanical and biological factors.

1.1 Basic concepts of bone biology

Bone tissue is an amalgamation of hydroxyapatite, collagen, trace proteoglycans, non-collagenous proteins, and water. The inorganic portion predominantly lends compressive strength and rigidity, whereas the organic portion is essential for tensile strength (1&2). Notably, the precise composition of bone can differ based on factors such as the species, individual age and sex, and the presence of any pathological conditions (3).

Bone tissue is characterized by its non-uniformity, porosity, and directional dependence and porosity levels can range broadly from 5 to 95%, with most bones exhibiting either notably low or high porosity. Trabecular, or cancellous bone, exhibits 50–95% porosity and is typically present in cuboidal and flat bones, as well as the extremities of long bones. Its structure is a network of interconnected pores filled with marrow and a matrix of trabeculae plates and rods with diverse configurations (2). Conversely, cortical or compact bone displays 5–10% porosity and encompasses various pore types. The most substantial pores are vascular, comprising Haversian canals aligned with the bone’s longitudinal axis and Volkmann’s canals that traverse these, housing capillaries and nerves. Additional porosities include lacunae, small cavities linked by canaliculi, and the minute spaces between collagen fibers and hydroxyapatite crystals. Cortical bone is composed of cylindrical units called osteons or Haversian systems and is predominantly located in the shafts of long bones and as a protective outer layer of flat bones, often observed in the anterior mandible (Fig. 1).

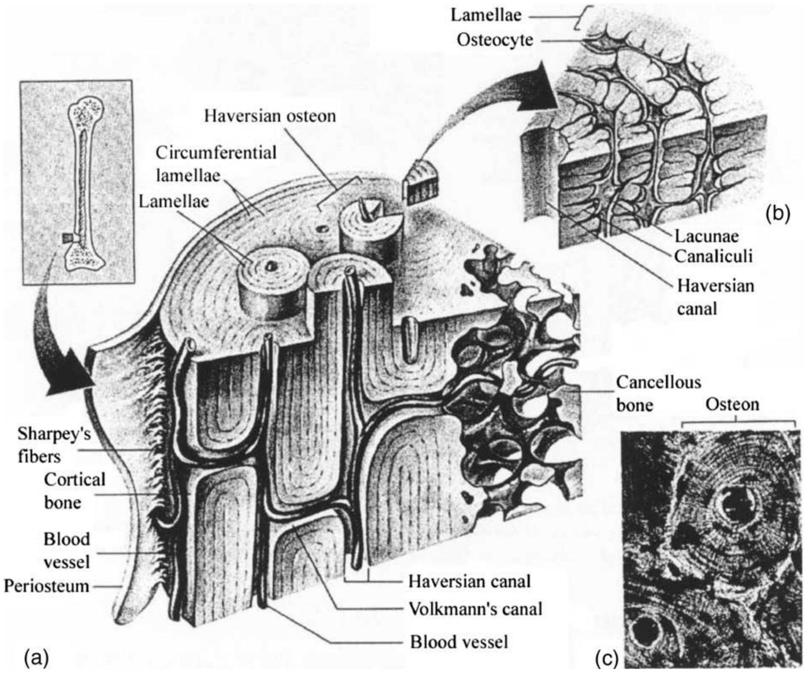

Figure 1: Microscopical structure of cortical bone. (a) 3D sketch of cortical bone, (b) cut of a Haversian system, (c) photomicrograph of a Haversian system (2).

The skeletal framework is composed of woven bone, which is subsequently supplanted by lamellar bone. Typically, woven bone ceases to be a component of the skeleton after the first four to five years of life, yet it re-emerges as part of the fracture healing process. These bone types exhibit considerable variances in their composition, structural organization, developmental processes, and mechanical attributes. Woven bone materializes rapidly and exhibits a disorganized structure, with collagen fibers and mineral crystals arrayed haphazardly. In contrast, lamellar bone develops gradually, is meticulously structured, and features aligned lamellae, enhancing its strength over woven bone. Bones possess the capacity for growth, reshaping through external remodeling or modeling, self-repair via fracture healing, and perpetual self-renewal through internal remodeling. These dynamic processes are regulated by a combination of mechanical forces, hormonal influences, and physiological mechanisms (4).

