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Forces transmission to the skull in case of mandibular impact

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ABSTRACT

Background: Forensic investigations have been reported regarding the loss of consciousness and cardiac arrests resulting from direct mandible impact. However, the mechanisms by which the forces are transferred to the skull through direct mandible impact remain unclear. We conducted a study regarding direct mandible impact on the level of energy required to create a mandible fracture and on the energy dispersion phenomenon to the skull and to the brain.

Materials and methods: This study combines an experimental and numerical approach. Mandible strike was studied using experimental trials performed on post-mortem human subjects. A finite element model of the head and face of a male was also developed based on tomodensitometry scans. The model was validated with literature data and experimental trials. A parametric study was then performed to study the effect of diverse variables such as the dentition integrity, cortical bone thickness, etc.

Results: The forces measured on our reference model were 3000 N on the chin, 1800 N at the condyles, and 970 N in the occiput. Of all the results, we observed a decrease of approximately one-third of the efforts from the chin to the base of the skull and a lower half of the still forces at the occiput, except in the edentulous and for the lateral and frontal impact where the force is transmitted directly to the skull base area.

Conclusion: This study allowed us to create a 3D model of the mandible and face bones to better understand the force transfer mechanisms into and from the mandible. The parameters of the model may be modified to suit the individual characteristics for forensic investigations and legal matters.

1. Introduction

Establishing the relationship between the death of an individual and a violent event is a common practice in forensic science. Many cases of death by violence are relatively obvious and are the result of major blood loss or the compression of organs caused by haemorrhage. However, the process of identifying the causes of the death is sometimes solely based on the time-event continuum between the violent act and the death without confirmation of the injury mechanisms. This situation may be the case when anatomical signs of the injury mechanisms are absent, such as death by reflex reactions related to nervous conduction (death by carotid compression, thoracic impact, compression of the ocular globes, etc.) [1] or injuries to the central nervous system (axonal damage). The hypothesis that forces are internally transferred to the brain, and more specifically the brainstem, is sometimes promoted for the latter case. At the Marseille forensic service, two deaths related to uppercut impacts were recorded, with the brain histological examinations only indicating lesions of the midbrain. Genarelli et al. [2] studied the conditions for the emergence of diffuse axonal lesions via tests using apes. They concluded the functional consequences resulting in loss of consciousness are directly related to destruction of axons at impact. Others (e.g., Besenski et al. [3], Povlishock et al. [4], Sahuquillo et al. [5], and Buki et al. [6]) demonstrated that the axon functional role can be altered even if it is not cut. These stretched lesions are found in lower resistance axons areas: the brain's area transitions between grey matter and white matter, periventricular white matter, corpus callosum and, with a higher severity degree, the dorsal mesencephalon [7]. Belingardi et al. [8] demonstrated that the

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brainstem pivots upon facial impact and suffers alterations by the subsequent shearing mechanisms. Without fracture, the skull movement at impact may still have caused a direct brain contusion. Different degrees of contusion are possible, ranging from simple transient local vasomotor paralysis to various extensive parenchymal tears, which inevitably involve vascular elements. We distinguish between a "blow" versus lesions of "backlash" that the inertia causes away from the impact point. These inertial effects can be observed when the head is violently set in motion without direct impact, e.g., the driver undergoing a "whiplash" when the vehicle is buffered from behind, the rugby player or football player pushed in the back, the boxer receiving an uppercut, or even with impacts suffered by a helmeted head [9]. Our study is primarily concerned with the understanding of energy transmission upon impact of the mandibular area to the rear of the face, through the condyles. We attempt to demonstrate how during a single impact, such as an uppercut, residual energy (some is absorbed by the face with broken bones) arrives at the brainstem.

Brain injuries sustained by boxers and American football players following a mandible impact have been reported recently [10,11].

Finite element models of the head have been proposed recently [12–15] to study this issue through parametrical analysis.

As a result, we decided to investigate the effects of mandible impact resulting from fighting.

To understand this injury mechanism, we conducted an experimental and numerical study with a validated head-face finite element model (FEM). We first demonstrate that the forces are transmitted from the mandible to the skull and, in particular, to the condyles. We then illustrate the energy transfer phenomenon in which part of the residual energy spreads to the brain and brainstem. We assess how some parameters may affect this transmission, namely the impact velocity, position and mass as well as the mandible physiology and biomechanical properties (Young's modulus, cortical bone thickness, bone density, etc.).

