J. Maxillofac. Oral Surg. (Apr-June 2012) 11(2):224–230
DOI 10.1007/s12663-011-0289-7

REVIEW PAPER

Biomechanics of Cranio-Maxillofacial Trauma

Biju Pappachan · Mohan Alexander

Received: 7 August 2011 / Accepted: 12 September 2011 / Published online: 9 October 2011

Abstract The forces to the cranium and facial skeleton can be applied from an anteroposterior, superior, inferior and lateral directions. These forces with level and location of point of impact will determine the pattern of injury. Fractures of the cranium rarely extend into the region of facial skeleton. On the other hand, fractures originating in the facial skeleton can extend into the cranium. This has got implications as facial fractures are associated with head injury. Understanding the biomechanics of craniomaxillofacial trauma gives an insight in understanding the pattern of injury. We have briefly reviewed the literature and discussed biomechanics of craniofacial trauma, and how it influences head injury.

Keywords Craniomaxillofacial trauma · Biomechanics · Craniofacial fractures · Head injury

The skull is composed of three principle bony structures: cranial vault, cranial base, facial skeleton.

The rigid cranial vault protects the brain from external injury. The brain rests on cranial base, which also has various vessels and nerves entering and exiting, through various foramina. This constitutes "neurocranium."

The facial skeleton which is connected with the cranial vault and cranial base can be divided for convenience into three parts, the upper third of facial skeleton being the part of cranial vault and comprising of frontal bone, the middle third comprising of central midfacial bone: the maxilla, the naso-ethmoid, and lateral midfacial bone—zygoma, and the lower third comprising of rigid bone—mandible, with its condylar articulation to base of skull. This constitutes with the oral cavity and other associated soft tissues, "viscerocranium".

The precise nature of injury to the cranio maxillofacial region is determined by the degree of force and the resistance to the force offered by the craniofacial bones. The severity of it being expressed by the direction and the point of application of the force. In addition the pattern will be determined by the cross-sectional area of the agent or object struck [1–4].

The forces to the facial skeleton can be applied from an anteroposterior, superior, inferior and lateral directions. These forces with level and location of point of impact will determine the pattern of injury. Fractures of the cranium rarely extend into the region of facial skeleton. On the other hand, fractures originating in the facial skeleton can extend into the cranium, i.e., fractures of the frontal bone, cribriform plate of ethmoid and fractures of the temporal bone. The significance of these displacing forces can be used to analyze the mechanism behind injuries sustained during road traffic accidents [1].

The concept of bony pillars in the midfacial skeleton has been said to be absorbing considerable amount of force from below, but the same bones are easily fractured by relatively trivial forces from other directions [5, 6]. Individually tolerance levels of each bone in midface and mandible have been studied (Fig. 1) [2, 7].

The nasal bones were the most fragile of the facial bones, with tolerance levels for minimal fracture in the 25–75 lbs range. The maxilla displayed low tolerance level in the range of 140–445 lbs, corresponding to the relatively thin anterior wall of maxilla. The relatively fragile zygomatic arch displayed tolerance levels between 208 and 475 Ibs, whereas the

B. Pappachan (✉)
Government Dental College, Raipur, Chhattisgarh, India
e-mail: biju_pappachan@yahoo.com

M. Alexander
Modi Nagar Dental College, Modi Nagar, Uttar Pradesh, India

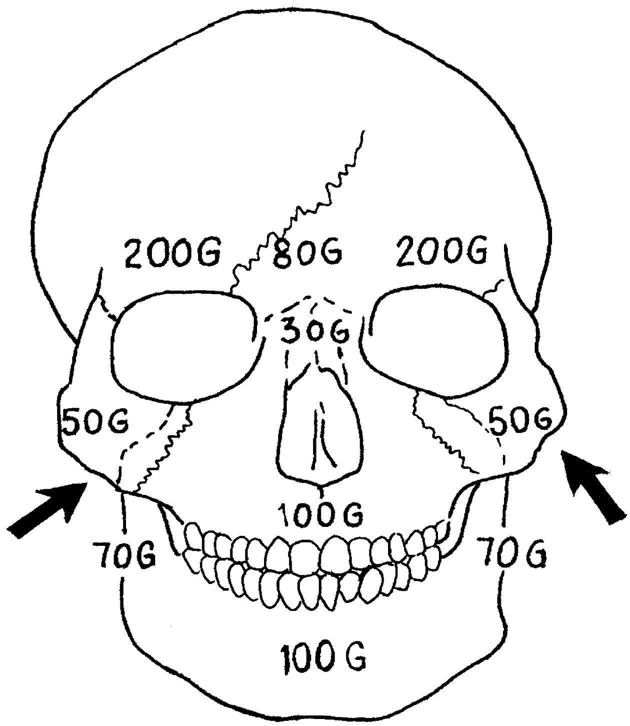

Fig. 1 Classification of the facial bones into degree of resistance to impact [7]

