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SPATIAL CONTROL OF BITING BEHAVIOR
– To bite and not to slip

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The cover illustrates the mandibular movements (plotted from a frontal view) from the start of the jaw opening to fracture of a hazelnut during a representative "first chewing cycle" by individuals with natural dentition (left) and subjects with fixed implant-supported prosthesis (right). Note the wider and smoother mandibular movement for those with natural teeth.
(Illustration: skillfully and kindly drawn by Lina Trulsson).

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Spatial control of biting behavior
- To bite and not to slip

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The only true wisdom is in knowing you know nothing

“”Εν οἶδα ὅτι οὐδὲν οἶδα”

Socrates – Greek Philosopher

To my beloved mother and father,
brothers, sister and most of all, my wife,
Marjaneh, and our wonderful children
Alexander and Adrian

ABSTRACT

Background: During biting and chewing the periodontal mechanoreceptors (PMRs) signal sensory information about the point of attack, the direction of the tooth loads and the intensity of the force with a high sensitivity to very low forces. The sensory information from the PMRs is used by the central nervous system (CNS) to control and position the food morsels and direct the force vectors during biting and chewing. In the absence of this information as for example in subjects with dental implants, control of food positioning, bite force direction and magnitude of force is hampered.

Aims: The present thesis examines the sensorimotor mechanisms involved in the spatial aspects of human jaw movements during biting and chewing. Further, it aims to identify specific sensorimotor impairments in patients rehabilitated with fixed prostheses supported by dental implants or natural teeth.

Material and methods: In a series of studies we investigated the effects of short-term training (Study I) and of transient sensory input deprivation due to local anesthesia (Study II) on oral fine motor performance in individuals with normal healthy dentition. Further, we evaluated sensorimotor impairments in patients with fixed tooth- and implant-supported prostheses during tasks involving biting (Study III) and chewing (Study IV).

Results: These results of the present studies revealed that short-term training of oral fine motor tasks increased the accuracy of task performance and decreased the duration of jaw movements required to complete the biting task (Study I). Transient deprivation of sensory inputs decreased the accuracy of task performance, yet had no impact on the duration of jaw movements required to complete the biting task (Study II). Sensorimotor impairment was observed in subjects with fixed tooth- and implant-supported prostheses compared to subjects with natural dentition during the oral fine biting task. This impairment was apparent from lower accuracy of task performance and a shorter duration of jaw movements compared to those with natural dentition (Study III). Moreover, when attempting to crush the food morsel during a chewing task, the subjects in the fixed tooth- and implant-supported groups exhibited significantly longer total duration of the jaw movement phases than individuals with natural dentition, owing to food morsel slippage (Study IV).

Conclusion: The findings of these studies indicate that short-term training leads to superior spatial control reflected in better performance and optimization of jaw motor functions. However, transiently or permanently altered inputs of sensory information from the PMRs perturbs the spatial aspects of oral fine motor control. It is apparent that lack of peripheral afferent input to the CNS attenuates fine-motor control of the jaws.

LIST OF SCIENTIFIC PAPERS

I. Effects of short-term training on behavioral learning and skill acquisition during intraoral fine motor task
Kumar A, **Grigoriadis J**, Trulsson M, Svensson P, Svensson KG
Neuroscience. 2015; 306:10–17

II. Perturbed oral motor control due to anesthesia during intraoral manipulation of food
Grigoriadis J, Kumar A, Svensson P, Svensson KG, Trulsson M
Manuscript

III. Alterations in intraoral manipulation and splitting of food by subjects with tooth- or implant-supported fixed prostheses
Svensson KG, **Grigoriadis J**, Trulsson M
Clin Oral Impl. Res. 2013; 24:549-555

IV. Motor behavior during the first chewing cycle in subjects with fixed tooth- or implant-supported prostheses
Grigoriadis J, Svensson KG, Trulsson M
Clin Oral Impl. Res. 2016; 27:473-480

CONTENTS

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
BIC	Bayes information criterion
CNS	Central nervous system
CPG	Central pattern generator
EMG	Electromyography
ISP	Fixed implant-supported prostheses
N	Newton
NAT	Natural teeth
PMR	Periodontal mechanoreceptor
r.m.s	Root mean squared
SD	Standard deviation
TMJ	Temporomandibular joint
TSP	Fixed tooth-supported prostheses

