Jaw muscle size and bite force magnitude in relation to craniofacial morphology

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CHAPTER 1 GENERAL INTRODUCTION

1.1 CRANIOFACIAL GROWTH REGULATION

Postnatal growth of the human craniofacial skeleton is characterized by a complicated interaction of bone apposition and bone resorption, leading to continuous changes in shape, size and relative position of the bony components, that together make up the face and skull (e.g., Enlow, 1975). Several theories about growth regulation of the craniofacial complex have been postulated, the contribution of growth regulating factors varying from mainly genetic to mainly environmental. Sicher (1952) assumed that craniofacial growth was principally regulated by intrinsic genetic factors, i.e., genetic influences originating from the craniofacial bone cells. Some modeling and remodeling would additionally be influenced by local environmental factors. One of the local environmental factors is the stress on the craniofacial skeleton from the muscles of mastication. In contrast, Van der Klaauw (1946, 1948, 1951, 1952) and Moss (1962) postulated that craniofacial growth would be totally secondary, i.e., due to epigenetic or environmental influences. Epigenetic influences are genetic influences originating from adjacent other tissues or organs. According to Scott (1962) and Van Limborgh (1971), both genetic and environmental factors are involved in growth regulation. In their theories, different craniofacial components were considered as being influenced in different ways. Van Limborgh (1971) differentiated between chondrocranial and desmocranial growth. Chondrocranial growth, i.e., growth of the cranial base, is mainly regulated by intrinsic genetic factors. Desmocranial growth, i.e., growth of the cranial fault and the face at the sutures and periosteum, is mainly dictated by epigenetic and local environmental factors. Hence, tensile forces of the jaw muscles are considered to be a growth-regulating factor in craniofacial morphogenesis.

1.2 JAW MUSCLE BIOMECHANICS

1.2.1 Muscle force

The maximum force a muscle can produce depends to a large extend on the so-called physiological cross-sectional area, i.e., the total cross-section of all muscle fibers. The physiological cross-section of a muscle is related to the muscle's cross-section (Weijs and Hillen, 1984). In vivo, the cross-sectional area can be estimated by computerized tomography (CT, Weijs and Hillen, 1985, 1986), magnetic resonance imaging (MRI, Hannam and Wood, 1989; Van Spronsen et al., 1989; Koolstra et al., 1990, 1992), or ultrasonography (US, Ikay and Fukunaga, 1968; Ruf et al., 1994; Close et al., 1995). Thus, the afore-mentioned techniques allow us to estimate the capacity of the masticatory muscles to exert mechanical stresses on the craniofacial skeleton in vivo. Ultrasonography is advantageous compared to CT because it has no known biological effects, and to MRI, because it is a rapid, inexpensive technique and the
equipment can be easily handled and transported. However, US also has some disadvantages. It allows for registration of superficial muscles only, and, because the transducer cannot always cover the total area of some jaw muscles, it is not always possible to register the muscle cross-sectional area. Therefore, in studies of the masseter muscle, several authors measured the muscle thickness as an indication of muscle size, instead (Kiliaridis and Kälebo, 1991; Bakke et al., 1992). Close et al. (1995) recorded both masseter cross-section, thickness and length. They found a high correlation between the cross-sectional area and the thickness of the masseter (R ≥ 0.93).

The maximum muscle force also depends on the length of the muscle fibers. The tension that can be generated by a muscle fiber partly depends on the degree of overlap between the actin and myosin filaments and, consequently, on the length of the sarcomeres. Maximum active tension can be developed at optimum sarcomere length and decreases with greater and with shorter length (Gordon et al., 1966). The spatial arrangement of muscle fibers within a muscle is of importance for the length and length changes of the sarcomeres during movement. The human jaw closing muscles are characterized by a complex architecture. Within and between these muscles there is a wide range in fiber lengths (indicative for the amount of sarcomeres in series), fiber angulations, ratios between fiber and tendon length, distances between origin and insertion, and three-dimensional positions and orientations of the fibers (Schumacher, 1961; Baron and Debussy, 1979; Van Eijden et al., 1997). Hence, at different jaw positions, sarcomere length, and thus maximum force cannot be expected to be the same for different muscles and different muscle portions. Although the fiber orientation can be visualized to a certain degree in vivo by MRI (Van Doorn et al., 1996) or US (Herbert and Gandevia, 1995), sarcomere length determinations in the human can generally only be done with information from biopsies or post mortem material (Van Eijden and Raadsheer, 1992; Van Eijden et al., 1996, 1997).