body of the zygoma displayed a higher tolerance level with a grouping in the 200–450 lbs range. The massive frontal bone displayed the highest tolerance levels with grouping between 800 and 1600 lbs. The mandible is much more sensitive to lateral than to frontal impacts. The anatomic configuration of the mandible approximates a rigid semicircular link with pinned joints at its free ends. When attempts were made to apply a force anteriorly to the midline symphysis of the mandible, instability was encountered unless the line of force passed through the condylar processes. For this reason, a force direction was necessary which combined anterior and submental vertical orientation. In this orientation, multiple fracture configurations could be produced, including fractures of the symphysis, body, or condyle. Mandible has complex geometry with differing modes of fracture failure and fracture tolerance levels for each area. The tolerance level increases in proportion to the relative size and area of the mandible involved. The lowest tolerance level of 425 lbs was associated with fracture of a single condyle. Fractures of both condyles occurred at 535 and 550 lbs. Fractures of the symphysis occurred at 850 and 925 lbs. In the test of tolerance of the midface as a whole, if the force is distributed evenly over the whole face by a form fitting moulded block, then the facial skeleton withstands very high forces, more than 3000 lbs, without fracturing. Under such circumstances much of the impact force would presumably be transmitted to the head as a whole and to the brain. But mostly the actual impacting agents load a restricted area of the face, which absorbs much of the impact energy [2].

A body in motion possesses energy, which must be dissipated, before that body can come to rest. In a motor vehicle accident, the energy of motion of the vehicle is dissipated during the impact by deformation of part of body of the vehicle. The energy of the motion of the occupant is dissipated by the destruction of the fragile soft and bony structures of the face. Thus, the facial structures act as cushion to dissipate the energy of motion of the occupant. When the impact tolerance of facial structures exceeds, a part of this energy may be transmitted to adjacent structures, which results in associated injuries [2].

Facial injuries are often accompanied with other associated injuries, like brain injuries [4, 5]. The impact on the facial skeleton can be transmitted to the base of skull; the effect can range from transient loss of consciousness to more dangerous cereberal laceration [9].

It is now generally agreed that a major cause of brain injury is tissue deformation induced by accelerations imparted to the whole head. When the head is struck, the skull is accelerated; the brain shows inertia and suffers strains of different types. An identical sequence of injury is seen when the moving head hits a rigid object and abruptly decelerates. These are also known as acceleration and deceleration injuries of brain [3].

The injuries to the head resulting from impacts in the maxillofacial region fall into four groups [10].

1. Open frontal fractures and penetrating wounds, with varying degrees of local cerebral damage.
2. Internal compound fractures of the anterior cranial fossa.
3. Closed brain injuries resulting from impact-induced acceleration or deceleration.
4. Secondary complications, of which the chief are
   - Intracranial hemorrhage
   - Cerebral edema and other types of brain swelling
   - Cerebral hypoxia
   - Cerebrospinal fluid leakage or pneumoencephalocoele
   - Intracranial infections
   - Carotid cavernous fistula
   - Post traumatic epilepsy.

Nahum [2] in the discussion of the biomechanics of maxillofacial trauma suggested that the injuries are entirely predictable according to certain variables: (1) Force and direction of collision; (2) Impact interface geometry (shape and texture of opposing surfaces); (3) energy absorbing characteristics of the opposing objects; and (4) use of restraints such as seat belts (Fig. 2). The force of impact can be derived from the equation F = ma (Force = mass × acceleration), in which if the head mass is 15 pounds and the

