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Modeling one-handed grip strangulation: intentionality of the gesture and age influence

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Abstract: Strangulation is a violent act which can be lethal and is often studied in forensic context. The neck includes several anatomical elements that can evolve with aging. We therefore created a numerical human neck model including the main anatomical elements and simulated one-handed grip strangulation cases. In addition, we created 3 models each representing age groups: 20-30 years old, 30-50 years old and over 50 years old. The main changes between the different age groups are the ossification of the cartilages and the muscles mechanical properties. Several initial and boundary conditions have been tested to perform a realistic simulation of one-handed grip strangulation. Stress analysis and fracture observation were compared with the grip strength of an average man, 552N, to look at the intentionality of the gesture. In each age group, the results show no model fracture for a force of 552N. It is necessary to reach a minimum of 1406N before observing a first fracture on the hyoid bone. However, it is possible to get stresses on the hyoid bone and on the thyroid cartilage way before 552N. It thus appears that the force created by one-handed grip strangulation is not sufficient to cause fractures of the bony elements of the neck, but it remains sufficient to compress the larynx and at least reduce airflow.

Key words: Strangulation, forensic science, finite element, hyoid bone, thyroid cartilage

1. Introduction

Violent death is a situation conventionally studied in forensic context. In addition to defining the cause and/or injury mechanisms, there are joint issues of compatibility with the environment of the alleged author's claims.

In case of manual strangulation, one of the frequent questions concerns the time required for cervical necking leading to death. This question is related to the knowledge on resistance to anoxo-ischemia of brain tissue [1]. Another relates to the force required to generate visually detectable cervical lesions, particularly those necessary to occur a fracture of the hyoid bone or the larynx. This problematic does not lead to a response as scientific as the previous one, due to a lack of precise physiopathological approach but also because of the diversity of the modes of grip of the cervical region. When the assailant invokes the accident on unsupported pressure, he mimics an anterior cervical grip gesture called one-handed grip that is to say, using hook thumb and fingers to grip the protruding reliefs of the neck. In that case, the assailant also claims the non-responsibility of the gesture.

Also, most of the published studies on this issue are access to this mode of strangulation from finite element models of hyoid bone subjected to pressure simulation. Although these studies, mainly conducted in our laboratory [2–5], provide important data useful for expert reports, it is not certain that the data obtained on bone isolated from its environment can be obtained when the bone is protected by the soft masses that surround it.

Following the case reported above, a mechanical neck model was created. The present study focused on this biofidel model of the neck except the blood vessels and the skin. Then 3 models were defined to consider the age evolution of the neck. The objective is to study the mechanical behavior of the different components and their interaction during a neck compression protocol, but also to compare with the average grip force of a man to study the intentionality of the gesture.

2. Materials and methods

2.1. Development of the numerical model

2.1.1. The mesh

Our numerical model, using finite element approach, is based on Niort et al. (2015) [4] and Gagnon et al. (2019) [5]. This model includes the hyoid bone and the thyroid cartilage.

First, the model was improved by adding the infrahyoid muscle, the cricoid cartilage, the larynx airway and the membranes that connect each part (fig. 1). This was made by using Hypermesh 2017© (Altair, Troy Michigan, United States).

2D and 3D meshes were used for the hyoid bone, the thyroid and cricoid cartilages, allowing the modeling of the cortical parts in 2D and the cancellous parts in 3D, and thus to consider the ossification of these anatomical elements. The muscles and the laryngeal airway were only represented by 3D elements.

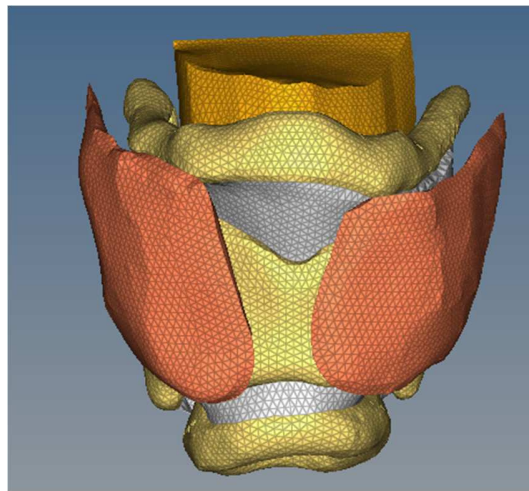


Figure 1: Numerical model

The posterior parts of the neck (vertebrae) were simplified and replaced by a backplate to stop the movement of the different components of the neck during strangulation. In addition, the section including the laryngeal airway has been modeled by a cartilaginous cylinder.