1.2.2 Bite force

Human bite forces are produced by a simultaneous activity of the jaw closing muscles. The magnitude of the maximum bite force does not only depend on the cross-sectional area and the length of the muscles, but also on fiber type composition (Ringqvist, 1974) and jaw muscle activation level (Van Eijden et al., 1990). Muscle activation might be limited by factors such as proprioception, pain threshold or motivation. To produce bite forces in different directions, the relative activation levels of the muscles or muscle parts must be changed (Blanksma and Van Eijden, 1990; Van Eijden et al., 1990, 1993). Therefore, the magnitude of maximum bite force depends on the bite force direction. The direction of the largest possible bite force was found to be different from perpendicular to the occlusal plane (Koolstra et al., 1988; Van Eijden, 1991; Osborn, 1996).

Furthermore, bite force magnitude is determined by leverage conditions and thus by the relative positions of the point of action of bite force, muscle forces and joint forces. Firstly, bite...
force magnitude is influenced by the antero-posterior position of the bite point, incisor bite force being smaller than molar bite force (e.g., Mansour and Reynik, 1975; Pruijm et al., 1980; Hagberg, 1987; Van Eijden, 1990). One of the reasons is that the lever arm between bite point and temporomandibular joint increases if the point is anteriorly shifted. Secondly, theoretical studies have demonstrated that changes in skull shape (e.g., inclination of the occlusal and mandibular plane, and size of the gonial angle) lead to changes in the spatial orientation of jaw muscles, teeth and temporomandibular joint to one another (Throckmorton et al., 1980; Haskell et al., 1986; Koolstra et al., 1988; Weijls et al., 1989; Osborn, 1996). Hence, these studies indicate that maximum bite force magnitude varies with craniofacial morphology.

1.3 JAW MUSCLE SIZE, BITE FORCE MAGNITUDE AND CRANIOFACIAL MORPHOLOGY

The mutual interaction between jaw muscle size, bite force magnitude and craniofacial morphology is widely accepted, both from studies of individuals within the range of normal morphological variation and from studies of pathological cases.

1.3.1 EMG activity and craniofacial morphology

Ahlgren (1966) measured the electromyographic (EMG) activity of the masseter and temporal muscles in children aged 9 to 14 years during chewing and other jaw movements and related the EMG activity to occlusal aspects and craniofacial dimensions. EMG activity showed no relationship with the kind of occlusion and only a weak relationship was found with facial morphology, namely, individuals with high EMG activity had a small gonial angle. Ingervall and Thilander (1974) measured the EMG activity in 52 children, aged 9 to 11 years. They found that children with high EMG activity of the masseter and temporal muscles during chewing and maximal bite force production showed a tendency to parallel palatal and occlusal planes and mandibular outline. Ingervall (1976) related the EMG activity of the temporal muscle during swallowing and chewing with facial morphology of 50 girls aged 9 to 13 years. It was found that the activity of the temporal muscle during chewing was negatively related to the anterior face height. Kreiborg (1978) reported a case of a girl, suffering from congenital muscular dystrophy. Longitudinal observation from age six to age twelve showed an extreme vertical growth of the mandible in relation to almost no EMG activity in the muscles of mastication. From the mentioned studies it can be concluded that the EMG activity correlates with craniofacial morphology. High EMG activity is found in individuals with short anterior vertical dimensions and an anteriorly converging maxilla, occlusal plane and mandible, whereas the opposite is true for low EMG activity.
1.3.2 Bite force magnitude and craniofacial morphology

Ringqvist (1973) recorded maximal voluntary bite force at the incisors and the molars in young adult females. Large bite forces were mainly associated with a long mandible (i.e., the distance between chin point and condyle) and a small gonial angle. Ingervall and Helkimo (1978) compared craniofacial morphology of men with large and small bite forces. Individuals with large bite forces showed an anteriorly upwardly inclined occlusal plane with a smaller anterior and a larger posterior face height and a smaller gonial angle. Comparing adult long- and normal-face individuals, Proffit et al. (1983) found that long-face individuals had significantly less occlusal force during maximum biting, simulated chewing and swallowing than individuals with normal vertical dimensions. Comparing long- and normal-face children, Proffit and Fields (1983) found no differences in bite force between the two groups. Kiliaridis et al. (1993) related maximal bite force at the incisors and molars to craniofacial morphology in 7 to 12 years old children and in 20 to 24 years old adults. They found a significantly positive relationship between incisor bite force magnitude and upper to lower facial height index in children, but not in adults. In patients with myotonic dystrophy, who had small bite forces, Kiliaridis et al. (1989) found a large angle between the mandibular and palatal planes. Apart from craniofacial characteristics (inclination of the mandible, size of the gonial angle, ratio between the posterior and anterior face height), Ingervall and Minder (1997) found a significantly positive correlation between bite force magnitude and the amount of interocclusal contacts. In conclusion, the mentioned studies indicate that bite force magnitude and craniofacial morphology are related. Larger bite forces were found in individuals with shorter faces and an anteriorly upwardly inclined occlusal plane.