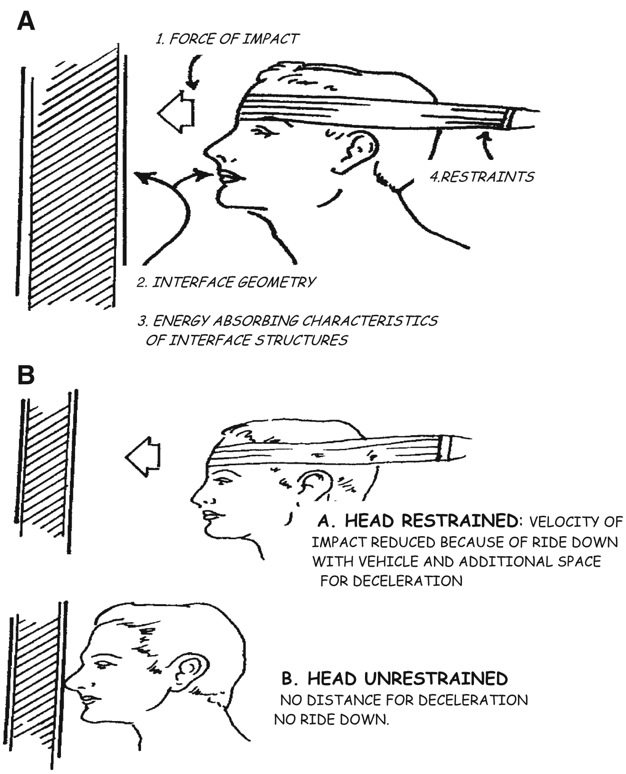

Fig. 2 **a** Collision variables influencing nature, location, and severity of maxillofacial injuries. **b** Advantages of restraints (seat belts) for prevention of facial trauma [2]

acceleration is 80 g (easily obtainable in a 30 mph collision), the force on the face would be 1200 pounds, which exceeds the fracture limit of most of facial bones. According to geometry of face, protruding areas are most likely to sustain injury; thus the nasal bones are most commonly injured, followed by malar bones, orbital rims, and symphysis of the mandible. As fracture occurs energy absorption takes place, thus protecting the brain from violent deceleration. According to their test, the area of the frontal bone is most resistant to injury.

Luce et al. [7] hypothesized that a high-g fracture (the force of gravity is often expressed as a g force) produced in a high-velocity collision may create a significant craniofacial skeleton impairment as well as severe associated injuries, which include head injury. The patients were divided by the circumstances of injury into a high-velocity (e.g., motor vehicular accident) group and a low velocity (e.g., assault) group. The high-velocity group was then further subdivided into subgroups of patients who sustained fractures of facial bones having a high resistance to impact (high "g"), or fractures of facial bones having a low resistance to impact (low "g")-according to the published data of Swearingen and others [11]. To test the hypothesis that facial fractures in areas of high resistance of impact would have more associated injuries, fractures of the supraorbital ridge was analyzed separately. The incidence of some types of life threatening injuries, not exclusive, in the low-g and high-g subgroups, respectively, was: central nervous system, 12% vs. 36%. The cases of supraorbital ridge fractures, alone and in combination with other fractures totaled 33. The incidence of major injuries associated with them was 23 (70%). They further made a note of crash research, which indicates that at the moment of accident a motor vehicle occupant, particularly if unrestrained, literally becomes an active missile within the passenger compartment—and that a second collision occurs between the interior of the vehicle and the occupant. The head, torso, or extremities are subjected to forces many times that of gravity. The tolerance of certain organ systems, or body regions, has been estimated, the probability of injury, if the impact force is known, can be predicted. For example, if the impact tolerance of the fractured face, or fractured part of face, is known, the probability of an associated central nervous system injury can be foreseen. The fractures of the various facial bones, with different impact tolerances, should reflect the impact delivered in high-velocity circumstance to other body regions.

Cannell et al. [12] surveyed head and facial injuries after low speed motor vehicle accidents. They found that the direct impact of the rider against an object is the most obvious cause of subsequent head injury after accidents. Frontal impact accidents tend to produce direct damage to the area of the head or face impacted against the object. In addition, the sudden deceleration, if great enough, would tend to produce intra-cranial damage by the contre-coup mechanism.

Huelke and Compton [13] in a study of facial injuries in automobile crashes concluded that, the facial area is the most frequently injured body region in passenger car occupants. Laboratory studies have indicated that the tolerance of facial bones to impact is relatively low. Most of these facial injuries are rated as minor. The windshield, steering wheel, and instrument panel are the major points of contact. Restraints, lap belts, and lap shoulder belts reduce the frequency of facial injuries at all levels of severity and also reduce the more severe and serious injuries to other body regions.