Then, we used HyperMesh V12.0 © to create a 2D meshes impactor, fitting the morphologic curvatures of the model. It represents 2 plates located on each side of the model, at the level of the infrahyoid muscle, the most anterior component of the model. The left plate represents the 4 fingers of a right hand and the right plate represents the thumb (fig 2).

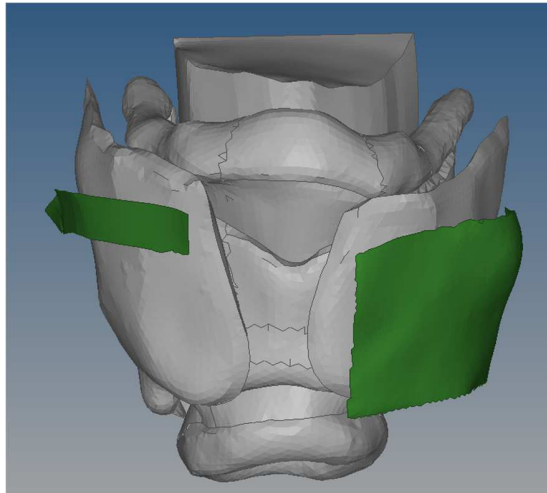


Figure 2: Impactors design fitting anatomical geometry (green)

All of these anatomical components combined in the same numerical model, excluding the backplate, were modeled with approximately 150,000 elements, including 9,000 2D elements and 141,000 3D elements.

2.1.2. Data input

The second step of numerical modeling involved data input using HyperCrash 2017© (Altair, Troy Michigan, USA). These data include mechanical properties, materials laws, contact interfaces, initial and kinematic conditions to the models. The different properties and materials used in these models come from older studies [3,4,6,7] (Table 1). Only the laryngeal airway properties are not directly issued from literature but based on the cartilage properties.

The bones were modeled by an elastoplastic law, but different properties are assigned according to the type of bones (cortical and cancellous) (Table 1). The cortical bone was modeled by 2D elements with an average thickness of 1,5mm, according to the study of Gagnon et al. (2019) [5].

For cartilaginous parts, 3D mesh was mainly used with an elastic law, when the cartilage is not ossified.

The impactor was defined as a rigid body that can move in rotation or in translation, depending on the type of load case, in direction of the hyoid bone and the larynx. Different types of load case have been tested during the study.

The backplate was also defined as a rigid body blocked in translation and rotation. In addition, numerical interfaces have been defined between the anatomical elements of the models in order to manage the contacts between these different structures.

2.1.3. Cartilage material law assessment

There is no consensus in literature concerning cartilage mechanical law description [6,8–10], more particularly to manage the cartilage damage. So, we decided to model the cartilage material with an elastic law considering the density, the stiffness and the compressibility coefficients only.

	Material	Density (g/mm ³)	Young modulus (MPa)	Poisson ratio	σ_{Yield} (MPa)	Failure plastic strain (MPa)	σ_{Max} (MPa)	Thickness (mm)
Cortical bone [3-4]	Elastoplastic/ Ductile Damage	0,002	3000	0,3	20	0,03	45	1,5
Cancellous bone [3-4]	Elastoplastic/ Ductile Damage	0,001	500	0,3	20	0,07	45	/
Membranes [7]	Elastic/ Linear elastic	0,001	31,5	0,4	/	/	/	3
Cartilage [7]	Elastic/ Linear elastic	0,001	50	0,47	/	/	/	/
Muscles [7]	Viscous elastic/ Generalized Kelvin-Voigt	0,0011	500	0,45	/	/	/	/
Laryngeal airway [6]	Viscous elastic/ Generalized Kelvin-Voigt	0,0012	500	0,4	/	/	/	/

Table 1: Mechanical properties

2.2. Types of load cases

The simulations were performed with Radioss© software and the results were analyzed (animations and curves) using HyperView© 2017 software. It is possible to visualize during the simulation the field of the stresses on the model and thus to identify the zones with strong concentration of stresses, zones often related to the appearance of fractures.

To simulate one-handed grip strangulation, different types of **dynamic** load case have been tested. The aim was to identify a load case that would lead to the injuries found in literature [2,11]. The main elements injured by manual strangulation are the greater horns of the hyoid bone and the upper horns of the thyroid cartilage.

