Neck function in rhythmic jaw activities

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UMEÅ 2004
Till Jan, Jens och Jacob.
ABSTRACT

Neck function in rhythmic jaw activities.

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Previous studies in animals and humans show anatomic and physiological connections between the trigeminal and the cervical regions. This investigation tested the hypothesis of a functional integration between the human jaw and neck motor systems in rhythmic jaw activities. By means of a wireless optoelectronic 3-D movement recording system, spatiotemporal characteristics of mandibular and head-neck movements were studied during rhythmic jaw opening-closing and chewing tasks, in healthy and in individuals with pain and dysfunction in the jaw and neck region following neck trauma, Whiplash-associated Disorders (WAD). As a basis, a methodological study evaluated the applicability of skin and teeth attached reflex markers fixed to the lower jaw and to the head in optoelectronic recording of chewing movements.

The results showed concomitant and coordinated mandibular and head movements during rhythmic jaw tasks. The start of the head movement generally preceded the start of the mandibular movement. For chewing, larger size and harder texture of bolus were associated with larger head extension and larger amplitude of both mandibular and head movements. Immobilization of the head by mechanical fixation deranged jaw motor behaviour with regard to speed and amplitude of mandibular movements. Even with head fixation, muscle activity was present in neck muscles during jaw activities. Compared to healthy subjects, WAD individuals showed smaller amplitudes and disturbed coordination of mandibular and head movements. Furthermore, a dynamic load test showed a reduced endurance during chewing in the WAD group.

In conclusion, the results suggest that optimal jaw function requires free unrestricted head-neck movements and support the hypothesis of a close functional relationship between the jaw and the neck regions in rhythmic jaw activities. A new concept for human jaw function is proposed, in which “functional jaw movements” are the result of activation of jaw as well as neck muscles, leading to simultaneous movements in the temporomandibular, atlanto-occipital and cervical spine joints. The finding of an association between neck injury and disturbed jaw behaviour suggest that assessment and management of neck injured patients should include jaw function.

Key words: chewing, head, human, jaw, mandible, motor control, movement, neck, temporomandibular disorders, whiplash injury
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This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:


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BACKGROUND TO THE PRESENT INVESTIGATION

Movement – a sign of life

Movement is one of the first signs of life. In the human foetus the first signs of movements can be observed at a gestational age of about 7 weeks. In the eight-week more general movements can be seen and at the end of this week also movements of the arms and legs appear (de Vries et al., 1985). Generally these early movements are generated spontaneously by the nervous system and not as a response to external stimuli (Hepper et al., 1998).

Movements involving the jaw motor system can be seen around week 12 as suckling and swallowing (de Vries et al., 1982; de Vries et al., 1985). Muscular response to a stimulus first develops in the perioral region - indicating that the trigeminal nerve is the first to become active. Furthermore, the first reflex that can be elicited in foetuses is the trigemino-neck reflex where trigeminal stimuli affects neck motoneurons (Humphrey, 1952). Other early signs of the close relationship between the jaw and neck regions can later be observed in yawning, where recordings with ultrasound technique have shown head movements accompanying jaw opening (Petrikovsky et al., 1999; Sepulveda and Mangiamarchi, 1995).

In the newborn baby, the ability to perform goal-orientated movements is limited, and many movements still depend on reflex mechanisms. Some of these, such as head aversion, are avoidance reflexes while some are survival reflexes, for example suckling. One notable reflex is the rooting reflex, active from birth through to the first couple of months. In this reflex, a light touch at the perioral area induces head movement towards the stimuli, accompanied by opening of the mouth (Sheppard and Mysak, 1984). Under development, the reflex based motor behaviour is gradually replaced by acquired motor skills, although many of the early established reflex patterns can be observed as components in the mature motor behaviour (cf. Eriksson and Zafar, 2005).

Jaw function

The temporomandibular joint (TMJ) consists of the lower jaw – the mandible, which articulates to the upper jaw – the skull, with two contact points. Mandibular movements are performed by paired, jointly activated, muscles, the masseter, the temporal, the medial and lateral pterygoid and the digastric muscles. These jaw muscles interact with other muscles, such as the supra- and infrahyoidal muscles, to allow movements of the mandible in three dimensions and with six degrees of freedom.
The primary function of the human jaw system is to enable eating behaviour, by executing mouth opening, biting, chewing and swallowing movements. These activities require complex neuromuscular activity to coordinate separate muscles and groups of muscles. For chewing, the rhythmic jaw movements are governed by rhythmic neural commands to the appropriate muscles. The circuitry controlling this cyclic movement pattern of the mandible is assumed to be constituted by central neural networks denoted as the “central pattern generator” (CPG), and presumably located in the brainstem. In the executed functional jaw movements, extero- and proprioceptive peripheral input interact with these central programs (Lund, 1991; Lund et al., 1998; Nakamura and Kataura, 1995).

**Neck function**

The neck is composed of the upper seven vertebrae of the spine and supports the head. A complex system of muscles connects to the vertebrae, the lower jaw, the upper ribs and the clavicles. The neck muscles support and move the head, to continuously maintain an optimal head position. Appropriate head positioning and head movements provide the basis for direction of visual gaze, stability and acuity and most neurophysiologic studies of control of head movements have dealt with gaze-shifting behaviour (Berthoz et al., 1992; Dutia, 1991; Peterson and Richmond, 1988).

**Relationship between the trigeminal and craniocervical regions**

A functional connection between the temporomandibular and the craniocervical regions is suggested by their intimate anatomical and biomechanical relationships (Brodie, 1950; Kraus, 1988; Thompson and Brodie, 1942). Also the location of the trigeminal nucleus, which penetrates into the upper cervical segments reflects a linkage between facial input and head movements (cf. Abrahams et al., 1993). A wide range of head-neck movements are influenced or initiated by input from oro-facial structures, indicating that movement of the head is an integral part of normal oral function (cf. Eriksson et al., 1998). In fact, the trigeminal input has been suggested to be one of the strongest to those neck motoneurons involved in head movement (Abrahams and Richmond, 1977).

Also studies in humans have reported reflex activities in the neck muscles following electrical stimulation of trigeminal nerve branches (Browne et al., 1993; Di Lazzaro et al., 1995; Goor, 1984; Sartucci et al., 1986). In addition, simultaneous activation of jaw and neck-shoulder
muscles during mandibular movements (Davies, 1979; Eriksson et al., 1998; Halbert, 1958) and clenching (Clark et al., 1993; Ehrlich et al., 1999; Hagberg et al., 1985) has been reported. Thus, in conclusion, previous studies in animals as well as humans not only show a close biomechanical and anatomical relationship between the jaw and neck neuromuscular systems, but also suggest a strong functional linkage between the trigeminal and craniocervical motor systems.
Introduction

Studies of movements

Kinesiology is the science of movement of the body: the term is a combination of the Greek for ‘kinein’ (to move) and ‘logos’ (to study). It is usually suggested that Aristotle (384-322 B.C.) is the “Father of Kinesiology”. In the work “On the Movement of Animals” Aristotle described the actions of the muscles and movements in the joints and carried out geometric analysis for the first time. Movement is the final outcome of neuromuscular activity and the movement patterns reflect the strategies adopted by the central nervous system to solve a specific task. Studies of movements may hence give insight into the central programs controlling the strategies for performance of motor tasks.

