Measurement of oral loads during chewing of food

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Abstract. *Oral forces acting on human teeth during mastication are the subject of many research works. In specialized literature, many measurement results relating to occlusion loads during chewing of various types of food can be found. However, besides the great dispersion of these values, attributed to the application of different measuring methods, usually only results concerning the force component in the normal direction to the tooth's occlusal surface are presented. The purpose of this study is to correlate quantitative data from chewing experiments with chewing cycles, and also to investigate the significance and effects of the tangential force component. A load cell was developed and temporarily implanted in a patient's arcade with a flawed dentition. While carrying out the functions of the missing tooth, it could record its state of strain due to resisted efforts during chewing of raw carrot and thin biscuits. Using these results of strain and equilibrium equations, it was possible to determine the normal and tangential components of the resultant oral force and their variation along the time. Both components were found to vary in agreement with literature's qualitative description of chewing cycle. It was observed that consistency of the food may have an influence upon lateral displacement of the mandible and consequently over the magnitude of the tangential force components.*

Keywords*: Mastication forces, dental loads, dental force measurement, chewing cycle*

1. INTRODUCTION

In an attempt to reach a better comprehension of the phenomena occurring inside the human mouth during the acts of biting and mastication and its consequences to the individual, oral forces acting on teeth have been the subjects of many research woks.

Information concerning external loads is an important piece of the input data for a stress-strain analysis of dental problems originated due to mechanical factors. Thus, a quantitative analysis using numerical methods, such as the Finite Element Method, will strongly depend on the quality of the load data (magnitude, orientation in space, time, etc.).

In specialized literature, many measurement results of occlusion loads during biting and chewing can be found. Cimini *et al.* (2000), published a literature review of this topic.

Using a strain gauge on a lower molar tooth, Anderson (1953) measured the mastication forces produced by a subject while four pieces of biscuits were being chewed bilaterally in eleven seconds intervals. The maximum values recorded ranged between 39 to 59 N.

Anderson (1956a) later used strain gauges placed in subject's lower molars. Assuming a uniform load distribution over the teeth surface and measuring the contact pressure exerted while the volunteers laterally chewed biscuits, raw carrot and cooked meat, the maximum forces recorded varied form 59 to 69 N.

In another paper, Anderson (1956b) followed the same procedure as in his former study but investigated the maximum forces developed taking into account the full molar contact surface. The same three food types were used for the bilateral mastication tests. The results obtained ranged from 112 to 146 N, 118 to 134 N and 71 to 114 N, for biscuits, carrot and meat respectively.

Howell and Brudevold (1950) used electronic strain gauges inserted under artificial teeth in which the forces were recorded as deflections on a strip chart. The subject, a 48-year-old man who had been wearing complete dentures for five years, was asked to chew three types of food: peanuts, shredded coconut and raisins, as to represent brittle and tough types of food. For the first molar sensor, it was recorded a maximum force of about 71 N while chewing raisins.

Gibbs *et al.* (1981) used a measuring method based on sound transmission to evaluate the mastication loads. Several volunteers were submitted to the tests, between men and women, ranging from 15 to 55 years old. As a result, the mean maximum mastication force was found to be 261 N.

Neill *et al.* (1989) used eletromyographic sensors to record electrical activity of the masseter and temporal muscles. The signal detected by those sensors was translated as a direct measurement of the mastication forces, which is clearly not directly related to the forces acting in a single tooth since those muscles act in a large area of the mouth. Out of the 10 volunteers, men and women of various ages, the highest recorded value was 1.13×10^3 N when chewing nuts; mastication of other types of food was also investigated.

It is not difficult to notice that the values of forces recorded show large variations from author to author. The main reason for these discrepancies is not only the different measuring methods but also the inherent variability of the mastication process, which is influenced by factors such as subject's physical conditions at the time of the tests, sex, race, age, alimentary habits, teeth geometry and muscular structure, etc. (Cimini *et al.,* 2000). Another important fact is that none of the researches took evaluated the tangential component of the oral forces in their analysis; its influence can be important and shall be investigated. Commonly, maximum load in the direction normal to the occlusal surface is the parameter obtained to represent the state of load. Nevertheless, biting is a complex dynamic process and demands more parameters to be fully described.