The imposed angular velocity results in a rotation of the impactors towards the model. This rotation represents the movement of the fingers and the thumb during strangulation. It also helps to focus the movement on the back of the impactors, which are the fingertips. The velocity of these impactors is adapted to the surface of contact with the model. Indeed, the contact surface of the thumb is smaller than the four fingers. Thus, the velocity of the thumb is 0.052m/s and 0.026m/s for the fingers. According to literature, these numbers are based on the average grip force of man, which is 552N [12].

To recreate this movement, the axis of rotation is placed at the front end of the impactors, thus the compression starts on the posterior part of the model, close to the horns and edges of the thyroid cartilage. The axis of rotation is blocked with boundary conditions to represent the junction of the fingers and thumb with the palm of the hand and then recreate the movement only of grip.

2.3. Influence of anthropological parameters

The model has been modified in terms of materials and properties to represent different adult age categories (Table 2). Different researches have shown the importance of studying the strangulation in adult [13–16]. The changes in the parameters mainly concern the thyroid cartilage which ossifies with age. Several studies have been performed on thyroid cartilage ossification and age estimation [17–19]. These studies indicate which parts of the thyroid cartilage ossify first, as well as the age group that may be associated, up to complete ossification [17–19]. The ossification of cartilaginous elements is characterized by those elements becoming bone tissue, using bone parameters in Table 1. In addition, the mechanical properties of the muscle have also been modified to make it softer with age, as the

muscles have a significative difference of the softness and strength according to age [20]. Based on those studies, the model will be adapted to 3 age groups: 20-30 years old, 30-50 years old and over 50 years old, which represent the 3 main categories of ossifications differences (Table 2). This study does not take in consideration children because of the extreme variability occur by the non-finish development.

It is well known that there is a sexual dimorphism according to the hyoid bone or the larynx [2,3,5,21–24]. This sexes differences concern mostly the lengths and angles measurements. In the present study, the model represents only women, because the study is related to an actual case, where the victim was a woman.

	Hyoid bone	Thyroid cartilage	Cricoid cartilage	Muscles stiffness (Young modulus MPa)
20-30 years old	Fusion body/greater horns cartilaginous	Horns ossified Lamina cartilaginous	Completely cartilaginous	500
30-50 years old	Completely ossified	Horns, lateral and inferior edges ossified	1/3 ossified	350
Over 50 years old	Completely ossified	Central part cartilaginous	2/3 ossified	250

Table2: Age categories

3. Results

3.1. Anatomical results

At first, the contribution of the infrahyoid muscles was tested. The model created from the HyperWorks 2017© softwares, was tested firstly with the muscles and another simulation without the muscles. The first results highlight the importance of muscles in the model. We observed different lesions according to both models. The lesions described in literature only occur for the model with muscles, this is why we only consider this type of model in our study.

3.2. Load case types

Different types of load case have been tested. An imposed angular velocity leads to a stability of computations and initial conditions of the model. It also led to injuries in accordance with literature.

3.3. Injuries assessments

The injuries occurred by the simulation of one-handed grip strangulation are variables according to age and anatomical part (Table 3). Those injuries were analyzed for a force of 552N, which is the average grip force of a man [12]. They were also analyzed over this average grip force, to identify the force needed to have the different injuries.

Fractures of the hyoid bone occurred for a higher force than the thyroid cartilage. Indeed, the hyoid bone breaks when it is subjected to a force between 1406 and 1535N and the force needed to observe element ruptures for the thyroid cartilage ossified is between 566 and 1130N. The fractures mostly occurred near the horns. Only ossified parts can show fractures, because of the material's mechanical laws. In our study, fractures are characterized by the rupture of element in the numerical model, using the "kill element" method, which is based on the maximal plastic deformation.

For the hyoid bone and the thyroid cartilage, the stresses are visible, at first, near the horns and then spread to the body. Regarding the laryngeal airway, almost the entire surface undergoes stresses except the parts which are not in contact with the hyoid bone or the thyroid cartilage. The stresses on the laryngeal airway increased with age. It means that the stress is higher on the airway for the model over 50 than for the model 30-50 and 20-30 years old. However, the stress is still low for a force of 552N, for each group.