Movement recording techniques

In studies of movements any undesired interference with normal motor behaviour performance should be avoided. The technical system used should ideally be non-invasive so that disturbances are minimized. In a clinical setting, movement analysis is often based on observation for practical reasons. However, in order to systematically quantify different aspects of movements, more objective methods are needed. Furthermore, in order to obtain valid results, the compound movement in space have to be measured - not only one-dimensional aspects of the movement patterns. Stereometric methods offer such a reconstruction in three spatial dimensions of body limb positions in a global coordinate system. To this end, high-speed photography was the dominant method until 1970’s, but with the introduction of optoelectronic techniques, automatic processing of kinematic information to electronic digital records could be achieved. The development of cameras equipped with CCD (charge-couple device) sensors improved the accuracy and minimized the geometrical distortion in movement records. New video based recording techniques that used cameras interfaced with computers with automatic marker detection were introduced. As this process is based on the recognition of defined marker shapes and not on their brightness, the reliability of the procedure is very high (Medved, 2001).

Studies of mandibular movements

Mandibular movements have been studied with a variety of techniques, such as photographic, photoelectrical, magnetic and optoelectronic (cf. Paper I). A common prerequisite for these methods is the need for attaching some type of marker to the moving body part. For mandibular movement recording, markers have been fixed to the mandible in two ways – either to the teeth via mounts (Airoldi et al., 1994; Duxbury et al., 1974; Jemt et al., 1979; Jemt and Karlsson, 1982; Joss and Graf, 1979; Kang et al., 1993; Karlsson, 1977; van der Bilt et al., 1991) or
the skin of the chin (Jemt and Hedegård, 1982a). In the latter case, the ensuing movement records may be distorted by soft tissue stretch, and hence the validity of the recording may be affected (Jemt and Hedegård, 1982b). Teeth attached markers reproduce the movement of the mandible more consistently. However, even optimally prepared and adapted mounts fixed to the teeth might interfere with the natural chewing behaviour, by altering the peripheral input and/or by making the subject more aware of the chewing procedure. Systematic evaluations of the reliability and validity of different marker systems in recordings of simultaneous mandibular and head movements during chewing have generally been lacking.

During recordings of jaw movements, the movements of the mandible in space are influenced by simultaneous movements of the head. In studies of mandibular movements where these head movements have been considered as a source of error, methods have often been adopted to restrict head motion (Feine et al., 1994; Joss and Graf, 1979; Kazazoglu et al., 1994; Morimoto et al., 1984a; Wood, 1979). However, such an approach will probably have the disadvantage of interfering with the natural jaw motor behaviour. So far, the possible effect of immobilization of the head on jaw behaviour in natural jaw activities has not been investigated.

In order to allow free unrestricted head movements in studies of jaw function, reference markers on the head can be used to enable mathematical compensation for the associated head-neck movements (Airoldi et al., 1994; Jemt and Olsson, 1984; Jemt and Hedegård, 1982b; Kang et al., 1993; Karlsson, 1977; van der Bilt et al., 1991). In a further step, markers on the head can also be utilised for analysis of simultaneous mandibular and head movements during jaw activities (Zafar et al., 1995). Compared to the long tradition of analysing rhythmic mandibular movements, systematic recordings of simultaneous mandibular and head movements during rhythmic jaw activities have generally been lacking.

Movement patterns of the mandible vary depending on the motor task and are in addition modulated in response to peripheral input. Thus, jaw opening during chewing varies with differences in size and weight of bolus (Daet et al., 1995; Lucas et al., 1986; Thexton et al., 1980; van der Bilt et al., 1991) and probably also with bolus texture (Horio and Kawamura, 1989; Peyron et al., 2002; Peyron et al., 1997). However, other studies reported no relation (Bishop et al., 1990; Plesh et al., 1986) or even decreased jaw opening with harder texture (Karlsson and Carlsson, 1989; Pröschel and Hofmann, 1988). Previous studies of the effect of size and texture of bolus have focused on the mandibular movements during chewing. However, if jaw behaviour such as mouth opening, biting and chewing, relies on a linked motor control of the
jaw and neck motor systems, it can be assumed that varying size and texture of bolus might alter the control of movements of not only the mandible, but also of the head-neck.

**Studies of jaw motor endurance**

Motor performance can be evaluated by amplitude, speed, force, coordination and endurance of movements. Reduced endurance is one sign of muscular dysfunction and endurance tests are therefore valuable in assessment of musculoskeletal disorders. During an endurance task, a subject will typically experience fatigue followed by pain. Fatigue describes a reduction in physical and/or mental performance and is usually separated into peripheral fatigue and central fatigue. Peripheral fatigue is considered to be due to mechanisms within the working muscles themselves, which impairs the ability of the muscle to generate force, in spite of maximal neuronal activation. Central fatigue describes mechanisms inside the central nervous system, which result in decreased voluntary activation, irrespective of the muscle’s ability to produce force. Central fatigue is also elicited by central reflex mechanisms in response to pain, resulting in decreased excitation, increased inhibition or an increased threshold to stimulation of the motor neurons (Enoka and Stuart, 1992).

Most studies on endurance of the human jaw motor system have used static tests, such as tooth clenching, to evaluate endurance capacity. A relationship has been demonstrated between the intensity of tooth clenching and the onset of fatigue and pain (Christensen et al., 1982) and endurance time (Clark and Carter, 1985; Clark and Adler, 1987; Dahlström et al., 1988; Naeije, 1984; Svensson et al., 2001).

Compared to static clenching tests considerably longer endurance times have been found for dynamic jaw tasks (Bakke et al., 1996; Christensen et al., 1996; Farella et al., 2001; Tzakis et al., 1992). Furthermore, these studies show that healthy subjects rarely report fatigue or pain during a relatively short chewing task. The finding of a longer endurance for chewing is not surprising, as the forces needed for chewing are far less than those required for maximal clenching (Gibbs et al., 1981a; Gibbs et al., 1981b). These observations, that the jaw system generally seems to be resistant to fatigue during dynamic loading accords with the fact that jaw-closing muscles are composed of a high proportion of fatigue-resistant (Type I) fibres (Eriksson and Thornell, 1983) and has a high density of capillaries (Stål et al., 1996).
Pain and dysfunction in the jaw-face and neck regions

Neuromuscular disorders can cause much suffering and cost for the individual as well as the society (Johansson et al., 2003). Typical symptoms are pain and impaired function, which can be reflected by reduced amplitudes, lower speed, disturbed coordination and reduced endurance of movements. Musculoskeletal pain and dysfunction in the jaw-face region is reported by about 10% of the population and an overlap of pain and dysfunction in the jaw-face and neck regions has been reported (Browne et al., 1998). Thus, patients with jaw-face pain and dysfunction may present with pain and dysfunction in the neck region (Clark et al., 1987; De Laat et al., 1998; De Wijer et al., 1996b; Gelb, 1977; Visscher et al., 2001) and vice versa (Ciancaglini et al., 1999; De Wijer et al., 1996a; Kirveskari et al., 1988).