Mastication is known as the first step of digestion process in which food is crushed by teeth to diminish the volume of the food inside the mouth and to increase its surface area, allowing a more efficient work of saliva and enzymes. It is also characterized by well-defined rhythmical movements of opening and closure of the mandible.

Each complete movement of opening and closing of the lower jaw – the only human face's bone that moves, during mastication and other activities, such as talking – draws a profile in the vertical plane that has the shape of a water drop - Figure 1 (Oskeson, 1992) - known as the chewing cycle. Therefore, mastication is nothing else but a series of chewing cycles in sequence.

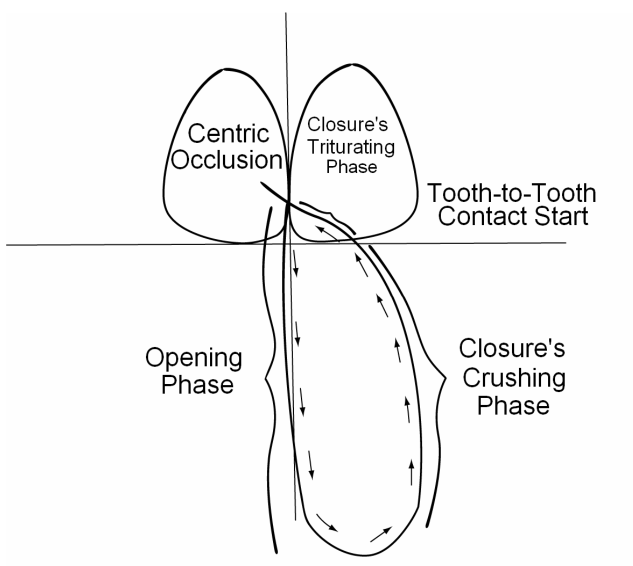

Figure 1. Chewing cycle drawn at the vertical plane

Each loop can be divided into two phases. The first is called opening phase and can be described as a vertical displacement of about 16 to 18 mm from the usual occlusion position followed by a horizontal displacement of 5 to 6 mm from the mean line. At the same time, food is placed between the teeth, driven by the cheeks and tongue.

At this point, the closure movement begins. The closure movement, second phase of the chewing cycle, can be subdivided in two steps. The first one, in which food is held between the teeth, is called the crushing phase. Afterwards, when the antagonist teeth become closer to each other, the lateral displacement is reduced so that, when they are separated by a distance of 3 to 4 mm in the vertical direction, they are also 3 to 4 mm from the chewing initial position in the horizontal direction. At this very position, upper and lower teeth's vestibular cusps, at the side in which the mandible has displaced, are almost at the same line. As the mandible continues to close, the food bolus is kept between the teeth and starts to be grinded. The grinding step is the second subdivision of the closing phase. During this period, the mandible is driven by the occlusal surfaces back to the intercuspal position promoting the food cut. Therefore, the participation of the teeth is fundamental from the positioning of the food until its grinding. After several cycles, the food bolus becomes wet and reduced to a semi-pasty form, ready for ingestion.

When the mouth starts to close, the distance between the teeth gets shorter in vertical and horizontal direction simultaneously as shown in Figure 1. This causes the value of the tangential component of the resultant force to start increasing due to the presence of food that tends to hinder the lateral movement. At the same time, the food is compressed, promoting the increase of the normal component, until it breaks.

2. METHODOLOGY

In order to measure the oral loads in all its characteristics (modulus, direction and orientation) a load cell was developed (Las Casas *et al.*, 2007). Its design concept was that it was to be implanted as prosthesis in a patient's arcade with a flawed dentition and therefore register the resisted forces during occlusion by a single tooth while carrying out its functions.