	Age	Stress area for 552N	Force first fracture (N)	Locations first fracture
Hyoid	20-30	Greater right horn	/	Cancellous bone of the greater right horn
	30-50	Greater right horn and right side of the body	1535.37	Cortical bone greater horns
	Over 50	Greater horns and posterior part of the body	1406.38	Cortical bone greater left horn
Thyroid cartilage	20-30	Upper edges	1130.03	Cancellous bone upper left horn
	30-50	Upper edges and right laminae	1063.69	Cortical bone left laminae
	Over	Upper edges	566.05	Cortical bone upper left

	50			edge
Laryngeal airway	20-30	Both side	/	/
	30-50	Right side	/	/
	Over 50	Right side	/	/

Table 3: Injuries assessments

Furthermore, the *Von Mises* contours show the main stress on the numerical model. The figures 3 and 4 show the stress according to the age group, for the maximal grip force of 773N [25]. The figures show an increase of the stress spreading with the older age group, especially at the level of the hyoid bone and thyroid cartilage (fig 3).

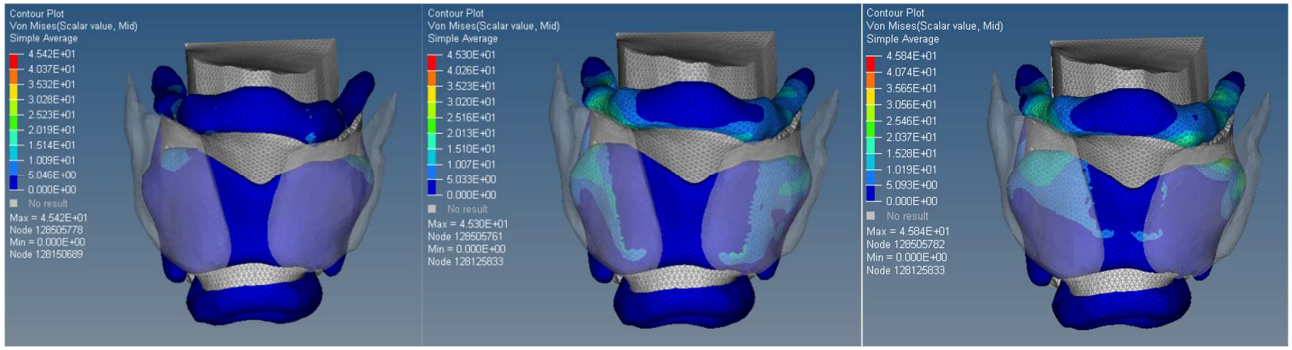


Figure 3: Von mises on the hyoid bone, thyroid and cricoid cartilage; 20-30 years old, 30-50 years old, over 50 years old

4. Discussion

The present study, in the light of the literature, is the first one proposing an analysis of a strangulation scenario based on a numerical finite element model of the neck, integrating bone, cartilage and some muscle elements, and considering the influence of age. The main result concerns the injury assessment: no fracture were observed on the whole model for an average force of 552N (average grip strength for a man) [12], in the 3 ages group, while fractures of the hyoid bone and larynx could be noted [3–5] in isolated part studies. Also, the force needed to provoke fractures is higher for younger group than the older. It is therefore essential to consider the anatomical aspect of the entire structure of the neck to answer the judicial questioning on the “intentionality” of the gesture.

4.1. Numerical model

4.1.1. Anatomical components of the model

The neck is a complex body segment to be modeled integrating elements of bone, cartilaginous, muscular and a set of blood vessels. One of the characteristics of our model with regard to existing models described in literature concerns the integration of the various bone and cartilage, but also the contribution of a muscular element considering the influence of age on its mechanical properties.

However, the present model has been simplified and does not include skin and blood vessels. The addition of these vessels would be relevant for studying the pressure to be applied on one of the carotid arteries to interrupt blood flow, resulting in unconsciousness, while considering the influence of the muscle hypotonia [26]. In the same way, considering the cutaneous coating will be the goal of future studies. However, this model has made it possible to address the initial problems raised by one-handed grip strangulation, in particular by considering the effects of age on the model's response and the most affected anatomical elements interactions.

4.1.2. Material law for cartilage

Concerning the cartilage numerical modeling elastic laws can reproduce its behavior under dynamic loads.

In the literature, only the values of density, compressibility and stiffness are consensual [8]. These 3 mechanical parameters used with an elastic law allow us to observe the stresses distribution and local concentrations areas.