Relationship between jaw pain and dysfunction and Whiplash-associated disorders

Pain and dysfunction in the jaw-face region have also been reported in association with Whiplash-associated disorders (WAD), i.e. neck pain and dysfunction following cervical trauma (Burgess, 1991). Common signs and symptoms for these patients are neck pain, impaired head-neck movements and headaches. Whiplash trauma involves hyperextension-flexion injury to the neck and was first described in the second part of the 19th century in relation to train accidents (cf. Evans, 1992). The term “whiplash injury” was later introduced by Crowe in 1928 to describe a syndrome resulting from rear end motor vehicle accidents. According to The Quebec Task force, “whiplash” is an acceleration-deceleration mechanism of energy transfer to the neck (Spitzer et al., 1995). It may result from a rear or side impact motor vehicle accident, but can also occur during diving or other traumas. The impact can result in a bony or soft tissue neck injury associated with a variety of clinical symptoms. Although most individuals recover from an acute whiplash injury, a substantial number of individuals will develop a late whiplash disorder (Freeman et al., 1999). Accordingly, although it has been reported that the incidence of jaw-face pain and dysfunction following acute whiplash injury is low (Heise et al., 1992; Kasch et al., 2002) chronic WAD patients report pain and dysfunction also in the jaw-face regions (Magnusson, 1994). It has been suggested that TMJ injury due to “mandibular whiplash” might occur concurrent with cervical trauma (Garcia and Arrington, 1996) but this proposal has been refuted (Bergman et al., 1998). Another explanation to post-traumatic jaw-face pain and dysfunction favours a neuromuscular basis, rather than a localised direct injury to the TMJ (Lader, 1983).
Introduction

It has been reported that almost 25% of patients with jaw-face pain and dysfunction have a history of trauma to the head-neck, mainly whiplash trauma (De Boever and Keersmaekers, 1996). Post-traumatic jaw-face pain and dysfunction patients report more severe and frequent symptoms and signs such as headaches, facial pain, severe jaw dysfunction, and sleep disturbances (Burgess, 1991; De Boever and Keersmaekers, 1996; Goldberg et al., 1996; Kolbinson et al., 1997a; Kolbinson et al., 1997b; Romanelli et al., 1992). These patients also respond less well in reaction time tests and overall tire more easily (Goldberg et al., 1996). Since many of these symptoms are associated also with closed head injuries (Merskey and Woodforde, 1972) centrally mediated changes may account for the uniqueness of jaw-face pain and dysfunction in patients with a history of head-neck trauma. It has also been suggested that the prognosis for recovery is lower for this patient group (Brooke and Stenn, 1978; Kolbinson et al., 1997a; Kolbinson et al., 1997b; Romanelli et al., 1992). If natural jaw function requires a healthy state of both mandibular and neck motor systems, injury to any of the joints involved might derange jaw function.
Aims of the Investigation

The general aim of this project was to test the hypothesis of a functional integration between the human jaw and neck regions during rhythmic jaw activities.

The specific aims were:

- to evaluate the mandibular and head-neck movements during rhythmic jaw activities (Paper II)
- to study the effect of size and texture of bolus on head movements during chewing (Paper III)
- to study the effect of head fixation on jaw behaviour during rhythmic jaw activities (Paper IV)
- to evaluate whether neck injury, leading to pain and dysfunction, can disturb natural jaw function (Paper V-VI)
- in order to answer the questions above, a methodological study was carried out to evaluate the applicability of skin and teeth attached markers in wireless optoelectronic recording of mandibular and head movements during chewing (Paper I).
MATERIALS AND METHODS

Subjects
All healthy subjects were free from pain and dysfunction in the jaw-face and neck regions. The subjects in the TMD and WAD groups were consecutively referred patients to the department of Clinical Oral Physiology at Umeå University Hospital for assessment and management of conditions with long standing pain and dysfunction in the jaw-face regions that had been present more than six months. For all study groups, the exclusion criteria were general joint and muscle disorders. All participants had given their informed consent according to the World Medical Association’s declaration of Helsinki and were unaware of the underlying aim of the investigation. The studies were approved by the Ethics committee of Umeå University.

Table 1. Subjects in the investigation

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<td>50</td>
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<td>27 (21-62)</td>
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a Seven subjects from Paper I
b Nine subjects from Paper III
c WAD, Whiplash-associated Disorders
d TMD, Temporomandibular Disorders

For the patients in the WAD groups, the pain and dysfunction in the jaw and neck regions had developed following a head-neck trauma. They had been diagnosed with WAD by routine medical examination procedures. Typically, in the aftermath of a neck trauma, these patients
had developed neck pain, impaired and painful head-neck movements, and tenderness to palpation in neck muscles. The traumas, predominately due to motor vehicle accidents, had resulted in a WAD of grade II-III according to the Quebec Task Force classification scale (Table 2) (Spitzer et al., 1995). For the WAD group, the exclusion criteria were reported jaw-face pain and/or dysfunction prior to the head-neck trauma.

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<td>Neck complaint&lt;sup&gt;a&lt;/sup&gt; but no physical signs</td>
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<td>II</td>
<td>Neck complaint and musculoskeletal signs&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>III</td>
<td>Neck complaint and neurological signs&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>IV</td>
<td>Neck complaint and fracture/luxation</td>
</tr>
</tbody>
</table>

<sup>a</sup> Pain, stiffness, tenderness  
<sup>b</sup> Decreased range of motion, pain on palpation  
<sup>c</sup> Impaired sensory function, decreased or absent tendon reflexes, weakness

Symptoms and signs of jaw-face pain and dysfunction were documented by clinical examination (Okeson, 1996) and the findings were summarized by Helkimo's anamnestic (Ai) and clinical dysfunction (Di) indices (Paper VI). In these indices, Ai0, AiI and AiII denote absence of symptoms, mild symptoms and severe symptoms, respectively, and Di0, DiI, DiII and DiIII denote absence of clinical signs, mild, moderate and severe signs of dysfunction (Helkimo, 1974). For the TMD group, the inclusion criteria were jaw-face pain and dysfunction of muscular origin, Group 1, Axis I, according to Research Diagnostic Criteria (Dworkin and LeResche, 1992). Exclusion criteria were temporomandibular joint disorders and/or a history of trauma to the head-neck regions.
Movement recording (Paper I-V)

Movement recording system

Movements of the mandible and the head were simultaneously registered in 3 dimensions (3-D), by means of a wireless optoelectronic recording system with a sampling rate of 50 Hz (MacReflex®, Qualisys AB, Gothenburg, Sweden). The basic principle of the system is to record the positions of a number of retro-reflective markers in space. The moving body parts to be measured are equipped with retro-reflective markers and the marker movements are registered by video cameras equipped with an array of infrared diodes, arranged around the lens, which illuminates the markers. The cameras are connected to a sampling computer via video processors. Infrared light is reflected back to the cameras and the video processors mathematically localise the markers and calculate the coordinates of the centre point (the centroid) of each marker at a resolution higher than the actual resolution of the recording camera sensors. By using two cameras (which each records the 2-D positions of markers over time) 3-D coordinates can be calculated off-line with dedicated software (Josefsson et al., 1996).