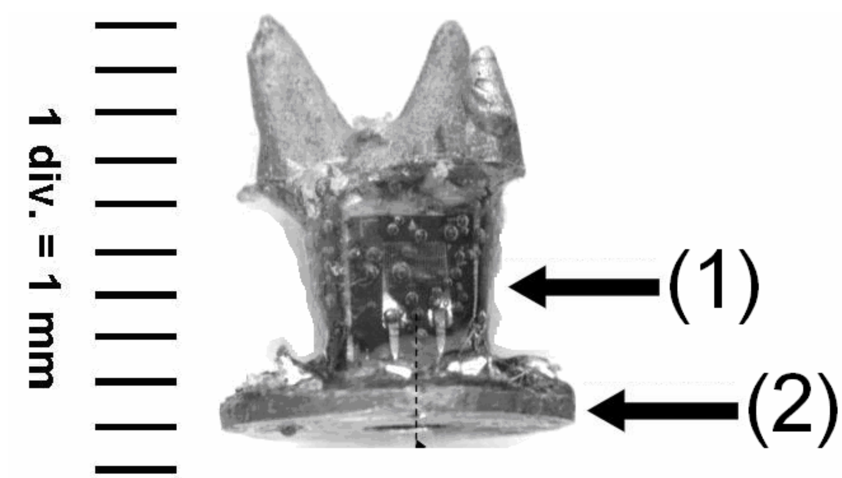

Figure 2. Load cell

The load cell consists of a square section column-type device made of a chrome-nickel alloy and instrumented with strain gauges glued onto each of its four larger faces. The assembly is made of three components (Figure 2):
(1) – Load resisting component – A 4 mm long main column with a square 3 x 3 mm cross sectional area and a concentric hole of 2 mm diameter. Four strain gauges were glued onto each face along the longitudinal central line at a distance of 2.2 mm from the bottom.
(2) – Ceramic crown bearing block – A disc of 8mm of diameter and 0.8mm thickness placed on the bottom of the component (1).
(3) – Intercuspal contact replica – A ceramic mold of the first molar (missing tooth) crown, not shown in Figure 2.

The base of the load cell is a mold of the superior first molar tooth root's canal and pulp and it is attached to the top of the main column. This makes the load cell even more specific, since each individual has its own tooth roots with a distinct shape, size and even different number. The personal and careful adjustment for the individual aimed at improving the reliability of the measurements. In fact, the chosen subject has fulfilled certain prerequisites such as tooth height larger than average and having a missing upper first molar.

After applying a cement of low tensile strength to the base of the load cell, it was easily implanted with no need of anesthesia application. The patient was asked to perform a series of experiments such as biting, breaking and chewing raw carrot and thin biscuits. After the measurements were done, the implant was removed.

Strain data from each strain gauge, recorded along the period of the tests, was transformed in load data using Hooke's law and equilibrium of forces and moments, as described by Las Casas *et al.* (2007). Computing the strain average for all gauges, the normal component of the resultant force could be determined. By calculating the bending moment and knowing the value of the lever arm (2.2 mm), the tangential component could be calculated. The usage of four strain gauges made possible the determination of the magnitude and the direction of the resultant efforts and their variation.

3. ANALYSIS AND RESULTS

From the strain data recorded and calculations, it was possible to generate graphs that present some interesting information as the evolution in time of the force components during chewing is analyzed.