1.2 Mechanisms of bone fracture

Bone fractures typically occur when an unexpected load surpasses the physiological limits, resulting in stress that exceeds the bone tissue’s adapted strength which we call a traumatic fracture and is the predominant cause of mandibular fractures. Such fractures can arise from two principal sources: an external force, such as one might experience in a fall, or from what are termed ‘spontaneous’ fractures, which are the result of muscular contractions without any external trauma. In older individuals who have conditions like osteoporosis or a significantly atrophied mandible due to complete edentulism for decades, the spontaneous is frequently observed, which can predispose them to these kinds of fractures (5).

Pathologic fractures often result from ordinary stresses applied to bones weakened by conditions such as disease or the natural aging process. These fractures are predominantly triggered by osteoporosis, particularly in older adults, and more frequently in women. In addition, Bone tumors also play a significant role in the occurrence of pathologic fractures by altering the mechanical properties of bone and creating areas of concentrated stress. The important factors that increase the susceptibility of mandibular bone fractures in the elderly patient including but not limited to osteoporosis, diminished capacity of soft tissues to dissipate the energy from impacts, and alterations in gait dynamics. These additional considerations contribute to the overall heightened fracture risk observed in the aging population.

The second category of fractures is associated with creep and fatigue where the long bone in extremities or mandible sustained loads over extended durations and repetitive loads that can lead to the formation of microdamage. When such microdamage accumulates more rapidly than the bone’s ability to repair itself through remodeling, the proliferation of microcracks can escalate into macrocracks, ultimately resulting in a complete fracture. This condition is medically recognized as a stress fracture.

1.3 Bone fracture healing

Bone development in embryos and children occurs through three primary pathways: endochondral ossification, where bone replaces cartilage; intramembranous ossification, where bone forms directly from osteoblasts in flat bones; and appositional ossification, where new bone layers are added from mesenchymal cells adjacent to existing bone or cartilage.

Fracture healing is a complex, natural process that restores the form and function of damaged tissue. Various cells including inflammatory cells, angioblasts, fibroblasts, chondroblasts, and osteoblasts in this process migrate, differentiate, and proliferate. These cells are responsible for synthesizing and secreting the bioactive components of the extracellular matrix essential for tissue regeneration. Fracture healing is categorized into primary and secondary types. Primary healing is characterized by high stability and minimal gap between bone ends, allowing direct bone formation. This is vitally important for the clinician to establish adequate reduction and internal fixation of fracture mandible to minimize the gap between the fractured segments and activates the primary healing process. Secondary healing is more common and occurs under less stable conditions with moderate gaps. It involves a multi-stage process where the periosteum and surrounding tissues form a stabilizing external callus. The callus works as internal bridge and reduce the instability of fractured segments. This process includes overlapping phases of inflammation, osteoid formation, and bone remodeling to restore function (6).

The initial phase of fracture healing is triggered by a fracture itself. Following the break, blood from damaged vessels floods the fracture site, forming a hematoma. Macrophages then clear away necrotic tissue and lay down granulation tissue, setting the stage for mesenchymal cells to migrate and form a preliminary callus for stabilization. These cells, originating from nearby soft tissues, proliferate and differentiate into various cell types such as chondrocytes, osteoblasts, or fibroblasts depending on the local environment and mechanical stressors. As healing progresses, these specialized cells produce the extracellular matrix pertinent to their lineage. Directly flanking the fracture gap, stem cells transform into osteoblasts, creating intramembranous woven bone that grows towards the callus's core. Concurrently, cartilage forms in the callus's central region through chondrogenesis, except near the fracture gap where conditions are too unstable for mesenchymal cell differentiation due to excessive movement (5).

In cases of displaced mandibular fractures, where segment instability is significant, a unique healing process unfolds where the callus, predominantly composed of cartilage, fills the fracture space, paving the way for endochondral ossification. This intricate process involves a series of cellular activities: the maturation and breakdown of cartilage, the establishment of blood supply, and the formation of new bone tissue. Typically, the healing of a fractured mandible occurs through intramembranous ossification, where osteoblasts directly lay down new bone and when there is minimal fractured displacement and gap. However, if the fracture segments lack sufficient stability, cartilage may form within the gap as part of the body's adaptive healing response (7). This finding shows the vital importance of thorough understanding of biomechanic of intact and fractured mandible and how the other factors such as a type of dentition and craniofacial form may affect the line of osteosynthesis and healing of fracture segment. The other factors including local soft tissue damage, and blood supply are very important to direct the primary or secondary healing process where undifferentiated mesenchymal soft originates from external soft tissue matrix.