Gennarelli and Thibault [14] in the discussion of biomechanics of head injury identify that most head injuries are due to one of two basic mechanisms, contact or acceleration. Contact injuries require that the head strike or be struck, irrespective of whether the blow causes the head to move afterward. Acceleration injuries result from violent head motion, irrespective of whether the head moves because of a direct blow or not. The mechanism suggested for most of the skull fractures are because of the contact effects due to impact. Concussions are produced entirely by inertial forces, contact forces are minimal. Contusions are divided into two, coup contusions occurring beneath the site of impact caused by local tissue strains that arise from local skull in bending, and contrecoup contusions where superficial focal areas of vascular disruption remote from the site of impact occur principally because of acceleration (inertial) effects. Epidural hematoma, like skull fracture, is related to contact skull deformation. Intracerebral hemorrhages are often associated with extensive cortical contusions. Subdural hematoma can occur either with contact or acceleration. Diffuse axonal injury, like cerebral concussion, is solely due to inertial effects and not to contact phenomena.

Lee et al. [4] in the discussion of biomechanical aspects of facial trauma state that: In motor-vehicle collisions, the head is often subjected to forces many times that of gravity. As fractures occur, the facial skeleton absorbs some of the impact and cushions the brain against some of its violent effects. The triplanar arrangement of the facial bones in the horizontal, sagittal and coronal planes may act as an effective cushion against violent forces to the cranium. The compressible air-filled energy-absorbing facial bones serve as a decelerating cushion to protect intracranial structures located behind them. This may be a major reason why extensive crushing injuries of the facial bones are frequently sustained with little apparent damage to the brain. In order to prevent serious injury to the brain in an accident involving facial injury, it is best to protect the areas of the forehead and the skull since injury to these areas is more likely to result in serious closed head injury than is injury to other areas of the face.

Complex midfacial fractures have been classified as orbitoethmoidal, zygomaticomaxillary, and Le Fort I, II and III. As the nature of motor-vehicle accidents in the past few decades has changed with high-velocity travel, previously unusual combinations of facial fractures have become increasingly common. Most important among these combinations are frontomaxillary fractures which are characterized by disjunction of parts of the frontal bone, the orbital roof, or even the sphenoid bone, so that both the midface and anterior base of the skull are separated from the main body of the cranium.

Over 75% of the patients in their study sustained high g trauma (such as in motor-vehicle, motor cycle, auto pedestrian, and industrial accidents). Under 25% of them were injured by low G impacts (for example, in assaults, falls, and sporting accidents).

Banks [15] in Killey's fractures of the middle third of the facial skeleton states that, because of the relative fragility of the midfacial skeleton, it acts as a cushion for trauma directed towards the cranium from an anterior or anterolateral direction. It is analogous to a "match box" sitting below and in front of a hard shell containing the brain, and differs quite markedly from the rigid projection of the mandible below (Fig. 3). These physical differences are extremely important for survival after head injury. An impact directly applied to the cranium may be sufficient to cause severe brain injury or death. This same force applied to the middle third of the facial skeleton is cushioned sufficiently, so that it may not even lead to loss of consciousness, though causing considerable damage to the bones and soft tissue of the face. If, however, the mandible alone withstands the impact, the cushioning effect is reduced and blows to the mandible are transmitted directly to the base of the skull through temporomandibular articulation. This in turn means that relatively minor mandibular fractures may be associated with a surprising degree of head injury; hence the effectiveness of the boxers knockout punch, according to them.

John Garfield [16] in Bailey and Love's Short Practice of Surgery in the discussion of Mechanism of injuries of the brain states that, at the moment of impact, a diffuse neuronal lesion is inflicted on the brain, which is responsible for the immediate clinical picture of brain injury. Secondary changes of brain swelling or intracranial hemorrhage take time to develop. The rise in pressure resulting from these causes leads to a deterioration in the patients level of consciousness a few hours after injury; the clinical picture in the early stages results from the neuronal lesion alone. All degrees of brain injury resulting in loss of consciousness, concussion, contusion, cerebral laceration of