1.3.3 Jaw muscle size and craniofacial morphology

Weijs and Hillen (1986) measured the cross-sections of the masseter, temporal, medial pterygoid and lateral pterygoid muscles by using computed tomography. They found that the cross-sectional areas of the temporal and masseter muscles were positively related to craniofacial widths, those of the masseter, medial pterygoid and lateral pterygoid muscles were positively related to the mandibular length and those of the lateral pterygoid muscle were negatively related to the cranial base length. Using magnetic resonance imaging (MRI), Hannam and Wood (1989) found significantly positive correlations between bizygomatic arch width and the cross-sectional areas of the masseter and medial pterygoid muscles. Van Spronsen et al. (1991), who also used MRI, found that the cross-sectional area of the temporal muscle related significantly positive to the cranial base flexure and craniofacial width. The latter related only moderately to the masseter cross-sectional area. No relationships were found with vertical dimensions, whereas, in a study in which Van Spronsen et al. (1992) compared long-face and normal-face individuals, vertical craniofacial dimensions were significantly related to the cross-sectional areas of both the masseter, anterior temporal and medial pterygoid muscles. Small muscle cross-sections were
found in individuals with relatively large anterior and small posterior face heights. From these studies it can be concluded that craniofacial morphology is significantly related to the cross-sectional areas of the jaw muscles in a way that large cross-sectional areas are present in individuals having broad faces with shorter anterior and longer posterior facial dimensions.

1.3.4 Jaw muscle size and strength reflecting general and local influences

The size and strength of skeletal muscles are influenced by an intricate neural, metabolic and hormonal interaction (Florini, 1987; Häkkinen, 1989; Deschenes et al., 1991). Therefore, a relationship between the size and strength of skeletal muscles to those of the masticatory muscles can be expected. This expectation is supported by the findings that skeletal and masticatory muscles react similarly on aging (Newton et al., 1987, 1993) and training (Ingervall and Bitsanis, 1987; Kiliaridis et al., 1995), and show similar gender-related differences (Helkimo et al., 1977; Waltimo et al., 1993). However, the studies mentioned in the paragraphs before clearly demonstrated a close relationship of jaw muscle size and bite force magnitude to craniofacial morphology. Furthermore, jaw muscle size and bite force magnitude are related to the amount of occlusal contacts, being an indication of occlusal stability (Bakke, 1993; Ingervall and Minder, 1997). Van Spronsen et al. (1996), therefore, postulated that the lack of occlusal stability might lead to an insufficient development of masticatory muscle strength, resulting in jaw muscle atrophy.

Hence, on the one hand, jaw muscle size and consequently the maximal possible bite force seem to be dependent on general muscular influences, whereas, on the other hand, they seem to be dependent on local influences on the craniofacial level as well.

1.4 OBJECTIVES OF THE STUDY

In the first part of this thesis the masseter muscle was used as a model for the study of jaw muscle morphology in relation to jaw muscle biomechanics and craniofacial morphology. The following items were dealt with:

- the relationship between sarcomere length and jaw position;
- the validity of ultrasonography to determine muscle thickness;
- the size (i.e., the ultrasound thickness) of the masseter muscle during growth.

From § 1.2 (jaw muscle biomechanics), it became clear that knowledge of the architectural design of a muscle is important for the understanding of its functional capabilities. Therefore, the first item of this thesis deals with regional differences in the architectural design of the masseter muscle and the consequences for the lengths of the sarcomeres at different jaw positions.

From the literature mentioned in § 1.3 (jaw muscle size, bite force magnitude and craniofacial morphology), the presence of a relationship between masticatory muscle size and
function is obvious. In adults, relations with craniofacial morphology were found for both size and functional variables, whereas in children, this relation was found for functional variables only. From studies in pathological cases (e.g., Kreiborg et al., 1978), it is tempting to assume a causal relationship between muscle function and skull shape. If the muscles of mastication do reveal a contribution to the regulation of craniofacial morphology, as postulated in the growth theory of Van Limborgh (1971), a relationship between craniofacial morphology and size and function of the jaw muscles should already be present during childhood. Because there is only little known about jaw muscle morphology in children (Schumacher, 1962), one of the aims of this thesis was to measure both craniofacial morphology and jaw muscle size in growing individuals, and to study a possible relationship.