2. Materials and methods

2.1. Experimental investigation

Three experimental trials were conducted on post-mortem human subjects (PMHS) to measure the forces involved and to validate the FEM. Two men and one woman aged above 75 years old sat in a tilting seat with a pre-set angle defined by the subjects' height. Two out of the three subjects were toothless. The subjects' anthropometric data are reported in Table 1. An uppercut strike was simulated by impacting the subjects on the mandibular symphysis with a 5-kg mass and impact velocity of 5 m/s. The impactor mass, a metallic cylinder of 76.5 mm in diameter and 458 mm in length, was mounted on a swing and dropped at a predefined height. A load cell placed on the impactor measured the forces transferred to the mandible, and an accelerometer placed on the forehead of each of the subjects measured its acceleration upon impact. The trials were filmed using a high speed camera (1000 fps) to record the impact kinematics.

The lower end of the face of each of the subjects was dissected after the impact to identify any potential fractures.

Table 1
Subject's anthropometric data.

	Age (y.o.)	Gender	Height (cm)	Weight (kg)	Dentition
Subject no. 1	75	Female	154	43	Complete
Subject no. 2	≥75	Male	173	94	Incomplete
Subject no. 3	≥75	Male	171	79	Incomplete

2.2. Numerical investigation

A previously validated 3D FEM of a human head created based on tomodensitometry scans was used in this study [12]. The model was first improved by adding the face and validated with the available literature data and our experimental trials. The effects of variations in the impact and biological parameters were then assessed.

2.2.1. FEM description

The skull geometry was created using a tomodensitometry scan with a slice thickness of 1 mm and then numerically reconstructed using MICMICS 12.3 software (Materialise, Louvain, Belgium). The main anatomical components (scalp, subarachanoid space and brain) were added in the meshing process. The meshing was produced using Hypermesh software, and the model properties were managed using Radioss (Altair Engineering, Inc., Detroit, MI, USA). The average element size was fixed at 2 mm. The skull was composed of three layers to recreate the trabecular and cortical bones. The cortical bone mesh used shell elements with three nodes, and the trabecular bone used tetrahedral elements. The brain and subarachanoid space acting as the cerebrospinal fluid situated between the brain and the skull were modelled using tetrahedral elements. The scalp was modelled using two layers of brick elements.

The facial bones were separately modelled using a parametric approach to define the size and cortical bone thickness. The sinus, teeth, mandible and articulation discs were added and sized based on literature data [16–22]. The model is presented in Fig. 1.

The FEM is composed of 700 000 volumetric elements (tetrahedral and brick) and 80 000 shell elements (3 and 4 nodes). The total mass of the model is 4.2 kg. All of the mechanical properties (Table 2) were taken from literature data [16–20,23,24].

2.2.2. FEM validation

The model was validated according to the following:

- Experimental trials conducted by Schneider et al. [25]. The resistance of the facial bones and mandible was assessed via 106 trials on 17 PMHS skulls. Two different positions were used to impact the mandibles: antero-posterior and lateral. Two Plexiglas cross members were affixed to the drop assembly and contained nylon bushings to minimise any frictional reaction with the steel guidewires. In addition, the heads were severed at the seventh cervical vertebra in the latter experiments to facilitate the placement of the skull necessary for antero–posterior mandibular impacts. The head, in all cases, was supported by wedges of soft polyurethane padding (the test conditions and limits are presented in Table 3).
- Experimental trials conducted by Viano et al. [10] where the effect of a boxer's punch was studied: eleven Olympic boxers weighing 51 kg (112 lb)–130 kg (285 lb) were included in the study. These boxers were instructed to strike the instrumented Hybrid III head with their gloved fist two times with four different punches: a straight punch to the forehead, a straight punch to the jaw, a hook, and an uppercut. Accelerometers were placed in the boxer's clenched hand (two Endevco 7264-2k accelerometers). The Hybrid III was equipped with the standard triaxial accelerometers (Endevco 7264-2k) (see Table 3).
- Experimental trials described previously in this study.

3. Results

3.1. Experimental investigation

The first PMHS trial (subject no. 1) resulted in a 2-cm-long laceration to the chin, linear fracture of the mandible symphysis,