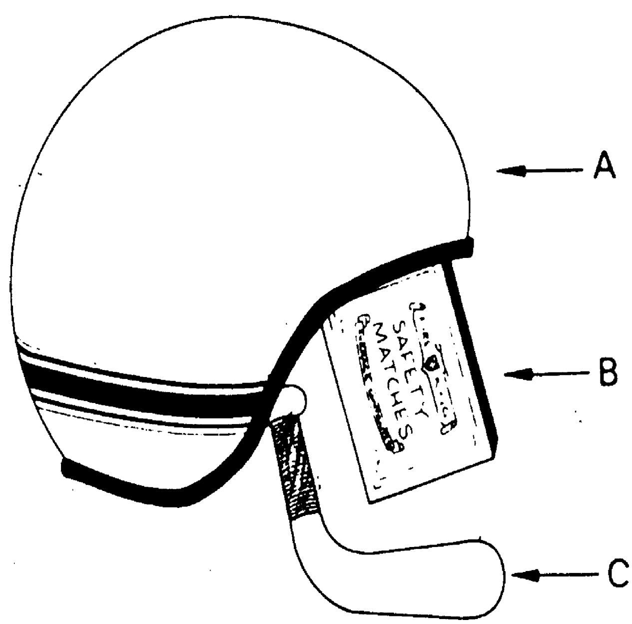

Fig. 3 Diagrammatic representation of the strength of the bones of the skull and face. The 'match box' structure of the midfacial skeleton cushions the effect of impact force B. Impact force A is transmitted directly to the brain producing the most severe injury. Impact force C is transmitted directly to the cranial base via the rigid structure of the mandible [15]

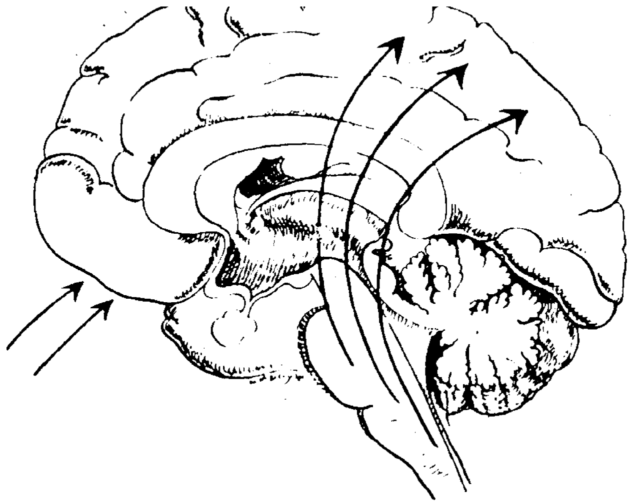

Fig. 4 Lines of the force acting on the hypothalamus and brain stem as the result of posterior displacement of the hemisphere [16]

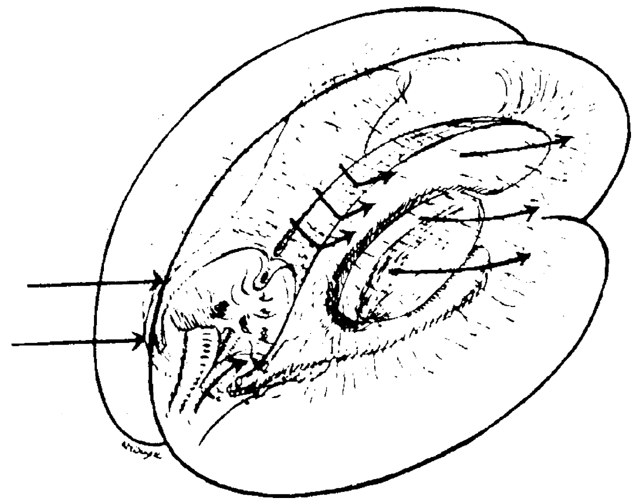

Fig. 5 Lines of the force acting on the corpus callosum and one peduncle as the result of anterior displacement of the hemisphere [16]

the brain are produced by one mechanism, namely displacement and distortion of cerebral tissues occurring at the moment of impact (Figs. 4, 5). The majority of severe craniocerebral injuries due to traffic accidents are the result of rapid deceleration when the moving head strikes an immovable object, e.g., the road. This produces the features of distortion aggravated by the brain mobility. The converse is the acceleration injury when a moving object strikes the stationary skull, e.g., assault. The skull will rapidly accelerate and therefore distort the stationary brain. The complexity and extent of brain damage may be increased if there is loss of consciousness, the subject falls to ground and the brain suffers a severe deceleration injury. He also discussed coup and contre–coup mechanism which are used to indicate the types of craniocerebral damage which may occur either on the side of the blow to the head (coup), or opposite (and often diagonally opposite to the position of the blow (contre–coup), Provided it is clear where, and where alone, the head was struck, this knowledge can provide a useful guide to pathology when used in conjunction with the lateralising signs of a compressing lesion like tentorial herniation (see Table [16]).