1.4 Biomechanics of fracture healing

Carter and colleagues in 1988 proposed a theory of tissue differentiation that links the formation of new tissue to the history of local stress and strain. This theory proposed that the pattern of ossification is qualitatively related to the history of mechanical loading (5). According to their model, depicted in a key figure, two distinct lines demarcate regions of different tissue types within the callus (Fig. 2). To the left of the designated pressure line, tissue experiences high hydrostatic pressure, which acts as a catalyst for the formation of a cartilaginous matrix. Conversely, on the right side where hydrostatic pressure diminishes, bone matrix production is initiated. The differentiation of tissue ceases beyond a certain threshold, defined by a boundary line to the right. When subjected to elevated tensile strains, beyond a specified tension line, the tissue forms a fibrous matrix, with the eventual composition of cartilage or bone contingent upon the level of hydrostatic pressure present. It is important to mentioned that this theory works when the soft tissue matrix and blood supply to the fractured mandible is intact (Fig. 3).

It has been suggested that the fibrous tissue will be formed even below the tension line threshold when there is remarkable soft tissue avulsion with fractured mandible such a gun shot wound and ballistic missile injury or if there is history of irradiated mandible where the blood supply to fracture line has been diminished significantly. The goal of ORIF is to prevent any mobilization of the fracture segment, otherwise, excessive strain can damage new capillaries at the fracture site and prevent effective vascularization of the callus between the fracture fragments.

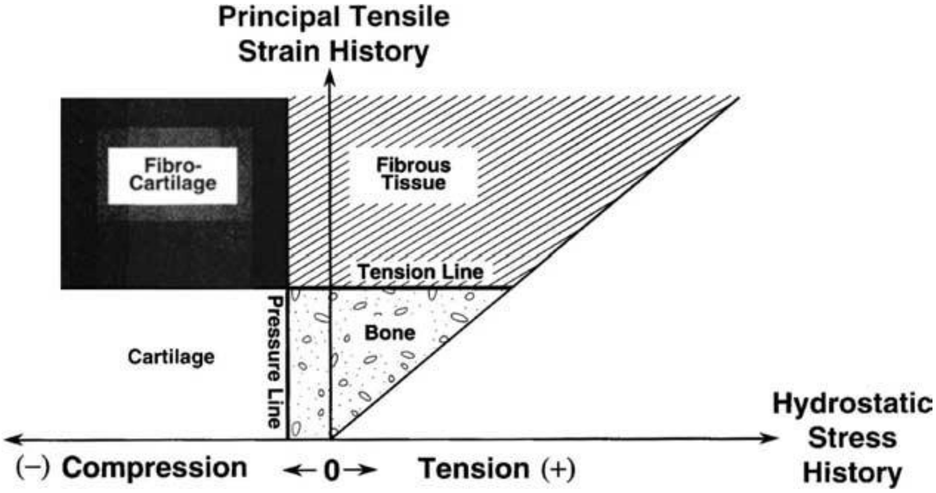

Figure 2: Relationship between mechanical stimuli and tissue differentiation. Adopted form Correlations between Mechanical Stress History and Tissue Differentiation in Initial Fracture Healing. Carter R et. el. 1988.

