Biomechanical analysis and development of design criteria of a joint prosthesis

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Short Abstract: A complete structured procedure should be used for a radical innovation when designing an articular medical device (MD). Studies were then carried out before the preliminary design stage of a temporomandibular joint (TMJ) prosthesis. To establish design criteria, muscle efforts were assessed experimentally by electromyography and magnetic resonance imaging; joint displacements and geometries were characterized by stereophotogrammetry. Results pointed out wide individual variations. This study describes the definition of a TMJ geometrical characteristic and its management using a modular design. Additive manufacturing opportunities are now out of the scope but will become solutions to face this problem of variability [B1].

Key words: Biomechanical Behaviour, Characterization, Inter-individual Variability, Articular Medical Device.

1 - Temporomandibular joint prostheses

The most common reason for replacing a TMJ is to relieve pain and to improve reduced function caused by arthritis. Total replacement of the joint involves removing the non-functional joint and replacing it with an artificial one. Due to the nature of the local bone structures, prosthesis design is somewhat complex, and materials and geometry play an important key role in enhancing the long-term life of the artificial joint [S1]. Occlusion corrections clearly give the patient both physical and psychological comfort and comparison of actual prostheses (Fig.1) underlines that the inter-incisor opening can reach twenty millimeters. These studies also point out different cases of failures that can require additional surgical procedures:
- inflammation can occur with persistence of pain revealing an imperfect osseointegration of the screws accompanied by implant micro-displacements with respect to the bone,
- prosthesis fracture (rare) happens near a screw or in a variation of the section where stresses tend to concentrate,
- bone fracture seems to be the result of an insufficient number of screws or a too high intensity of loads on the mandible condyle [W1].

2 - Characterization of the joint geometry

2.1 – Experimental device

Different techniques allow to re-create bone shape based on X-Rays or Magnetic Resonance Imaging [M1]. To describe the displacements of the mandible with respect to the skull and then the geometry of the articular surfaces using stereophotogrammetry, three reference points were located both, on the mandible and on the maxilla (Fig.2).
Precision was essential and these reference points could not be located on the skin [C1]. To define and fix the two reference frames, two gutters interdependent of the dental arches, were moulded using orthodontic equipment. The cranial reference on the upper plate was defined using the three target points; the lower reference was associated to the mandibular plate in the same way.

2.2 – Repeatability and recordings
To analyze the repeatability of the protocol, the two plates were fixed to a base. The relative positions of the targets were thus constant. The equipment was moved within the field; the amplitudes of the displacements were much greater than the amplitude of the articular displacements. Data were processed and thus the results quantified the uncertainty of the measurement associated with the displacements of the plates. The error value remained less than 0.7mm while displacement from condyle centers could reach 20mm at maximal opening. The value of the ratio 2x0.7/20 (7%) confirmed that the method was valid. The coordinates of the projected center of the condyles in the sagittal symmetrical plane were calculated during the open-close movements.

2.3 – Geometrical characteristic
The open-close movement, facilitated by the TMJ meniscus, is the result of sliding on contact and of the simultaneous rotation of the mandible with respect to the skull. A relation between rotatory and translatory displacements was defined quantifying a "preponderance coefficient" as follows:

\[ C_p = \frac{\text{Rotation}}{\text{Translation}} \]

Using the values of the horizontal and vertical displacements of the condyle centers, the value of the slope angle was determined to characterize the geometry of the temporal bone. The value of the slope angle, in relation with this ratio \( C_p \) characterized the volunteer studied [M2].

3 - Design criterion
A statistically significant sample of thirty volunteers exhibiting no joint dysfunctions participated in this study. The volunteers were told to perform free open/close movements. Their manducatory system was analyzed and judged clinically to be within the normal limits.

3.1 – Inter-individual variations
In a healthy volunteer, three to five recordings enabled to establish significant values of the inter-incisive maximum opening distance, the displacements of the condyle center in the sagittal plane and hence of the temporal slope angle. Inter-individual variations were linked only to anatomical factors which are specific to the volunteers (distribution of biological tissue...).

3.2 – Geometrical criterion
The distribution of the preponderance coefficient values allowed to discriminate among the volunteers, regardless of any jaw opening values. Three groups were isolated relatively to three kinematic models. The correlation between the kinematic characters and the disc-condyle trajectories along the temporal facet provided the mean value of the temporal slope angle for each group (Fig.3). Each group presented small variations of maximal translation and of maximal mandible rotation.

4 - First conclusion
The implantation of a TMJ prosthesis concerns fewer than five thousand patients every year. These investigations and results are useful for the TMJ prosthesis design and tend to guide the designer towards a modular temporal component. By providing the surgeon with a range of three to five modules, the slope angle can be chosen using a pre-operative scan image.

5 - References