Coup	Contre-coup
Scalp laceration	–
Skull fracture	–
Extradural hematoma	–
Subdural hematoma	Subdural hematoma
Cerebral laceration and contusion	Cerebral laceration and contusion
Brain edema	Brain edema
Intracerebral hematoma	Intracerebral hematoma

Chang et al. [17] stated that during the first collision in accidents, part of the impact energy is absorbed by the facial soft tissues and skeleton, and part of the energy is transmitted into the intracranium. Thus, the force of the impact is a pertinent factor in determining the severity of the facial fracture and head injury. The severity of intracranial injury can be caused by direct impact or indirect force transmitted through the facial skeleton. Most high-energy direct impacts to the central region of the craniofacial skeleton create severe central craniofacial fractures that involve the nasal, lacrimal, vomer, maxillary, ethmoidal, and frontal bones. In these central craniofacial fractures, the maxilla is not only important for functional, physiological, and esthetic reasons but together with other bones of the central area, it forms a structure capable of absorbing considerable impact energy, thus protecting the brain from direct collision. Analyzing these patients, there should be a direct correlation between the severity of maxillary fracture (in the central cranioface) and that of the initial head injury.

Gennarelli and Meaney [18] further divided the contact injuries into two types.

1) Effects that occur locally at or near the site of impact and
2) Effect that occur remote from the area of impact.

In both instances, contact forces cause focal injuries that are either surrounding or remote from the impact site. Contact forces do not cause diffuse brain injury (Figs. 6, 7, 8). Acceleration or inertial head injuries were also again divided into three types: (1) translational, (2) rotational, and (3) angular (Fig. 8).

O'Sullivan and others [19] stated that more diffusely applied high-energy forces are responsible for midfacial

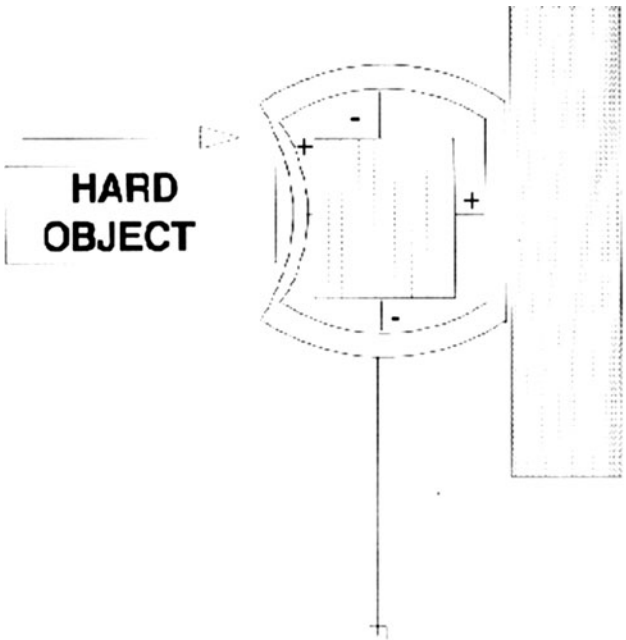

Fig. 6 Impact loading with no head motion. Impact to the idealized, immobile head causes both local and remote skull deformation. Local skull in bending creates an area of high pressure immediately beneath the impact site, while simultaneous outbending outside the impact location causes negative pressure at the top and bottom of the idealized skull [14]