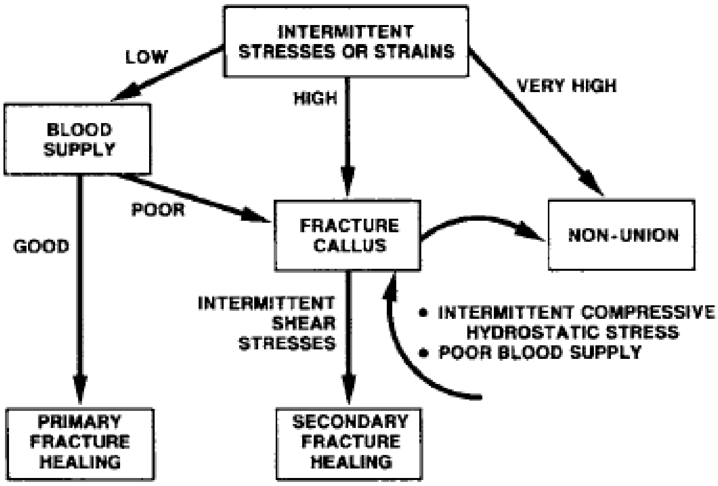

Fig. 3. Hypothesis for the influence of intermittent stress and vascularity on differentiation of mesenchymal tissue. Adopted form Correlations between Mechanical Stress History and Tissue Differentiation in Initial Fracture Healing. Carter R et. el. 1988.

The tissue differentiation theory can elucidate the occurrence of malunion healing and fibrous tissue formation at the gap in inadequately secured mandibular fractured segments. This example underscores the significance of a comprehensive understanding of the biomechanics of intact and fractured mandibles in influencing the efficacy of fixation techniques and the subsequent healing process. It is crucial to assess the displacement of the tension and compression zones in a fractured mandible, as may influenced by various dentition types and craniofacial forms to enhancing overall treatment quality.

1.5 Champy's lines of osteosynthesis

In 1976, Maxime Champy proposed the development of two distinct zones in the mandible upon anterior loading (8). These zones include a tension zone that forms along the superior section of the mandible and a compression zone along the inferior section (Fig. 4). He also developed the ideal lines of osteosynthesis across the mandible (Fig. 5). This model has been instrumental for decades in shaping the approach of oral and maxillofacial surgeons towards the treatment of mandible fractures. It provides a fundamental understanding of the biomechanics involved in such fractures and guides the choice of treatment strategy. However, this model is oversimplified and assumes a standard mandible structure and does not account for individual variations. These variations can include differences in dentition types and craniofacial form, both of which can significantly affect the magnitude and location of bite forces.

On the other hand, these zones of tension and compression may change under different loading conditions. For example, the zones could shift or alter when the mandible is subjected to postrior occlusal forces, as opposed to anterior one. This highlights the need for a more personalized approach to treatment, considering the unique characteristics of each patient's mandible, current dentition and the specific circumstances of the fracture. The tension and compression zones will differ between a patient with a Class I Kennedy and bilateral posterior edentulous dentition with a mandibular body fracture, and a patient with a Class IV Kennedy and anterior edentulous dentition with the same fracture. However, both patients will be treated similarly, with the plate placed superiorly against the line of the tension zone.

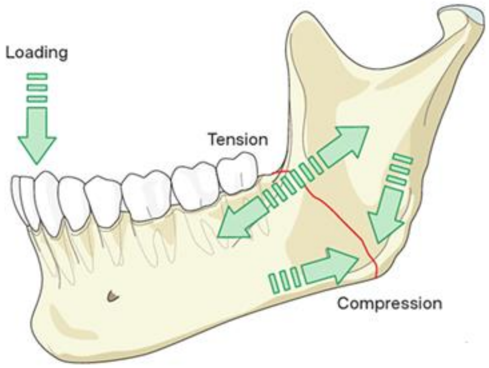

Figure 4: A zone of tension along the superior section of the mandible and a compression zone along the inferior section. Adopted from Biomechanical basis of mandibular osteosynthesis according to the F.X. Chamoy at. al. 1976

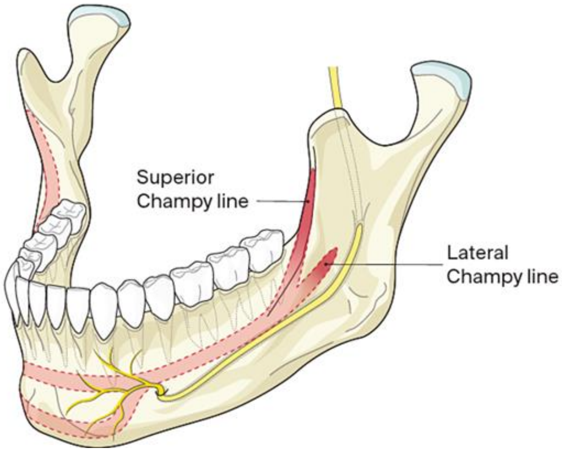

Figure 5: Champy's lines of osteosynthesis. Adopted from Biomechanical basis of mandibular osteosynthesis according to the F.X. Chamoy at. al. 1976