Figure 2. Marker arrangement for the methodological study (Paper I). Tripods of markers attached to the upper and lower teeth and skin attached markers located on the forehead, the bridge of the nose, nose tip and chin. Two video cameras connected to a sampling computer via a videoprocessor.
**Marker arrangement**

Spherical low weight retro-reflective markers (5 mm in diameter) were attached to the mandible and to the head, either to the teeth (Paper I-II) or to the skin (Papers I-V). In the methodological study (Paper I), skin attached markers were fitted by trimmed double-sided adhesive tape applied at the mid line of the face on the forehead (1 cm above nasion), at the bridge of the nose, at the nose tip, and at the centre of the tip of the chin. Teeth attached markers were attached by means of two individually configured mounts covering the buccal surfaces of the upper (head) and lower (mandible) front teeth (Fig. 2). Triplets of reflex markers were fixed to each mount by rigid dental steel wire with the middle markers positioned along the mid line of the face.

**Basic set-up**

Two cameras were placed at a 45° angle approximately 1.5 m in front of the subject with an inter-camera distance of 1.5 m. This set-up allowed movements to be recorded in a working volume of $45 \times 55 \times 50$ cm which provided a spatial resolution of 0.02 mm.

**Data acquisition and conditioning**

Marker positions were determined on-line and position data were transmitted to the computer. Verification of marker identity and marker trace continuity, as well as computation of the coordinates of the markers’ 3-D positions, was made off-line with dedicated software. After graphical display of the movement traces for visual inspection and identification of the defined key events, the parameters under study were digitally quantified from the recorded signals.

**Compensation for head movements**

The movements of a body part in space are the result of the combined movements of all the body segments to which it is attached. Thus, an adequate strategy must be adopted to separate the mandibular and the head movements in the quantification of the kinematic data. Analysis of the isolated mandibular movement was enabled by recording the actual mandibular and head movements in space followed by a mathematical conversion to relate the mandibular movements to the head. A method was adopted from a 3-D coordinate transformation technique originally developed for use in stereometric radiography (Selvik, 1974). By using markers arranged in a tripod a 3-D plane could be defined and movements of the head could be described by the orientation of this plane in space. By means of coordinate transformation, the changes in 3-D position of the lower jaw markers were adjusted for the changes in 3-D position of the head markers. This mathematical 3-D compensation for head movement allowed detailed segmental analysis of the isolated mandibular movements in relation to the head (Zafar et al., 2000a).
**Test procedures**

*General set-up for movement analysis (Paper I-V)*

The subjects were seated comfortably in an upright position, with back support up to the mid-scapular level but without headrest. Prior to the start of each recording, the subject was instructed to position the teeth in light contact in the intercuspal position and this position was used as a reference. Each motor task was recorded twice with an interval of two minutes between each recording.

*Standard test protocol (Paper II, IV, V)*

Three standardised motor tasks were performed; i) self-paced continuous maximal jaw opening-closing movements, ii) paced continuous maximal jaw opening-closing movements in time with a metronome set at 50 beats/minute, and iii) unilateral chewing of soft chewing gum on the subjects preferred chewing side.

*Chewing test (Paper I - V)*

For the chewing tasks four different standardised boluses were used; 3 pieces (weight 3 x 1 g) of pre-softened chewing gum (V6®) (Paper I - V), and 9 pieces (weight 9 x 1 g) of pre-softened chewing gum, and small (3 g) and large (9 g) pieces of spherical rubber silicone (Optosil®)(Paper III).

*Repeated tests (Paper I, IV)*

In papers I and IV the recording sessions were repeated after a rest period of 20 minutes. In Paper I the movements were first recorded using both the teeth and the skin attached markers in place. In a repeated recording the teeth markers were removed and the movements were recorded by means of skin markers only. This procedure enabled an evaluation of the possible influence of teeth attached markers on the jaw behaviour. In paper IV the movements were first recorded as described above (*cf*: standard test protocol) with subjects seated comfortably but without headrest. In a repeated recording the head was immobilized by means of a rigid head-neck fixation frame. This procedure enabled an evaluation of the possible influence of head-neck fixation on the jaw behaviour.

**Electromyographic recording (paper IV)**

In Paper IV the movement recording was combined with simultaneous registration of myoelectric activity of jaw and neck muscles using a commercially available system for signal amplification and A/D conversion (MP100®, BioPac Systems, Inc.) linked to the movement
recording system with a maximal time lag of 20 ms. Surface electrodes were located over one mandibular depressor muscle (m. digastricus anterior), one mandibular elevator muscle (m. masseter), one neck muscle (m. sternocleidomastoideus), and one neck/shoulder muscle (m. trapezius). Muscle activity was recorded during the first 20 seconds of each task at a sampling rate of 200 Hz. The recorded bioelectric data were merged with kinematic data off-line, using a standard software for signal conditioning and analysis (AcqKnowledge®, Biopac Systems, Inc.). The first five jaw opening-closing cycles in each recording were analysed and values higher than the mean resting value + 2 SD, in the jaw opening and closing phase, were classified as a significant change in activity.

**Dynamic endurance test (Paper VI)**

The subjects were seated comfortably in an upright position, with back support up to the mid-scapular level but without headrest. They performed unilateral chewing of a standardised bolus (3 × 1 g) of chewing gum (V6®) for five minutes on their preferred chewing side. Subjects were free to discontinue from the task at any time if fatigue/pain was intolerable, and this information was incorporated into the data analysis. They were instructed to report such fatigue and pain during the test by pointing on a standardised clipboard.

**Analyses**

**Definitions**

The start of a mandibular movement cycle was defined as the time point at which the mandible began the downward, jaw opening, movement. The peak was defined as the time point for the most inferior position of the mandible, i.e. at the shift from the jaw opening phase to the jaw closing phase. The end of the closing phase was defined as the time point at the end of the upward movement of the mandible. The duration of each cycle (time/cycle) was defined as the time between two consecutive start points.