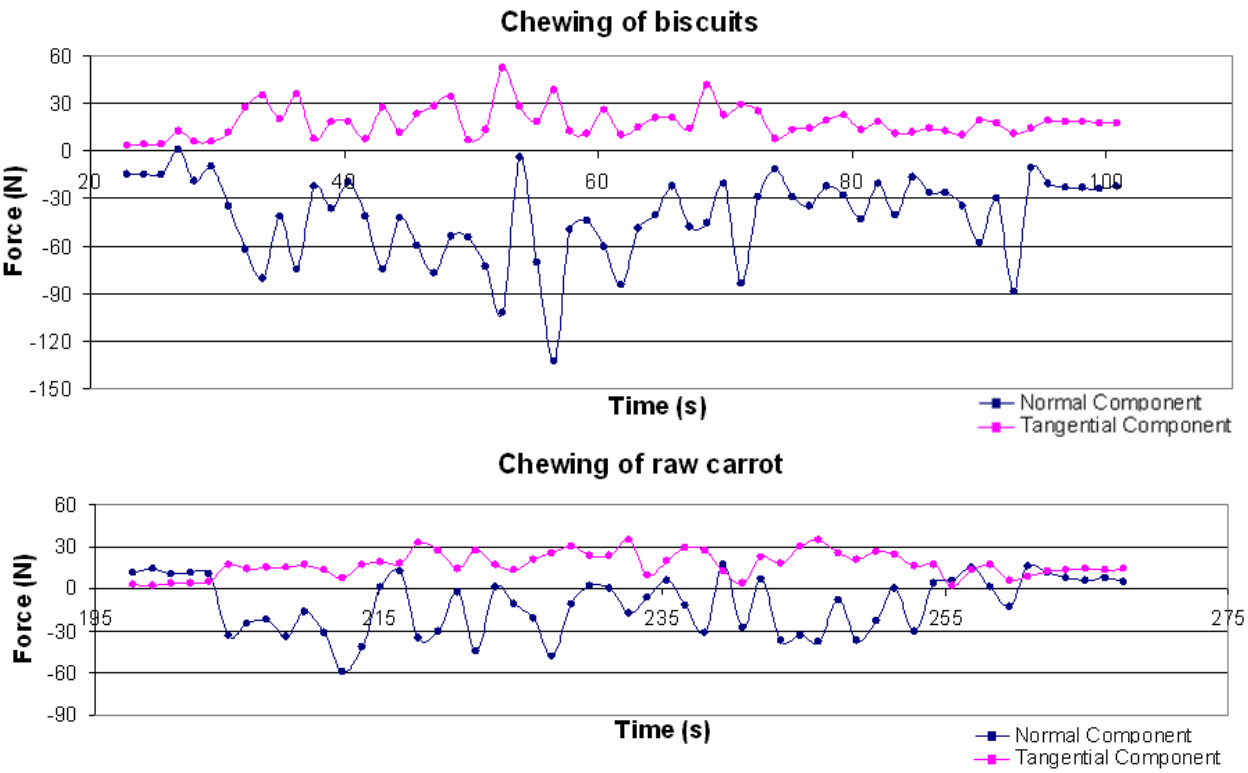

Figure 3. Normal and tangential forces in the mastication of biscuits and raw carrot

The graphs of Figure 3 were plotted with the magnitudes of the tangential and normal force components against time. The purpose was to compare the significance of each component on the state of load during chewing, usually only the normal component is presented in the literature. Normal component of the mastication forces shows negative and positive values along the mastication of both types of food tested. It is reasonable to suppose that the former indicates food compression or tooth-to-tooth contact and the latter represents a stress on load cell tending to pull it out from the mouth, which may be caused by the suction promoted at the end of the cycle and tongue movement. The representation of the tangential component above shows only its modulus variation along time, there is no indication of its direction nor the orientation on the occlusal plane. The simultaneous growth of the normal (increasing in modulus) and tangential components indicate mouth closure and food breakdown as well as the approximation of the curves to the zero line represents the unloading caused by mouth opening.

The discontinuities noticed in the graphs of Fig. 3 may be explained by the food breakdown, typical of the mastication process. When a large piece of food is hold and crushed between the antagonist teeth, the resultant force starts to increase until the food is broken in pieces promoting a sudden relief in both force components. It is most likely to happen when it comes to chewing of brittle food, this is also a hypothesis to explain the behavior of the curves at the graph.

The tensile forces observed in the normal component's curves are clearly less representative and less frequent than the compressive forces for both tests, especially for biscuits mastication. The higher frequency of the tensile forces that occur in carrot mastication could be explained due to the major need of suction and tongue movement since this type of food was consumed in much larger pieces compared to biscuits.

