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Forces and motor control mechanisms during biting in a realistically balanced experimental occlusion

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ABSTRACT

Temporomandibular joint and masticatory muscle forces generated during bilateral biting on an experimental device simulating a symmetrically balanced maximum intercuspation, are unknown. The basic motor control strategies during such tasks, executed either strictly controlled or developed rather habitually, are also quite unclear. The main goal of this study was to compare muscle and joint forces at various magnitudes of force under two experimental conditions: (1) generation of a bite force vector perpendicular to the maxillary occlusal plane, (2) development of a directionally unrestricted (quasi-habitual) bite force, both with identical magnitude. Additionally, the experimental results were evaluated on the basis of optimisation strategies displaying physiologically reasonable neuromuscular objectives for coordinated muscle contraction.

In 10 normal subjects, the electric activities of all jaw muscles were recorded bilaterally. Intraoral force transfer and force measurement were achieved by a measuring device with one anterior and two posterior force transmission points. Prior to the experiments, the force transmission was balanced at a directionally unrestricted resultant bite force of 100 N. Under visual feedback-control, the subjects generated resultant forces of 50, 100, 150, 200, 300, and 400 N, respectively. Joint and muscle forces were calculated based on the electromyograms of all jaw muscles, lines of action, geometrical data of the skull, and physiological cross-sectional areas acquired from all subjects. To identify possible motor control strategies, various physiologically reasonable objective functions were applied. The results revealed significant differences in force patterns generated under the two experimental conditions. Directionally unrestricted biting created higher forces in nearly all muscles and in the jaw joints. Muscle forces normalised with the magnitude of the inherent resultant force, and the findings from the optimisation calculations indicate variable central control mechanisms under the two experimental conditions, both minimizing energy consumption.

1. Introduction

Co-contraction patterns of masticatory muscles during biting are traditionally estimated by electromyograms (EMGs).[1,2] However, only biomechanical modelling permits the evaluation of muscle forces and temporomandibular joint reaction forces on the basis of simultaneous *in vivo* measurement of EMGs of all relevant masticatory muscles and the three bite

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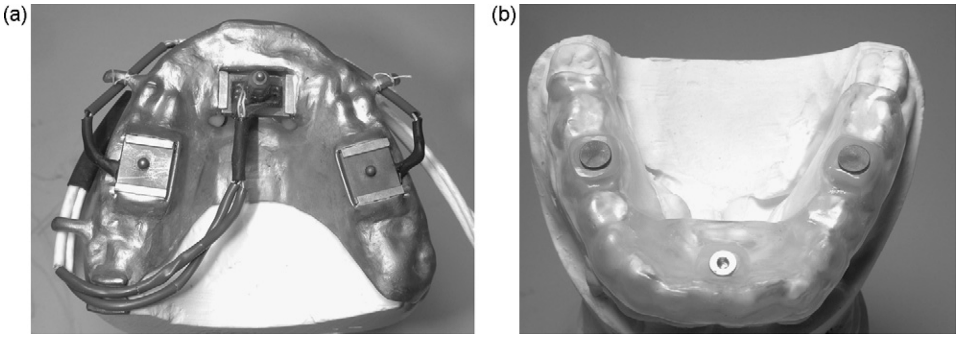

Fig. 1 – Force transducer array for the upper jaw with two posterior and one anterior sensor mounted on a metal splint (a). Plastic splint for the lower jaw with three force transmission points consisting of small metal plates. Notice the perforation in the front plate (b).

forces $\vec{B}_j$, and subsequent calculation of all forces from the static equilibrium conditions.[3–6] The underlying motor control strategies are typically investigated by optimisation algorithms based on physiologically reasonable neuromuscular strategies for coordinated muscle co-contraction, *e.g.*, minimisation of joint forces, minimisation of overall muscle forces or minimisation of applied elastic muscle energy.[5–12] Preconditions for both biomechanical methods are geometrical data of the skull, lines of action, physiological cross-sectional areas (A_i) of the muscles, their pennation angles (α_i), and the intrinsic muscle strength (P).

Thus far, co-contractions of the jaw muscles have been controlled by force transducers placed unilaterally or midsagittally between the tooth rows.[4,7,13,14] Yet, a more realistic modelling of a symmetrically balanced maximum intercuspation requires a force transmission between the tooth rows in at least three force transmission points arranged in a triangle, and simultaneous measuring of all transmitted force components. As given in the case of natural occlusion, rotation of the mandible with respect to the x-, y-, and z-axis was restricted in this case.

The main objective of this study was, therefore, to perform biomechanical simulations based on realistic physiological and anatomical data of test subjects and synchronous measurement of EMG and bite force utilising a force transducer with three force transmission points. Particularly, we intended to calculate all muscle and joint forces developed during (1) biting with a consciously generated pure vertical force, and (2) under ''normal'' biting (*i.e.*, with directionally unrestricted force components), both with identical magnitude of the resultant bite force $F_{\text{res}} = |\Sigma\vec{B}_j|$. Furthermore, the motor control strategies under both experimental conditions were scrutinized on the basis of optimisation algorithms.

2. Materials and methods

2.1. *Subjects*

Ten healthy male subjects (average age: 32 ± 5.7 years; range 24–39 years) took part in the experiments. The subjects had Angle class I or mild class II dentitions. Exclusion criteria were skeletal anomalies (*e.g.*, short-faced or long-faced) or distinct malocclusions. The study was approved by the Ethics Committee of the University of Freiburg, Germany (no. 25/02, amendment 04). All participating subjects gave their written consent to the experiments, which were conducted in accordance with the Declaration of Helsinki.

2.2. *In vivo measurements*

2.2.1. *Intraoral force measurement*

For the individual set-up of the measuring device, the plaster casts of the subjects' upper and lower jaws were mounted in an articulator. Jaw separation as measured at the incisor region ranged between 7.5 and 10.5 mm. Initially, the upper device (Fig. 1a) was waxed-up utilising a template which enabled the alignment of the three force transducers parallel to the maxillary occlusal plane. The guidance faces for the three transducers were placed bilaterally over the first molars and midsagittally between the canines. The points of force transmission formed isosceles triangles (legs: 31 ± 1.5 mm, base: 42 ± 2.0 mm). The two posterior transducers transmitting only forces perpendicular to the maxillary occlusal plane, consisted of a base plate (length 9 mm, width 10 mm, height 1.5 mm) and a small metal sphere (diameter: 1.5 mm) attached to the centre. The base plate of each transducer was equipped with a strain gauge (6/120 LY 11, Hottinger Baldwin Messtechnik, Darmstadt, Germany) mounted at the underside. The midsagittally placed transducer, transmitting vertical as well as horizontal forces, consisted of a base plate with bearing pin (pin: height 10 mm, diameter 4 mm; base plate: length 20 mm, width 10 mm, height 1.5 mm). For horizontal force measurement, the cylindrical profile of the pin was equipped at half the height with four strain gauges (3/120 LY 11, Hottinger Baldwin Messtechnik), offset 90° to one another. For vertical force registration, the base plate was provided with a fifth strain gauge (6/120 LY 11, Hottinger Baldwin Messtechnik) mounted at the centre of the underside (Fig. 2). The mandibular occlusion was covered by a plastic splint bearing three round metal plates in the region of force transmission (Fig. 1b). A 1.3-mm deep perforation in the anterior metal plate enabled a joint connection with a loose fit between the maxillary bearing pin and the mandibular splint to ensure that no torque could be transmitted within the connection. This configuration allowed the transmission and measurement of