**Evaluation of skin- vs. teeth- attached markers (Paper I)**

The displacement of the skin attached markers was assessed with reference to the teeth attached markers. The skin marker displacement at the start and at the peak of each cycle was assessed from the change in 3-D distance (D) between the coordinates of the teeth attached marker (t) and the skin attached marker (s) according to the formula:

\[ D = \sqrt{(X_s - X_t)^2 + (Y_s - Y_t)^2 + (Z_s - Z_t)^2} \]
where x denotes the lateral, y the vertical, and z the sagittal dimension. To quantify the possible
effect of the chin marker displacement on the estimates of the defined time points of mandibular
movements, movement data from the chin marker were compared with those of the marker
attached to the lower front teeth. The teeth attached marker was used as a reference, and the
differences between skin and teeth marker time estimates were determined. To evaluate the
possible influence of the teeth attached markers on chewing behaviour, data from the first part
of the recording session (recorded with teeth and skin attached markers) were compared with
the data from the second part (recorded with skin markers only).

3-D movement amplitudes (Paper II-V)
The individual 3-D movement amplitudes for the mandible and the head were calculated as
the difference between the start (s) and peak (p) positions according to the formula:

$$D = \sqrt{(X_p - X_s)^2 + (Y_p - Y_s)^2 + (Z_p - Z_s)^2}$$

Statistics
Median, range, mean and standard deviation were used for descriptive statistics (Paper I-VI).
Intra-individual, cycle-to-cycle, variability (Paper V), was described as coefficient of variation
(CV) for movement amplitudes, variance for time points, and also as a spatiotemporal index
(STI) (Zafar et al., 2002). Intra-individual differences between repeated recordings, different
motor tasks and sessions were tested by means of the Wilcoxon matched pairs test (Paper
I-V). Differences between groups were tested by means of the Mann-Whitney U-test (Paper
II, V-VI) and the 2x2 chi-square test (Paper VI). In all tests, a probability level of 0.05 was
considered as statistically significant.
RESULTS

Evaluation of skin and teeth attached reflex markers (Paper I)

Skin attached markers on different locations of the face showed different extents of displacement during chewing. While the marker located on the chin showed displacement with each chewing cycle, the displacement was considerably less for the head markers, particularly for those on the bridge of the nose and the forehead. When the temporal estimates of mandibular movements of the skin marker on the chin was compared with those of the marker attached to the lower incisors, the differences in time estimates were less than 20 ms. When mandibular movements during chewing were compared in sessions with and without teeth attached markers in place, a larger vertical amplitude was found in the presence of teeth attached markers.

Coordinated mandibular and head movements in rhythmic jaw activities (Paper II)

The spatiotemporal characteristics of mandibular and head movements were studied for three different modes of rhythmic jaw activities. Associated head movements were found during all jaw tasks. There was a marked individual variability in the pattern as well as in the magnitude of both the mandibular and the head movements. An example of mandibular and associated head movements during different jaw motor tasks is shown in Fig. 3.

Figure 3. Mandibular and head movement patterns for one male subject during chewing (A) and maximal jaw opening-closing movements (B). Icons on top of figure indicate frontal and sagittal views of the movement patterns.
A general finding was an initial change in head position (i.e. initial head extension; cf Fig. 4) at the first mandibular movement cycle. For the following movement cycles the head remained in the extended position. This initial change in head position was larger for the continuous jaw opening-closing tasks compared to that of chewing.

In addition to the prevailing head extension, concomitant and coordinated head extension-flexion movements were seen during each maximal continuous jaw opening-closing cycle (Fig. 4). The additional head movement amplitude was larger for the self-paced than for the paced continuous movement, both of which were larger than that of chewing.

For the two continuous opening-closing tasks there were significantly smaller head movement amplitudes for the females. For chewing no gender difference was found. For the continuous opening-closing tasks, the ratio between the total head movement (initial head extension + additional head movements) and the mandibular movement was larger for males than for females, both at self-paced (0.72 versus 0.34) and paced rate (0.59 versus 0.26).

For the two continuous maximal jaw opening-closing tasks, the start and the peak of each head movement cycle were analysed with reference to the start and the peak of the corresponding mandibular movement cycle. Generally, the head preceded the mandible at the start of the mandibular movements cycles. At the peak of the mandibular movement, the head generally reached the peak after the mandible.
Effect of bolus on head movements during chewing (Paper III)

Both mandibular and head movements varied with size and texture of the bolus (Fig. 5). A small preparatory shift in head position was generally seen before the start of chewing. This shift was related to size, but not texture, of the bolus. A general finding in all sessions was also a change in head position, *i.e.* head extension at the start of chewing. Larger bolus size was correlated with larger head extension throughout the chewing sequence. Harder bolus texture was correlated with larger head extension during the first part of the chewing sequence. For all boluses, the largest increase in head extension was seen during the first part of the chewing sequence (Fig. 6).

![Figure 5](image.png)

**Figure 5.** Examples of mandibular and head movement patterns for one subject during chewing of different boluses, displayed in frontal view (A) and as movement amplitudes against time (B).

In addition to the preparatory head extension before the start of chewing and the head extension during the complete chewing sequence, each chewing cycle was also accompanied by head extension-flexion movements. Larger amplitudes of both mandibular and head movements were found for the larger (9 g) boluses compared to chewing of the 3 g boluses. For the small boluses, a harder texture was related to larger amplitude of both mandibular and head movements.
**Results**

Head immobilization can derange jaw behaviour (Paper IV)

Notably, even in the sessions with head fixation, head movements were registered albeit with smaller amplitudes. The mandibular movements were reduced in sessions with head fixation for the self-paced maximal jaw opening-closing task. Furthermore, with head fixation a shorter mandibular cycle duration was found (Fig. 7). Even with head fixation, activity in neck muscles was seen during jaw opening, and this was a general finding for the maximal jaw opening-closing tasks. For jaw closing, sternocleidomastoid muscle activity was seen during chewing in 58% of the cycles without and 80% of cycles with head fixation.

![Figure 7](image)

**Figure 7.** Head and mandibular movements during maximal jaw opening-closing with (A) free, unrestrained head and (B) head-neck fixation.
Disturbed jaw behaviour in Whiplash-associated Disorders (Paper V)

Some WAD subjects showed very limited and irregular head movement patterns, as exemplified in Fig. 8. Compared with earlier findings in healthy (Paper II), the WAD group showed smaller head and mandibular movement amplitudes for the two continuous jaw opening-closing tasks. These findings were confirmed in a separate comparison of the female individuals in the WAD group (n = 10) compared to the female subjects in the healthy group (n = 7). The WAD group also had a lower ratio between head and mandibular movements for the self-paced and paced opening-closing tasks (16% and 12%, respectively), in comparison to the healthy subjects (40% and 34%, respectively).

For chewing, the WAD group showed a longer duration of the mandibular movement cycle, and the closing phase compared with the healthy subjects. For the two continuous jaw opening-closing tasks, the start of the first mandibular movement cycle preceded the start of the head movement. During the subsequent mandibular movements cycles the head preceded the mandibular movement. Thus, compared to the healthy group, the WAD group showed a delayed start of the head movement in relation to the start of the mandibular movement at the first mandibular movement cycle. Compared with healthy subjects, the WAD group had higher coefficients of variation for head movement amplitudes, and higher variances for both the start and the peak time points of the movement cycles. The spatiotemporal index (STI) of the head movements also showed higher values for the WAD group.