2: LITERATURE REVIEW

In 1992, Ruddermann et al. showed that using simple beam models to predict mandibular behavior is problematic because the Champy’s model of tension and compression zone did not take the three-dimensional nature of the mandible into account (9). On the other hand, the mandible is not suspended at a single point and the logical step is to evaluate a beam model suspended at both end as hinge axis. In this suspended beam model, when the masseter and medial pterygoid muscles apply upward forces to balance the beam, and a third force is applied at the center when the patient bites on the incisors, an unusual effect occurs. The bite forces, generated by muscular activity pushing the mandible against the maxilla, create a midline bite force. This results in the boundary opposite the applied force becoming a tension zone.

In addition, he showed an intriguing finding of inversion of the zones of tension and compression along the body/angle of the mandible under 1st molar biting conditions. Specifically, the inferior section was under tension, while the superior section was under compression (Fig. 6). This is not in consistent with Champy's line of osteosynthesis, the superior border of the mandible is under tension, while the inferior border is under compression. This principle guides the placement of plates for optimal fracture stabilization. The result of his studies also revealed that under a simulated midline load, compression occurs at the upper margin directly at the load point. Tension zones extend laterally from this upper midline area. Additionally, a tension zone is present at the inferior midline margin, extending from the buccal to the lingual surface, with the lingual side experiencing relatively higher tension (Fig. 7). Rubberman et. al. primarily focused on the effect of location of occlusal load, without considering the potential influence of varying craniofacial morphology on stress distribution. This presents a notable gap in the literature, as studies that simultaneously consider variations in both craniofacial morphology and dentition are sparse.

He came into this conclusion that the compression zone appears at the upper edge at the bite point and spans across the midline when a one-sided asymmetric load in the molar area has been applied. The upper edge at the bite point experiences more compression than the lower edge on the opposite side. Additionally, there is a tension zone along the upper edge opposite the bite load side and another tension zone along the lower edge on the loaded side. As the bite force moves from a posterior position along the upper edge across the midline to the opposite side, the zones of tension and compression shift from the upper to the lower edge (9).

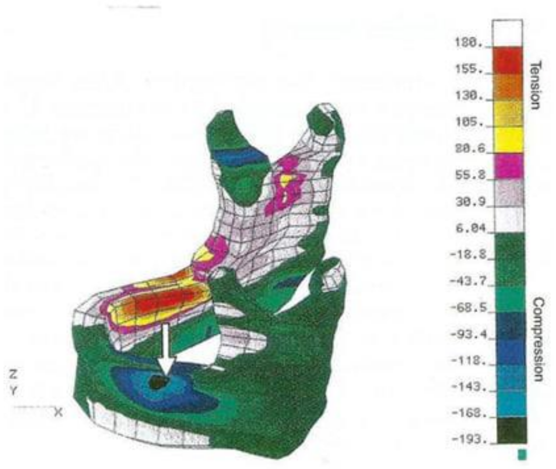

Figure 6: Finite element model of a mandible, molar region load.
Note the zone of tension along the upper margin contralateral to the
bite load side. Adopted from Biomechanics of facial skeleton, Rudderman et. al. 1992.

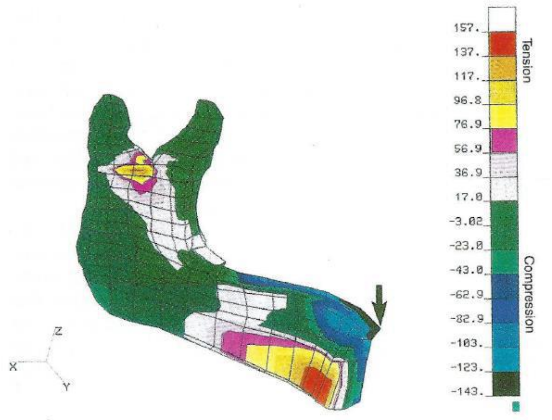

Fig. 7. Finite element model of a mandible, midline load, and midline view.
Adopted from Biomechanics of facial skeleton, Rudderman et. al. 1992.