. However, it was not possible to apply the method used to simulate bone fractures, i.e. elastoplastic law with “kill element formulation”. Indeed, this approach requires three more parameters: the yield stress, the maximum stress and the maximum deformation at fracture. For these ones, we did not find any consensus in the literature [6,8–10].

Thus, we decided to use an elastic law, making it possible to overcome the influence of the parameters related to the fracture while preserving the possibility of visualizing the stress concentrations.

4.2. Influence of the age

4.2.1. Definition of 3 age groups

The difference between age groups is mainly due to ossification of the thyroid cartilage and muscles stiffness. Thus, as the age increases, the thyroid cartilage ossifies and turns into compact bone, which increases the risk of fracture. Our model does not simulate fracture of cartilaginous elements.

The stresses on the laryngeal airway begin before 552N. This compression will cause the obstruction of air. Depending on the age group, the laryngeal airway is not subject to the same stresses. Indeed, as the age increase, there are more stresses visible on the larynx airway. However, this is a first level of information collected from these simulations. As previously stated, the influence of age on the muscles is not only related to a loss of stiffness but certainly also related to a loss of muscles volume, we must keep a critical look at this result and check this trend during new simulations varying the muscular volume.

4.2.2. Injury assessment

It is stated in literature that the average grip strength for man is 552N and 444N for woman [12], the maximum being up to 773N for man and 466N for woman [25]. The age and sex of an individual therefore influence the grip strength.

For the 3 defined age groups, we applied the imposed angular velocity described above and analyzed the lesions. The higher the level of effort, the more lesions are observable, but in order to make a comparison with literature, and thus with the average grip strength of a man, no fracture is observable when a force of 552N was detected. The force of a single hand does not seem sufficient to cause a fracture of the neck components but remains sufficient to cause stresses on the laryngeal airway and on the other part of the model.

4.3. Comparison of isolated anatomical parts

In the case of our modeling we decided to apply our load case on a model integrating the main anatomical elements of the neck. The obtained results showed similarities but also differences compared to previous studies.

In this study of complete neck model, the load case is not done directly on the anatomical elements such as the hyoid bone or the thyroid cartilage; in fact, muscles stand for dampeners absorbing part of the energy of impact. This result in “shock” behavior and different lesions compared to previous

studies [3,5]. In addition, the muscles are attached to the hyoid bone and thyroid cartilage. This causes a different constant, with the possibility of observing on our model a propagation of these stresses from one anatomical element to another, which cannot be observed and analyzed from an isolated model, resulting in different and overestimated lesion in the case of an isolated model. This demonstrates that the environment and the interaction between anatomical parts modify the reaction to the stresses.

4.4. Limits

A limit of this study is the validation of the numerical models. Indeed, numerical studies are often associated with experimental studies; therefore it is difficult in this case to do one-handed strangulation experimental test on PMHS (post-mortem human subject). An experimental approach is also limited by the interindividual variability and the absence of muscular tonicity. These models allow us to do relative comparison according to the age for the distribution of the stress on each anatomical part. They are not, for now, used to establish injuries criteria.

5. Conclusion

This study allowed us to assemble the different components of the human neck and to develop a finite elements numerical model. We do not find the same type of lesions as in the literature [3–5], because unlike the previous studies, our study does not focus on the isolated anatomical elements, but on a model linking the different structures between them. In terms of results, this comparative study allows to evaluate the influence of the age on the model response, but also to underline the importance to consider anatomical elements in their environment in order to take into consideration interactions between them. For one-handed grip strangulation, we observe no fracture of the hyoid bone in our complete model for a force of 552N. But this average grip force is not far from the force needed to fracture the thyroid cartilage for the older group, which is 566N. The results allow us to say that the average force of one hand, does not seem sufficient to cause fractures of the neck from a one-handed grip, but it seems sufficient to compress and stress the different anatomical elements and thus does not remove the possibility of asphyxiation. It is also possible to say that the force needed to fracture any neck structure is higher for younger age group than for older one. This numerical model study can be useful during autopsies to understand injury mechanisms and to look for the stress and injuries localization according to the age.

It would be interesting in future studies to improve our model by integrating other anatomical elements, like blood vessels (carotid arteries and jugular vein) and other muscles (sternocleidomastoid). It would also be interesting to apply other types of load cases, such as two-handed grip, strangulation using an object (rope or pipes) or the vascular neck restraint to visualize other types of lesions and injury mechanisms, just as it would be important to include the sexual dimorphism of the neck.

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