1 INTRODUCTION

Mastication is among the most complex sensorimotor behaviors that humans can perform. Masticatory function is controlled by the central nervous system (CNS) in interaction with sensory signals that primarily originate from mechanoreceptors in the oral cavity. The basic sensorimotor mechanisms responsible for the control of mastication have been studied both in animal models and in humans (Dellow and Lund, 1971, Lund and Kolta, 2006, Trulsson, 2006, Woda et al., 2006). Microneurographic recordings of signals from single nerve afferents in humans have demonstrated that the periodontal mechanoreceptors provide temporal, intensive and spatial information when food is positioned and manipulated between the teeth in preparation for biting and chewing actions (Trulsson, 1993, Trulsson and Johansson, 1994, Johnsen and Trulsson, 2003, 2005). Accordingly, individuals lacking PMRs, such as patients with dental prostheses supported by the oral mucosa or dental implants, show a marked disturbance in the control of the amplitude of biting forces used to hold and manipulate food morsels between their teeth (Trulsson and Gunne, 1998, Svensson and Trulsson, 2011). However, the consequences of loss of sensory information on the "spatial control" of jaw actions during food biting and manipulation are not well understood.

Masticatory function is an important aspect of oral health and all oral rehabilitation procedures should aim to maintain or restore adequate function. The use of dental implants in oral rehabilitation procedures has increased substantially during the last decades and implants are considered highly significant in enhancing oral rehabilitation (Feine et al., 2006). Studies have indicated that although contemporary prosthetic treatments present excellent possibilities for anatomical restoration of lost teeth, they still fail to fully restore oral function (Grigoriadis et al., 2011, Svensson and Trulsson, 2011, Grigoriadis et al., 2014). Clinical methods are still lacking for objective assessment of masticatory functions, which hampers treatment evaluations and makes treatment choices difficult.

Accordingly, the aim of the present thesis is an in-depth analysis of the sensorimotor mechanisms and spatial aspects of human jaw movements during food positioning, biting and chewing. A further aim is to identify specific sensorimotor dysfunctions in patients rehabilitated with fixed prostheses supported by dental implants or natural teeth, with the ultimate future objective of improving masticatory performance in these patient groups.

2 BACKGROUND

2.1 Mastication and oral fine motor control

Mastication, as described above, is among humankind's most complex sensorimotor behaviors. The digestive process starts as soon as a food morsel is placed inside the oral cavity and mechanically fragmented into smaller pieces; mastication mixes the food with saliva and forms it into a soft lubricated bolus with properties suitable for swallowing (Pedersen et al., 2002, Woda et al., 2006, van der Bilt, 2011, Pereira and van der Bilt, 2016). Like locomotion, mastication is an intermittent, rhythmic, semi-automatic movement in which the jaw muscles, temporomandibular joints (TMJ) and tongue act in coordination with each other to position the food morsel between the teeth and fragment it into smaller pieces (Lund, 2011). To achieve this precise and well-coordinated act, masticatory jaw movements are modulated by sensory afferent inputs from several microstructures or receptors (nerve endings) in various orofacial tissues (Dellow and Lund, 1971, Klineberg, 1980, Lund, 1991, Jacobs and van Steenberghe, 1994, Capra, 1995, Trulsson and Essick, 2004, Lund and Kolta, 2006). One such important and specialized receptor is the periodontal mechanoreceptor (PMR). The PMRs, which are imbedded in the periodontal ligament (a dense collagenous tissue) extending along the roots of the teeth, provide important sensory information to the central nervous system (CNS) regarding the level and direction of the force, the position of the food and its spatial orientation during the initial tooth-food contact (Trulsson et al., 1992, Trulsson and Johansson, 1996b, Trulsson, 2006). Absence of such vital information decreases the oral fine motor control and results in impaired masticatory function. Further, it is suggested that primary motor cortex and somatosensory cortex are important for initiation and fine regulation of the self-perpetuating cycle of mastication (Sessle et al., 2005, Lund, 2011, Sessle et al., 2013)