In 2019, Bohluli et al. reported that Champy applied force to the mandibular front teeth using a beam model, forming the foundation for almost all treatment approaches. However, trauma patients who have undergone internal fixation are advised not to use their front teeth for several weeks, even under ideal conditions, as they will not naturally exert force on these teeth during this recovery period (10). This observation aligns with the findings of renowned oral and maxillofacial surgeon Edward Ellis III. He noted that in 17 patients with isolated angle fractures, there was a significant reduction in molar bite force on the fractured side during the six-week healing period. During this time, all patients relied on their posterior molars for chewing, even all the patients were advised to be on soft diet (11). Additionally, a study indicates that targeting a bite in front of the main vector of the masseter muscle results in increased bending stresses. The muscle’s supportive effects decrease with incisor loads, and as the lever arm lengthens from a posterior fracture to the bite target, the likelihood of motion at the fracture site increases, reducing the stabilizing role of soft tissue. We previously discussed that repeated cycles of high shear or tensile hydrostatic stresses might encourage fibrous tissue formation instead of bone growth, potentially leading to non-union healing (12). The author personally believes that the body’s protective neuromuscular mechanism favors biting on molars over incisors to shorten the lever arm and minimize motion at the fracture site.

Bohluli et al. performed a finite element analysis (FEA) using a 3D model created from a computed tomography scan of a mandible. The FEA results indicated that posterior loading completely reversed the stress distribution pattern, showing compression at the superior border and tension at the inferior border which was consistent with the findings of study conducted by Ruddermann et al (Fig 8). Despite this, Champy’s concept remains fundamental in treating mandibular fractures, where patients continue to chew using their molars and apply posterior loading. This indicates that the beam model is inadequate for addressing the complex biomechanics of the mandible, which includes a hinge axis. Therefore, the current practice of placing the plate against the tension zone at the superior border needs to be reconsidered.

Moreover, the variations in stress distribution patterns between central incisor biting and first molar biting conditions suggest the intricate mechanics of the mandible. However, with the help of central incisor biting conditions stress distribution becomes more uniform, whereas first molar biting conditions causes stress concentration and load distribution asymmetrically. These findings emphasize the need to consider the position and nature of occlusal forces when analyzing biomechanics fractured mandible and planning for ORIF (12).

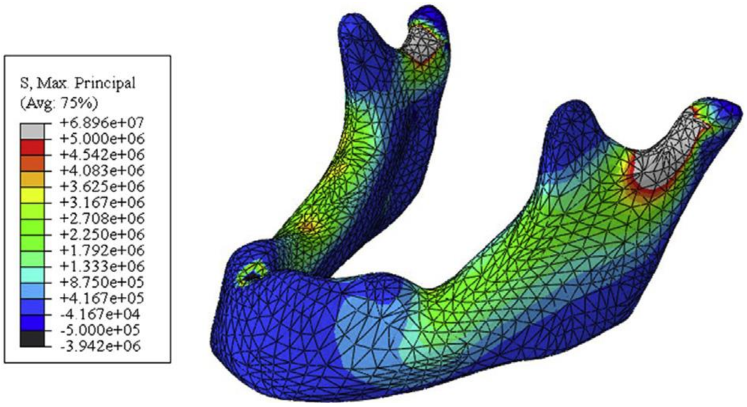

Fig. 8. Finite element model in anterior loading shows that a negative strain or tension is mostly seen on the superior border. Adopted from Treatment of mandibular angle fracture: Revision of the basic principles. Bohluli et. al. 2019.

To the best of the author's knowledge, the impact of craniofacial form on the biomechanics of both intact and fractured mandibles has not been explored. Craniofacial form directly influences the magnitude of masticatory forces, potentially altering the distribution of tension and compression stresses.

Currently, patients with varying craniofacial forms but the same type of mandibular fracture often receive identical treatment regarding the placement and number of plates in internal fixation. This approach oversimplifies the mandible model, assuming that the tension and compression zones, as well as the magnitude of masticatory forces, remain consistent across different craniofacial forms. Adequate internal fixation hardware must be used to withstand the maximum masticatory forces, influencing the size, diameter, and number of plates required for different types of mandibular fractures. As masticatory forces and occlusal loads increase, there is a greater need for either two plates or a large, thick reconstruction bone plate along the inferior border.