Figure 8. Head and mandibular movement amplitudes during a sequence of maximal jaw opening-closing movements for a healthy subject (from Paper II), and a WAD patient.
More subjects in the WAD group reported fatigue and pain compared to both the healthy and the TMD groups. Furthermore, these WAD subjects reported an earlier onset of fatigue compared to both the healthy and TMD subjects, and an earlier onset of pain compared to the TMD subjects. A majority of the WAD subjects discontinued the task, whereas all the healthy subjects completed the chewing test. In addition to discontinuing the task more often than the TMD and healthy groups, the WAD subjects who failed did so at an earlier point in the task than that for the TMD subjects that discontinued (Fig. 9).

Fatigue was reported more often by women than men in the TMD group. The women in the WAD group, who reported fatigue or pain, did so earlier in the task than men did. In both the TMD and the WAD groups, the women who discontinued the task tended to do so at an earlier point than men did.
Figure 9. Time for onset of symptoms for the subjects in the healthy (n = 50), TMD (n = 50) and WAD (n = 50) groups who reported fatigue (A), or pain (B). In (C) are shown the time points for failure for the subjects being unsuccessful to complete the task. In all panels, vertical lines indicate median values, and numbers in parenthesis indicate the number of subjects in each group who reported symptoms and/or discontinued the task.
DISCUSSION

This investigation tested the hypothesis that the jaw and the neck motor systems are functionally integrated in rhythmic jaw activities. As a basis, the methodology for analysis of simultaneous mandibular and head-neck movements during chewing was evaluated (Paper I). Thereafter concomitant mandibular and head-neck movements during rhythmic jaw activities were studied (Paper II), including the effect of bolus size and texture on head movements during chewing (Paper III). Furthermore, the effect of mechanical restriction of head-neck movements on jaw behaviour was evaluated (Paper IV). To further test the hypothesis, the effect of pain and dysfunction in the jaw-face and neck regions on amplitude and coordination of mandibular and head-neck movements were analysed in WAD individuals (Paper IV). Finally, WAD individuals and healthy subjects were examined for endurance during chewing (Paper VI). Taken together, the results suggest a functional linkage between the jaw and the neck motor systems in rhythmic jaw activities, and an association between neck injury and deranged jaw function.

Methodological considerations

The analysis of teeth versus skin attached reflex markers revealed advantages and disadvantages for both techniques. Whereas teeth attached markers reliably reproduce mandibular movements, this study showed that they can disturb natural jaw behaviour. The finding of larger mandibular movement amplitudes in recordings with teeth attached markers in place is probably due to changes in feedback provided by various receptors in the orofacial region. The light skin attached markers, on the other hand, were displaced during chewing due to soft tissue stretch. However, the displacement of the chin marker was reproducible and did not affect the temporal estimates. Based on these findings, although teeth attached markers are not subjected to displacement due to skin stretch, they may interfere with natural jaw motor behaviour. We suggest that reliable data in optoelectronic studies of chewing behaviour can be recorded by means of skin attached markers. Hence, in this investigation skin attached markers, which also have the advantage of relatively low cost and short set-up time, were used.

Coordination of mandibular and head movements

During continuous jaw opening-closing movements, the start of the head movement preceded the start of mandibular movement (Paper II). This suggests that there is an anticipatory, feed forward, mechanism in adjustment of head position to prepare for jaw opening. The fact that the head preceded the mandible in the jaw-opening phase, but reached the peak of movement
Discussion

after the mandible, indicates a special need of prompt activation of neck muscles in jaw opening. These results, together with findings in single jaw opening tasks (Zafar et al., 2000b) and ultrasonic findings in foetal yawning that head movements occur before jaw opening (Sepulveda and Mangiamarchi, 1995) may reflect an innate nature of this jaw-neck behaviour. However, a possible anticipatory mechanism in the head extension control does not rule out that parallel reactional adjustments organised in a feedback mode from joints, muscle, skin etc., may also take place during each jaw opening-closing cycle. A significant contribution to reflex modulation of neck motoneurons might be provided by proprioceptors (muscle spindles) in the jaw closing muscles, which are known from studies on man to be of extraordinary large size and complexity (Eriksson and Thornell, 1987; Eriksson et al., 1994), and by other sensory input from the orofacial region (Trulsson, 1993).

**Head position and head movements in jaw activities**

Head movements during rhythmic jaw tasks were preceded by adjustments of head position in two phases. A minor head extension was seen before the start of jaw activities and was termed "preparatory head extension". A second adjustment, "initial head extension", took place during the first jaw opening-closing cycle. Thereafter, during the consecutive jaw opening-closing cycles, head extension-flexion movements were seen in addition to the extended head position.

*Preparatory head extension*

The finding of a minor "preparatory head extension" (Paper III) indicates that the placement of the bolus in the mouth triggered an early extension of the head even before the start of chewing. This again reflects a feed forward nature of activation of neck motoneurons in order to position the head in a favourable position for expected jaw activities. This could correspond to the forward anticipatory activation that has been demonstrated for jaw elevators (Ottenhoff et al., 1992; Ottenhoff et al., 1993).

*Initial head extension*

The "initial head extension" at the first mandibular opening-closing cycle showed different magnitudes for different jaw activities, which indicates a task dependent behaviour. A task dependent relationship is supported also by the fact that the head extension amplitudes were proportional to the mandibular movement amplitudes (Paper II), related to size and texture of bolus (Paper III), and by recent findings of an initial head tilt in speech (Miyaoka et al., 2004). That texture of bolus can modify mandibular movements in the first cycle of chewing
has previously been demonstrated (Peyron et al., 1997).

**Maintained head extension**

Following the "preparatory" and "initial" head extension phases, the head generally remained in an extended position throughout the jaw task (Paper II). The notion of a prevailing head extension in jaw function is in agreement with studies of single jaw-opening tasks (Eriksson et al., 1998) and supported by recent findings of a “sustained” head extension in speech (Miyaoka et al., 2004). For chewing, there was also a tendency for an increasing head extension during the test period (Paper III). A more extended head position could facilitate jaw opening (Mohl, 1984; Visscher et al., 2000a) and force production. Such an interpretation is corroborated by the finding of increased bite force following head extension (Hellsing and Hagberg, 1990), and that head extension can increase the stability of mandibular closing movements (Yamada et al., 1999). A more extended head position may also increase the muscle length (Winnberg et al., 1988) and torque of suprahyoidal muscles, which could in turn increase force production in the jaw opening muscles (Koolstra and Eijden, 2004).