Studies in which volunteers participate, should be conducted by the highest principles of human subject welfare, especially when children are involved. Therefore, for the imaging of the jaw muscles an in vivo technique was chosen that was non-invasive and had no (known) cumulative biological effects, and that could be quickly performed: Ultrasonography (US). US has already been used to measure the thickness of the masseter muscle in vivo (Kiliaridis and Kälebo, 1991; Bakke et al., 1992). However, because no appropriate evaluation of US as measuring instrument of the masseter muscle was available, the accuracy and reproducibility of ultrasonographic measurements of the masseter muscle thicknesses were determined.

In the second part of this thesis the three-cornered relationship between jaw muscle size, bite force magnitude, and craniofacial morphology was unraveled. Furthermore, it was studied in how far the size of the jaw muscles is influenced by factors that generally determine the size of all skeletal muscles. The following items were dealt with:

- the relationship between bite force magnitude, jaw muscle size and craniofacial morphology;
- the relative contribution of general muscle variables and variables of craniofacial morphology to the size and strength of the jaw muscles.

By measuring maximal voluntary bite force magnitude, jaw muscle size and craniofacial morphology in one study, an attempt was made to assess the relative contribution of jaw muscle size and craniofacial morphology to the maximal bite force magnitude. Although many studies have been performed on the relationship between jaw muscle size, craniofacial morphology, and/or bite force magnitude, the relationship between all three variables have not been studied all together. Also, in studies, in which bite forces were assessed, the bite force was measured in one dimension only (i.e., perpendicular to the occlusal plane). Because bite force magnitude depends on the bite force direction (Koolstra et al., 1988; Van Eijden, 1991; Osborn, 1996), in the present study, bite forces were measured in all three dimensions. This also allowed for
estimating the bite force moments, which was necessary in order to make an appropriate comparison with maximal forces of the arm flexor and leg extensor muscles possible.

By comparing the sizes of the muscles of mastication to those of the arm flexor and leg extensor muscles and to the force moments they produce, a distinction was made between the contribution to jaw muscle size and strength of influences affecting all muscles, such as general metabolic and hormonal ones (Florini, 1987; Häkkinen, 1989; Deschenes et al., 1991), and local influences, such as craniofacial morphology, possibly leading to an insufficient development of the masticatory muscles (Van Spronsen et al., 1996; Ingervall and Minder, 1997).

1.5 CONTENTS

Chapter 2 Heterogeneity of fiber and sarcomere length in the human masseter muscle contains a description of the architectural design of the human masseter muscle, especially on the level of fiber and sarcomere length at different locations across the muscle. Changes in sarcomere length for different jaw positions were predicted in order to relate the morphological findings to possible functional consequences.

Chapter 3 A comparison of human masseter muscle thickness measured by ultrasonography and magnetic resonance imaging provides an evaluation of ultrasonography as a method to measure the thickness of the masseter muscle in vivo. This was done by comparing the ultrasound registrations with thicknesses, obtained from MRI-images of the same subjects.

Chapter 4 Masseter muscle thickness in growing individuals and its relation to facial morphology comprises a study in which the thickness of the masseter muscle was cross-sectionally measured in growing individuals. These thicknesses were related to craniofacial morphology in order to find out whether a relationship between jaw muscle size and craniofacial morphology is already existent during growth.

Chapter 5 Contribution of jaw muscle size and craniofacial morphology to human bite force magnitude reveals a study in which both maximal voluntary bite force magnitude, thicknesses of the masseter, temporal and digastric muscles, and craniofacial morphology were measured. By relating muscle thicknesses and craniofacial morphology to bite force magnitude, an indication was obtained of their relative contribution to the bite force magnitude.

In Chapter 6 Human jaw muscle strength and size in relation to limb muscle strength and size the thicknesses of some jaw muscles were compared to those of the arm flexor and leg extensor muscles. Also, the magnitudes of the maximal voluntary bite force moment, arm flexion moment and leg extension moment were measured and compared to one another. Hence, a distinction was made between general influences of muscle metabolism and more local influences, such as craniofacial morphology.

Chapter 7 contains a Summary and conclusions.