Two studies have noted variations in facial morphology that influence human facial height and corresponding bite force capabilities in individuals with long versus short facial types (13&14). It's evident that those with skeletal open bites cannot generate the same bite force magnitude as short-faced individuals with skeletal deep bites.

Throckmorton and colleagues (1980) suggested that factors such as muscle size, architecture, fiber type distribution, activity levels, and mechanical advantage contribute to these differences (15). They found that any changes reducing the muscle moment arm or increasing the tooth load moment arm decreased the muscles' mechanical advantage. Observations of long- and short-faced individuals indicated that the higher bite forces in short-faced individuals were due to morphological differences that enhanced mechanical advantage. When a bite target is on the right posterior teeth, the masseter on that side becomes stiffer and helps carry some of the load while generating force. The contralateral masseter also generates force to stabilize the mandible from rotation, creating a circuit of force.

Moreover, Finn reported that the maximum biting force in the molar region was twice as high in normal subjects compared to dolichofacial (long-faced) subjects, with brachyfacial (short-faced) subjects exhibiting even higher maximum forces. The result of a study conducted by Toro-Ibacache et. al. has pointed out that changes in the shape of the skull may have an impact on the amount of force transmitted through the jaws (16). The different facial morphologies have variations in the distribution of occlusal forces which may change the mechanical response of the mandible to biting and chewing. This result is in consistent with the mentioned above finding of Finn research where subjects with a shorter face may experience an increased force amount as against those with a longer face which may bring about differences in stress distribution patterns within the mandible

The occlusal load directly influences the thickness of the plate, and the number of screws used on each side of a fracture segment. Clinicians may opt for a stronger plate for ORIF mandibular angle fractures in short-faced individuals compared to similar fractures in long-faced individuals. To the best of the author’s knowledge, no study has yet investigated the impact of craniofacial form on the line of osteosynthesis and the zones of compression and tension in both intact and fractured mandibles.

3.0 CONCLUSION

The primary objective of open reduction and internal fixation of fracture mandible is obviously to ensure stability at the fracture site. This is achieved by directly manipulating the fractured bone fragments into the correct position when the fractured segments have been reduced and securing them with internal fixators such as screws and plates. it is crucial to secure these zones with a fixation plate to prevent any movement of the fracture segment which can lead to complications postoperatively, such as malunion or non-union of the fracture.

Champy's model represented an oversimplification of the complex system of mandibular biomechanics. The results of literature review above suggested that tension-compression stress distribution may dramatically alter, depending on the point and magnitude of force application in setting of the same remained geometry of the mandible. So, if the fracture at the angle or body does not coincide with the location of the biting force, the tension manifesting in the upper section and compression in the lower section; however, if the fracture line coincides with the location of biting force whether first or second molar depending upon the type of dentition and edentulous region, this reverse pattern will be observed and will affect remarkably the effectiveness of fixation. This reversal extends a certain distance from the first molar where the maximum occlusal forced is directed to be applied in both directions, eventually realigning with the stress patterns observed on the contralateral side of the mandible. In the scenario of body fracture at the first molar when the patient bites on, we may observe a crack or area of displacement at the inferior border of the fracture line if the location of fixation plate follows the Champy's model (Fig. 9). Obviously, displacement at the inferior border leads likely callus formation, fixation hardware failure, and constat irritation and compromise the quality standard care and obviously, jeopardize the outcomes.

Fig. 9. A crack or area of displacement at the inferior border of the fracture line (red arrow) where the location of fixation plate follows the Champy's model and placed against the superior border. Note that the patient does not have anterior mandibular teeth.

In conclusion, conducting a more precise and comprehensive simulation assessment of intact and fractured mandibles, considering different types of dentition and craniofacial morphology, is essential. This approach will enable clinicians to accurately identify and understand the tension and compression zones in various craniofacial forms, dentitions, and occlusal force locations. Consequently, it will aid in applying the most effective fixation techniques, ensuring optimal patient outcomes, and guiding postoperative management and rehabilitation, thereby contributing to the overall success of the treatment.

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