**Additional mandibular and head movements**

In addition to the extended head position during jaw activities, head extension-flexion movements accompanied the mandibular opening-closing movements (Paper II). Generally, a relationship was seen between the magnitudes of these mandibular and head movements, a finding later confirmed by others (Kohno et al., 2001b). Moreover, the amplitudes of both mandibular and head movements were related to size and texture of bolus (Paper III). The relationship between the magnitude of mandibular and head movements was reinforced in the experiment where the cycle time was determined by a pacemaker (Paper II) which reduced the amplitudes not only of the mandibular movements as indicated in previous studies (Morimoto et al., 1984b; Naeije and Honee, 1979; Plesh et al., 1993; Widmalm and Hedegård, 1977), but also of the head movements.

**Active or passive head movements**

This study showed that head-neck fixation can lead to a deranged jaw behaviour, as indicated by reduced amplitudes of mandibular movements and shorter duration of jaw opening-closing cycles (Paper IV). This suggests that optimal jaw function requires free unrestricted head-neck movements.
In an upright sitting position, the centre of gravity of the head lies in front of the atlanto-occipital junction and the neck extensor muscles counteract gravity, thus preventing the head from tilting forward (Kapandji, 1974; Vig et al., 1983). Similarly, the centre of rotation for the head during rhythmic jaw movements seems to be located near the centre of gravity (Kohno et al., 2001a). The hypothesis that rhythmic jaw activities involve an active repositioning of the head was tested by investigating the effect of immobilizing the head (Paper IV). The small head movements seen despite head fixation, were probably due to soft tissue stretch allowing movements within the frame and give indirect support for an active head repositioning.

Furthermore, the study showed activity in the sternocleidomastoid and trapezius muscles during jaw opening, which suggests an active repositioning of the head and add further evidence to previous findings in human (Eriksson et al., 1998; Torisu et al., 2001) and animal studies (Igarashi et al., 2000). Finally, the finding that neck muscle activity was present in sessions both with and without head fixation supports the hypothesis of an active repositioning of the head. It therefore seems unlikely that the observed changes in head position (extension) and extension-flexion movements could be due to passive mechanical adjustments of the head relative to the cervical spine, as a result of gravitational effects on the head mass. In the newborn baby, feeding is facilitated by the rooting reflex, which induces head movement towards the stimuli accompanied by opening of the mouth (Sheppard and Mysak, 1984). This provides positioning of the gape - which involves both head and mandibular movements. Gradually, during the first 4-6 months of infancy, head control gradually develops and the rooting reflex diminishes. Our study in adults suggests that positioning of the gape is provided by an integrated jaw-neck activity to facilitate natural jaw activities.

**Deranged jaw behaviour in WAD**

Compared to healthy subjects, the WAD individuals showed smaller amplitudes and lower speed of mandibular and head movement, which suggests that jaw function was deranged in this group (Paper V). Furthermore, the finding in this group, that the head lagged behind the mandible at the start of the first movement cycle, reflects that the anticipatory, feed forward, positioning of the head seen in healthy subjects (Paper II) was disturbed.

Another observation in the WAD group was the reduced stability in the coordination between the mandibular and head movements. Thus, even though the spatiotemporal index for the mandibular movements in space, *i.e.* the combined movement of the mandible and the head, did not show any divergence as compared to healthy, the WAD-group showed higher cycle-
Discussion

to-cycle variability in the coordination of mandibular and head movement time points. This indicates instability in the control of the integrated jaw-neck behaviour for WAD individuals. The finding of stability of mandibular movements in space may reflect an ability of the jaw-neck motor system to compensate for the instability in head-neck behaviour in order to ensure an invariant, albeit “faulty” jaw function.

Both mandibular and head movement amplitudes were reduced in the WAD group. However, due to the relatively larger reduction of the head movements, the ratio between head and mandibular movement amplitudes was smaller in WAD individuals than for healthy. This ratio reflects the positioning of the gape in space with reference to the start position. Therefore, the smaller ratio for the WAD group indicates a “faulty”, too low, positioning of the gape following a neck injury, which in turn may hamper optimal jaw activities (Eriksson et al., 2004; Zafar, 2000).

**Reduced endurance**

Long-standing pain will hamper muscle usage, which in turn will lead to a decreased ability to transport oxygen and metabolic waste products, *i.e.* reduce the resistance to fatigue and therefore affect the endurance. That all healthy subjects completed the task and that very few reported fatigue or pain (Paper VI) is in line with previous reports of no symptoms (Farella et al., 2001), or low frequent fatigue and pain (Bakke et al., 1996), during chewing of soft gum.

It is known that many will complain of weakness, rather than fatigue, during a fatiguing exercise (Newham, 2001). The fact that we pooled “fatigue”, “stiffness” and “weakness”, all of which are characteristic symptoms of muscle overuse, may explain why 20% of the healthy subjects reported fatigue. The finding that TMD patients reported fatigue and pain more often than healthy subjects corroborates with previous reports that fatigue and pain are common symptoms in TMD and that chewing can increase these symptoms (Dao et al., 1994; Gavish et al., 2002). The WAD individuals differed significantly from healthy and TMD by reporting fatigue and pain more often and earlier, and by discontinuing the chewing task. This implies a marked impairment in endurance during chewing for this group, and that WAD individuals may suffer also from disturbed eating behaviour. The reduced endurance during chewing seen for WAD individuals suggests an association between neck injury and impaired functional capacity of the human jaw motor system.

The dynamic loading test used in this study showed a good ability to correctly identify healthy individuals and could be useful in screening examination for jaw dysfunction. It has been suggested that dynamic tests can be useful in assessment of jaw-face pain and dysfunction
(Visscher et al., 2000b). The present test allows implementation in clinical use also for non-dental professions and could therefore be a cost-effective tool in interdisciplinary programs for assessment and management of WAD patients.

Pain is probably one explanatory factor for the disturbed jaw function seen in the WAD group. It has been reported that trigeminal nociceptive input to the brain stem can reduce amplitude and speed of mandibular movements (Lund et al., 1991; Stohler, 1999; Svensson and Graven-Nielsen, 2001). Other studies have proposed that the fusimotor muscle spindle system plays an important role in the development and spread of musculoskeletal pain conditions (Johansson et al., 1999; Johansson et al., 2003), and that such a mechanism exist also in the jaw system (Capra and Ro, 2000; Ro and Capra, 2001). It has also been shown that reflex connections between chemosensitive muscle afferents and the fusimotor system exist intersegmentally, i.e. between the trigeminal (masseter muscle) and the cervical regions (Hellström et al., 2000). Furthermore, there is support for intersegmental nociceptive connections between the cervical spine and the trigeminal regions (Hu et al., 1993; Svensson et al., 2004; Yu et al., 1995). Taken together, these data suggest a tight coupling between the jaw and the neck sensory-motor systems in the onset and spread of pain and dysfunction in the jaw and head-neck regions. Our present results are consistent with these experimental data.

