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Numerical modeling of human mastication, a simplistic view to design foods adapted to mastication abilities

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HIGHLIGHTS

- A 2D third order lever model was developed to simulate mastication.
- Force available for food fracture depends on food size and position in the jaw.
- The model is in agreement with force distribution experimentally measured.
- The model can be to design foods aligned with physiological capabilities.

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ABSTRACT

The human diet contains a large variety of aromas, tastes and textures. The latter is particularly important since it determines whether foods are difficult to process orally and thus can be one source of food avoidance. It has also been reported in recent literature that food texture was a main driver for satiation processes and thus it is of interest for the food manufacturing industry to be able to control textural properties of food within the limits of acceptability for the consumer. For solid foods, fracture force is an important aspect of texture and we were interested in understanding the physiological drivers of this variable.

We present a third order lever model of human bite force and the space between teeth based on data from the literature on human oral anatomy. The results from the model are compared with experimental data available in the literature. The model compares well with the experimental data ($r^2 = 0.95$, $p = 0.0010$, $MPE = 0.18$), and can thus be used to derive a diagram of how food properties such as piece size or fracture force can be used to define whether foods are close to the limits of what the human jaw is capable of breaking. Such modeling tools can be used to define texture rules for tailor-made nutrition for specific populations based on their mastication abilities. The limitations of this modeling approach are also discussed, particularly the fact that tooth shape should also be considered, as this will ultimately define fracture stress, which is the deterministic factor of food fracture.

1. Introduction

Understanding how foods are broken down in the mouth has attracted interest from the food science community in the last two to three decades [1–4]. At the heart of this interdisciplinary science lies the anatomy and physiology of the oral cavity [5], as well as the properties (e.g. brittleness and fracture strength) of the food [1,6]. Researchers often work using model systems [7], which are attractive because of their well-controlled properties, however this approach does not offer a full view of the variety of mechanical properties that would be offered by natural foods [6,8]. The first bite is decisive in the path of oral food breakdown as it defines whether a food can be eaten at all. Two important factors control whether a first bite is successful or not [5,9,10], (a) is the food small enough to fit between teeth and (b) is the maximum available bite force greater than the fracture strength. Although those statements seem evident, finding accurate experimental data to design foods close to the boundaries in resistance and size of what can be eaten can prove difficult. In addition, there is not a single force or distance characterizing the human mastication system as measurements would depend on the distance between the point of measure and the condyle (jaw joint) [11]. The available data from the literature indicates that force increases as biting position is closer to the condyle [12–15]. This is compliant with Eckermann's model [11] describing jaw clenching as a third order lever, where the condyle is the point of rotation, the muscles anchor points being the point of effort and the measurement location being the point of resistance[11]. Such data can be seen in Fig. 1, although force values reported are different (a) at first sight between different studies, all experimental data folds on the same master curve

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when normalized to the first incisors (b). This led us and others [11,16] to think that bite force at each tooth is mainly controlled by muscle force and tooth position. A recent 3D simulation work [16,17] has already offered thorough insight on the human mastication forces during static biting although those models are probably too complex and computationally demanding [17] to allow them to be used for rapid prototyping of foods. With this in mind, it seems that a simple model, taking into account the masseter muscle as the only jaw closing muscle and the different dimensions of the jaw ramus, jaw corpus and palatal vault as well as the gonial and occlusal plane angles, should be sufficient to build a diagram of food size and food hardness that are breakable in the mouth.

2. Modelling strategy

The actuators of clenching the jaw are the temporalis and masseter muscles; for the sake of simplicity we will only represent the masseter muscle effect in our model. The ramus and corpus can be defined by their length and the angle existing between them. We define *A* as the point representing the condyle, *M* as the gonion (where the masseter is anchored on the mandible) and *D* as the gnathion.

Thus *AM* is the ramus length and *MD* is the corpus length. The angle $\left(\overrightarrow{MA},\overrightarrow{MD}\right)$ is defined by the physiological value of the gonial angle. The point *B* defines the intersection between the occlusal plane and the jaw ramus (the occlusal plane is oriented so that $\widehat{\left(\overrightarrow{BA},\overrightarrow{BC}\right)} = \left(\overrightarrow{MA},\overrightarrow{MD}\right) - \left(\overrightarrow{BC},\overrightarrow{MD}\right)$). It is located at the middle of [*AM*]. *F* is the point where the food is located along the occlusal plane (*F*'s most forward position is *C*, most backward being *R*), whose shape is defined by using a second order polynomial function [18].

Finally, point *K* is the anchor for the masseter muscle on the maxilla, defined by its distance to *M* (*MK*) supposed equal to the ramus length and the angle $\left(\overrightarrow{MA},\overrightarrow{MK}\right)$.

During mastication, the rotation of the mandible around the condyle (*A*) by an angle θ defines the distance between teeth. In this process, each point (except *K*, which is located on the maxilla) is associated with a point after rotation, noted with an *r* subscript so that the image of *B* by the rotation is B_r, *D* is D_r, *R* is R_r *M* is M_r, *F* is F_r, *R* is R_r and *C* is C_r. According to this definition, distance between the teeth where the food is located (and thus food size) is FF_r and the maximum opening of the mouth is CC_r (Fig. 2).