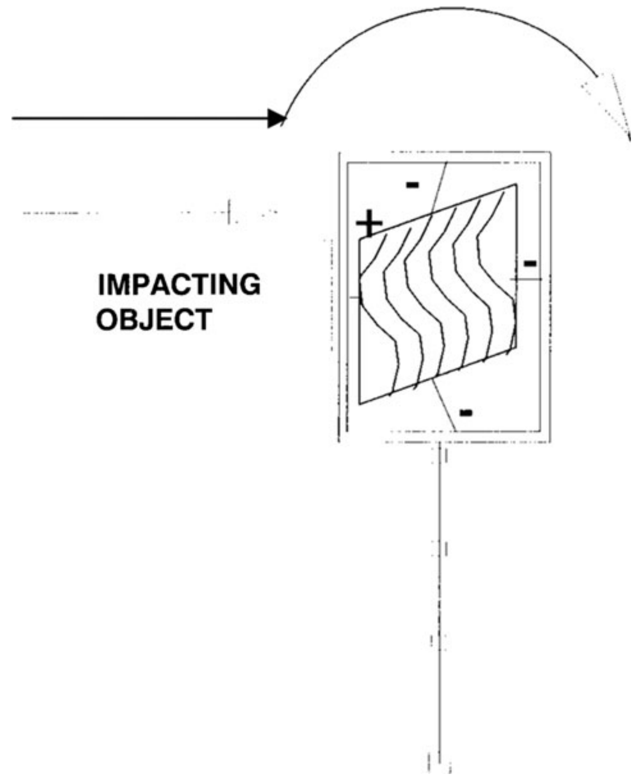

Fig. 7 Impact loading with head motion. In contrast to Fig. 6 allowing head motion after impact causes the brain to deform as a result of including rotational acceleration. Impact to the idealized skull pictured above causes the brain to move slightly toward the impact site, creating areas of high pressure beneath the contact site and negative pressure opposite to impact location. In addition, the head acceleration caused by allowing the head to angulate about the point in the lower to midcervical spine creates shear strain within the brain tissue. Injuries caused by these rotational acceleration effects include tearing of parasagittal bridging veins, cerebral concussion, and diffuse axonal injury [14]

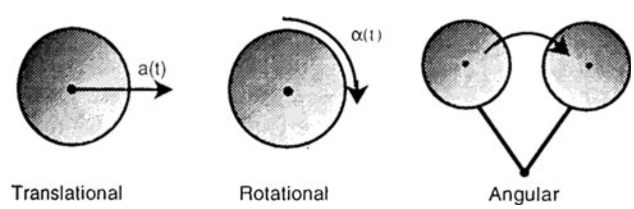

Fig. 8 Types of acceleration experienced by the head. Translational acceleration occurs when the center of mass of the head is moved or slowed in a straight line, whereas rotational acceleration occurs when the head is rotated about its center of mass. With the exception of horizontal plane movements, pure rotational acceleration of the head is uncommon. Rather, the most common form of acceleration is angular acceleration, where the head's center of mass angulates about a point in the lower or midcervical spine. Angular acceleration contains components of both translational and rotational acceleration [14]

injuries. In clinical practice, the classic Le Fort fracture patterns are rarely seen in isolation. Maxillary fracture patterns are more commonly asymmetric and frequently occur at multiple levels, reflecting the high-energy injuries seen in modern practice relative to the low-energy impacts used in Le Fort's classic experiment. The complication rate associated with maxillary fractures is high, which is probably a reflection of the high-energy nature of the majority of injuries in this series. Dissipation of energy at a distance from the impact may account for the high incidence of orbital complications, and occasionally it results in neurologic injury also.

Whereas most of the authors like Bank, Lee et al. [15, 4] reported that facial fractures are associated with a decreased risk of brain injury, Davidoff et al. [20] and very recently Keenan and others [21] found facial fracture to be highly associated with traumatic brain injury. They concluded that facial bones might not act as cushion to protect the brain against impact but infact are markers for increased risk of brain injury.

The age factor: Though a number of studies have quantified the tolerance levels of various bones, it should be interpreted cautiously. The cadavers in which the study was conducted were often elderly [3]. In the old, the limits of skeletal tolerance and even the fracture patterns may not be the same as in healthy young adults. Certainly these experiments cannot be extrapolated to the pediatric age groups. But anatomical and clinical experience suggests that impact tolerance and fracture patterns show age related differences in infants and children. In early life, the calvarial bones are much thinner than in adult and their internal architecture is different. They contain hemopoeitic marrow and the diploe bone is not fully modelled in the cellular compartments seen in mature calvarial bone. When struck, the infant frontal bone dents and the child's frontal bone suffers a depressed fracture under force loads much less than those needed to cause fractures in adult. Similarly in midface, child's facial bones are elastic. It is incompletely pneumatized and it is covered by soft tissues, which are usually thicker than in adult giving better padding [8].

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