**Differences between females and males**

The findings in healthy that head movement amplitudes and the ratio between head and mandibular movement amplitudes generally were smaller for females (Paper II) probably reflect differences in musculoskeletal and biomechanical relations. The predominance of females in the patient groups (Paper V, VI) represents differences between males and females for referred patients to our clinic during the study period. In the endurance task (Paper VI), there were no differences in the WAD group between males and females in reported fatigue and pain, but females reported an earlier onset of both fatigue and pain and also discontinued the task earlier. These findings may reflect a lower functional capacity of the jaw motor system in females, which in turn might contribute to a higher susceptibility for developing more and more severe pain, exhaustion and dysfunction in the jaw motor system. The results are consistent with indications that compared to males, females seem to respond earlier to nociceptive input, have a lower pain threshold (Plesh et al., 1998; Wise et al., 2002), and lower pain tolerance (Bragdon et al., 2002; Plesh et al., 1998; Wise et al., 2002). They also seem to report more pain after tooth clenching (Plesh et al., 1998) and chewing (Karibe et al., 2003). Many persistent pain conditions have a higher prevalence in females (Unruh, 1996), although the neurobiological mechanisms underlying sex differences are unknown.
Cervico-Cranio Mandibular Disorders (CCMD)

Based on the result from the present investigation and from previous reports suggesting a functional association between the jaw and the head-neck sensory-motor systems, in health and disease, we suggested that a suitable term for the condition with both neck and jaw disorders could be “Cervico-Cranio Mandibular Disorders” (CCMD) (cf. Eriksson and Zafar, 2005; Paper VI). In a future perspective, these results suggest a revised approach in research on jaw motor control, and for assessment and management of pain and neuromuscular disturbances in the jaw and head-neck regions.
In this investigation, concomitant mandibular and head-neck movements were analysed for different rhythmic jaw tasks, and under different test conditions.

- The analysis of skin versus teeth attached reflex markers for optoelectronic movement recording revealed advantages and disadvantages for both techniques. Whereas skin attached markers were displaced due to soft tissue stretch, teeth attached markers lead to larger mandibular movement amplitudes (Paper I).

- Mandibular opening-closing movements were paralleled by firstly a change in the head position, ”initial head extension”, and thereafter by coordinated head extension-flexion movements. Furthermore, a relationship was seen between the mandibular and head movement amplitudes, and generally, the start of the head movement preceded the start of the mandibular movement (Paper II).

- A minor head extension seen before the start of chewing was termed ”preparatory head extension”. There was an association between the size and texture of bolus and the magnitude of head extension and of head and mandibular movements. Larger head movement amplitudes were related to larger size, and to some extent, to harder texture of bolus (Paper III).

- Head-neck fixation lead to reduced movement amplitudes and shorter duration of jaw movement cycles. Furthermore, neck muscle activity was present in rhythmic jaw activities both with and without head fixation (Paper IV).

- Compared to healthy, WAD individuals showed smaller amplitudes and disturbed coordination of head and mandibular movements in rhythmic jaw activities, and reduced endurance during chewing (Paper V-VI).
Conclusions

CONCLUSIONS

- The results suggest that optimal jaw function requires free unrestricted head-neck movements, and support the idea of a functional relationship between the jaw and the neck neuromuscular systems.

- Based on these findings, a new concept was introduced for human jaw function, in which “functional jaw movements” are the result of activation of jaw as well as neck muscles, leading to simultaneous movements in the temporomandibular, atlanto-occipital and cervical spine joints.

- Changes in oral input can influence head-neck behaviour during chewing.

- Head immobilization can hamper natural jaw function by disturbing mandibular movement control.

- The finding of an association between neck injury and disturbed jaw function underlines the concept of a functional coupling between the jaw and neck motor systems in natural jaw function and suggests that assessment and management of neck injured patients should also include jaw function.
POPULÄRVETENSKAPLIG SAMMANFATTNING


Resultaten visade att gapningsrörelser åtföljs av koordinerade rörelser i huvud-nacke och aktivitet i såväl käk- som nackmusklar. Under tuggning så användes huvud-nacke mer vid stora tuggor och när tuggans konsistens var hård. När huvudet fixerades så att nackrörelser ej kunde utföras orsakade detta störningar även i gapningsförmågan. Dessa resultat tyder på att de system som styr käkens och nackens muskler är sammankopplade, och att naturlig käkfunktion kräver att man är frisk i både käke och nacke.

Hos individer med whiplash skada sågs mindre och långsammare huvud- och underkäksrörelser, och försämrad koordination mellan underkäks- och Nackrörelser. De nackskadade var mindre uthålliga under tuggning. De blev också mer uttröttrade och avbröt ofta undersökningen. Resultaten tyder på att den finstämda samordningen mellan käkens och nackens funktion kan bli störd som följd av nackskada och därmed även orsaka svårigheter att äta.

Sammantaget tyder resultaten från denna undersökning på att när man äter, gapar och tuggar använder man inte bara käkleden. Även nackens muskler och leder sätts i arbete i samverkan med rörelserna i käkdelen. För fullgod käkfunktion, dvs för att obehindrat kunna gapa, tugga och äta krävs hälsa inte bara i käkdelen och käkmuskulerna utan även i nackens leder och muskler. En nackskada kan således leda till svårigheter att äta på ett obehindrat sätt. Nackskadade individer bör därför erbjudas undersökning även av käkfunktionen.
ACKNOWLEDGEMENTS

This investigation was carried out at the Department of Odontology, Clinical Oral Physiology, Umeå University, in collaboration with the Centre for Musculoskeletal Research, Gävle University, Sweden. I wish to express my sincere gratitude to all those who have helped and supported me during this investigation. In particular, I would like to thank:

Professor Per-Olof Eriksson, my supervisor, for providing laboratory facilities and invaluable help during the clinical examinations, and for his patience, support and enthusiasm throughout this thesis.

Dr. Erik Nordh, my co-supervisor, for introducing me to research and for his advice, fruitful discussions and encouragement.

Dr. Hamayun Zafar for his patience, advice and great knowledge in the field of movement analysis.

Dr. Anders Wänman for advice and valuable comments.

Dr. Catharina Österlund for great company and encouragement. Thank you for all your help with practical matters when I was away.

Dr. Susanna Marklund for great company, support and help.

Staff and colleagues at Clinical Oral Physiology, Department of Odontology, Umeå University for their help and support.

All participants in the studies.

Mr. Jan Öberg for his skillful technical assistance.

Dr. Albert Crenshaw for linguistic revision.

Marina Heiden for statistical advice.

My mother and late father for always supporting me and my brother Johan for his great sense of humour.

To Jan, Jens and Jacob for their love, understanding and tolerance.

This work was supported by Umeå University (Department of Odontology), the Swedish Dental Society, The Public Dental Health Service, Västerbotten, Trygg-Hansa Foundation Fund and Arnerska Forskningsfonden.
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"If at first you don't succeed, skydiving is not for you."

~ Arthur McAuliff