It is believed (Oskeson, 1992) that the amount of lateral displacement of the mandible varies with food consistency. The harder the food, the larger the lateral displacement and consequently, tangential forces also get more intense. The experiment has shown that, except for peak values, chewing of raw carrot presented higher values of tangential forces than chewing biscuits. The higher peaks recorded for the latter are believed to be due to direct tooth-to-tooth contact. The biscuits employed in the experiment were very thin and would have been easily wetted, thus offering less resistance to direct contact between antagonist teeth. The magnitudes recorded for the biting experiment - tooth-to-tooth contact (Las Casas *et al.,* 2007) - are similar to those recorded at the high peak forces during chewing of biscuits.

As the times advances, food gets more triturated, watered and pasty, consequently less effort is required to promote food breakdown. Then, the values of the mean magnitudes of both tangential and normal components tend to show a little reduction.

In a general manner, in subjects with higher cusps and deeper pits, the vertical movement verified is more intense. On the other hand, in worn or plane teeth, which are the case of the artificial crown developed for the experiment, chewing has wider amplitude in horizontal direction (Oskeson, 1992) and therefore may also cause higher tangential forces.

The following tables present a summary of the information generated. Table 1 shows the maximum and average values of both force components along mastication. Although the maximum occlusion force occurs for biscuit mastication and is more than two times the value found for carrot, the maximum tangential force components for both types of food differ less than 6N from each other, and also, the mean tangential force component for carrot mastication is greater than the biscuit one. This could be explained by the greater carrot's hardness, as said before.

Table 2 shows a summary of the maximum occlusion loads during mastication of similar types of food obtained by other authors. Here, it is important to note the conditions in which these data were recorded and the difference in results. A main difference is that in the three first references as well as in this study, the force components were evaluated as acting on a single tooth while the references (Gibbs *et al.,* 1981) and (Neill *et al.,* 1989) presents results for the mouth as a whole.

Table 1. Maximum and mean values of chewing force components calculated for both mastication tests.

Mastication test	F_N max [N]	Mean F_N [N]	F_T max [N]	Mean F_T [N]
Raw carrot	-55,37	-11,14	47,48	29,52
Biscuits	-128,34	-40,25	53,18	21,84

Note that in table 1 the values for maximum F_N and maximum F_T do not correspond to the same instant.

Table 2. Maximum values of mastication forces obtained by other authors.

	Maximum mastication forces [N]			
Reference	Raw carrot	Biscuits	Measurement location	Method
Anderson (1953)	-	39 – 59	Lower 1st molar	Strain gauge
Anderson (1956a)	59 - 69*		Lower 1st molar	Strain gauge
Anderson (1956b)	118 - 134	112 – 146	Lower 1st molar	Strain gauge
Gibbs *et al.* (1981)	261*		Extra oral	Sound transmission
Neill *et al.* (1989)	673	700	Masseter muscles	EMG sensors

* These values do not necessarily correspond to carrot or biscuits mastication but were obtained from a set of experiments containing one or both of these types of food.

4. CONCLUSION

It was possible to correlate the qualitative description of chewing cycle found in literature with the quantitative data recorded. Tangential and normal components of occlusion loads were found to grow simultaneously; the former is less intense and may be even lower than those measured in healthy patients since the artificial crown might have induced more lateral movement.

The tangential component of the chewing force was shown to represent a significant amount of the resultant and consequently it is believed that the presentation of only the normal component is insufficient information about the loading acting over the tooth.

The values found for maximum mastication loads are near those presented in some of the references (Anderson 1956a and 1956b) although the differences in food conditions are not well defined. In these studies strain gauges were also used as main device to record data from the chewing process and these data were also evaluated in a single tooth. It is important to notice that these values can vary with a large series of aspects, from characteristics of the subject himself to the way the food was prepared. It is also important to notice that in mastication, rather than in biting, the influence of tongue movement, deglutition, food consistency, etc., cannot be easily distinguished.

The large amount of data recorded along the tests is also serving to help developing a computational model of the load cell based on finite element method. Through reverse engineering; and that is, applying to a model the calculated forces to obtain values of strain at the load cell locations and then comparing to those recorded in the experiment; it would be possible to validate the load estimation. The resultant forces could then be used to study a wide range of dental problems with more reliable computer models, achieving good accuracy levels without causing disturbances to human subjects, also saving time and money.

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