Once the geometry is defined using the values collected in the literature as summarized in Table 1, one can compute the forces available during mastication at different distances from the condyle (*A*) and for a given angle θ. Force (1) and moment balance (2) can then be applied to the maxilla/mandible system;

$$\begin{aligned}&\overrightarrow{FoA}+\overrightarrow{FoK}+\overrightarrow{FoF}=\overrightarrow{0}\\&\overrightarrow{FoA_r}+\overrightarrow{FoM}+\overrightarrow{FoF_r}=\overrightarrow{0}\end{aligned}\tag{1}$$

$$\begin{aligned}&\overrightarrow{AK}\times\overrightarrow{FoK}+\overrightarrow{AF}\times\overrightarrow{FoF}=\overrightarrow{0}\\&\overrightarrow{AM_r}\times\overrightarrow{FoM_r}+\overrightarrow{AF_r}\times\overrightarrow{FoF_r}=\overrightarrow{0}\end{aligned}\tag{2}$$

where $\overrightarrow{FoF}$ represents the force applied at point *F* and $\overrightarrow{FoF_r}$ at point F_r. Since *A* is the center of rotation: $\overrightarrow{FoA}+\overrightarrow{FoA_r}=\overrightarrow{0}$. Also, the force coming from the masseter muscle is assumed to be symmetrical between the two bodies, thus $\overrightarrow{FoK}+FoM_r=\overrightarrow{0}$. According to Eq. (1), $\overrightarrow{FoF}+FoF_r=\overrightarrow{0}$.

By substituting $\overrightarrow{FoF}=-\overrightarrow{FoF_r}$ and since all the vectors belong to the same plane (2D model) Eq. (10) can be simplified into Eq. (3).

$$\begin{aligned}&\left(AK_x\cdot FoK_y-AK_y\cdot FoK_x\right)+\left(AF_x\cdot FoF_y-AF_y\cdot FoF_x\right)=0\\&\left(AM_{rx}\cdot FoM_{ry}-AM_{ry}\cdot FoM_{rx}\right)+\left(AF_{rx}\cdot FoF_{ry}-AF_{ry}\cdot FoF_{rx}\right)=0\end{aligned}\tag{3}$$

which can be solved using the linear system of Eq. (4)

$$-\begin{pmatrix}-AF_y & AF_x\\ AF_{ry} & -AF_{rx}\end{pmatrix}\cdot\begin{pmatrix}FoF_x\\ FoF_y\end{pmatrix}=\begin{pmatrix}AK_x\cdot FoK_y-AK_y\cdot FoK_x\\ AM_{rx}\cdot FoM_{ry}-AM_{ry}\cdot FoM_{rx}\end{pmatrix}\tag{4}$$

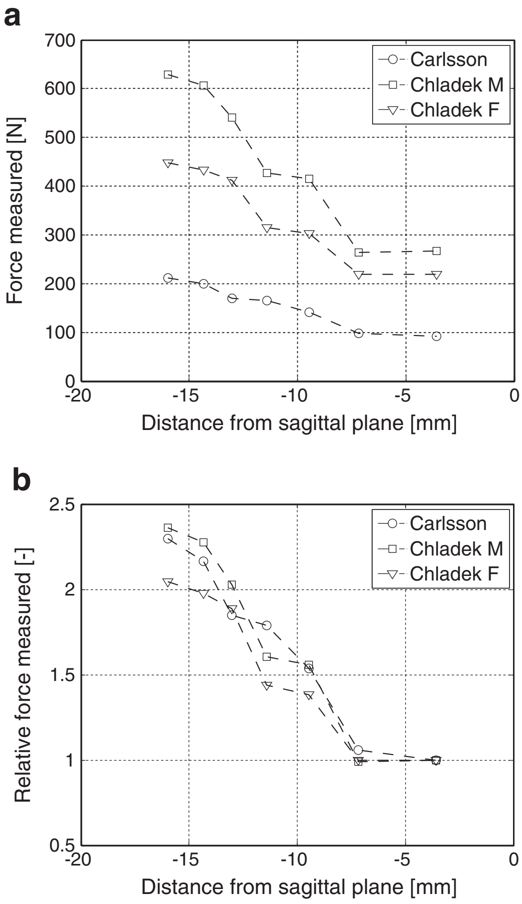

Fig. 1. (a) Force measured at different tooth locations in the literature [12,13] and (b) relative force measured at different tooth locations in the literature normalized against first incisor force.

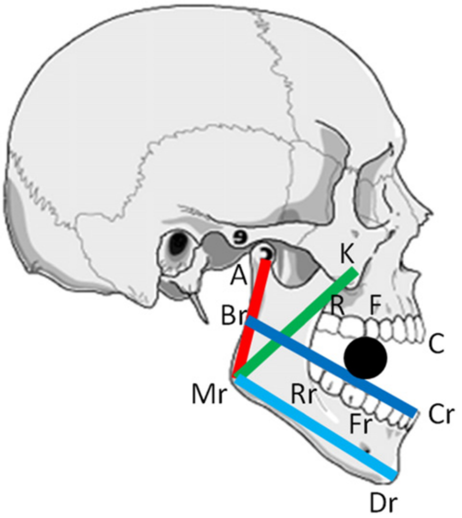

Fig. 2. Schematic sagittal view of the human mandible and maxilla and reference to the anatomical landmarks used for the simulation. A hypothetical food item is represented by the black disk, which is in contact with the jaw at points F and Fr.