2.2 Neuronal control of mastication

The rhythmic masticatory movements are generated by a neuronal network in the brainstem called the central pattern generator (CPG) (Dellow and Lund, 1971, Lund and Kolta, 2006, Morquette et al., 2012). The CPG along with adequate inputs from CNS is responsible for activation of the jaw-opening and jaw-closing muscles in the alternating pattern seen during normal mastication. However, the CPG in itself is unable to adjust the muscle force to deal with the changing properties of the food morsel during mastication (Lund, 1991, Lund and Kolta, 2006, Westberg and Kolta, 2011). The sensory information provided by the peripheral receptors (e.g., PMRs and receptors in mucosa, tongue, muscle spindle, TMJ) is therefore used in a feedback manner to regulate the relatively low manipulative holding forces such as when

food is held between the teeth (Trulsson and Johansson, 1994, Johnsen and Trulsson, 2005). However, motor commands from the CNS during rapid, rhythmic chewing movements can also be generated in anticipation, in a predictive feed-forward manner (Ottenhoff et al., 1992a, b, Komuro et al., 2001). This enables adjustment and adaptation of the motor program employed when splitting food morsels with high biting forces (Wolpert, 1997, van der Bilt et al., 2006, Grigoriadis et al., 2011, Lund, 2011, Svensson and Trulsson, 2011). Moreover, signals from the PMRs may contribute to the selection of the most appropriate motor program, depending on the physical characteristics of the food morsel (Flanagan et al., 2006).

2.3 Behavioral learning and skill acquisition

Several studies during the last decades have focused on the ability to enhance oral motor skills and motor performance through training of various orofacial motor tasks, both in animal models and humans (Sessle et al., 2005, Svensson et al., 2006, Boudreau et al., 2007, Kothari et al., 2011, Kothari et al., 2012, Kothari et al., 2013, Komoda et al., 2015a). These experiments involved tongue protrusion and tongue-lifting tasks, repeated clenching and repeated splitting of food morsels (Svensson et al., 2006, Iida et al., 2014, Komoda et al., 2015a, Kumar et al., 2015, Zhang et al., 2016). Training of orofacial motor tasks supposedly leads to neuroplastic changes indicated by an increased corticomotor representation of the trained muscles, relevant to the task (Svensson et al., 2003, Svensson et al., 2006, Kothari et al., 2011, Komoda et al., 2015b).

Successful completion of object manipulation tasks (e.g., manipulation of objects with the fingertips) involves a sequence of actions dependent on discrete signals from the peripheral receptors. It is suggested that skill acquisition and motor performance during such object manipulation tasks involves optimizing the linking of action phases, relevant to the task (Johansson and Flanagan, 2009, Säfström et al., 2013). Previous studies on digital motor control have shown that these different action phases involve certain mechanical events that serve as sensorimotor control points, defining the task sub-goals (Johansson and Flanagan, 2009, Säfström et al., 2014). Further, in connection with most such manipulation tasks, the CNS not only forms and plans a series of desired task sub-goals, but also predicts the sensory events necessary to achieve the objectives of the tasks (Flanagan et al., 2003, Westberg and Kolta, 2011). Successful completion of the task sub-goals would not only depend on sensory information from the periphery, but would also require the motor command to be executed in anticipation of an upcoming movement (Flanagan et al., 2003, Flanagan et al., 2006). The brain predicts the outcome of the movement and identifies the commands required for optimal achievement. Such predictions can be acquired and updated by previous experience (learning)

and may also aid in optimizing motor performance (Reilmann et al., 2001, Flanagan et al., 2003, Wolpert et al., 2011). Failure to achieve the task sub-goals, e.g., due to local anesthesia of the fingertips during dexterity tasks, results in substantial errors and lengthens the time required for completion (Flanagan et al., 2006, Johansson and Flanagan, 2009).

Therefore, in the present thesis we hypothesized that short-term training on an oral fine motor task (i.e., repeated splitting of food morsels), in subjects with natural dentition, would increase the accuracy of task performance and optimize jaw movements, thus reducing the time required to perform the task. Moreover, we hypothesized that transient deprivation of sensory input due to local anesthesia would perturb oral fine motor control and increase the time to task completion.

2.4 Cutaneous mechanoreceptors

The microneurography technique, developed by Vallbo and Hagbarth in 1968, is a method to record action potentials from the peripheral nerves of human subjects (Vallbo et al., 1985). With this technique, the innervation and somatosensory characteristic of glabrous skin of the hand have been studied in detail (Johansson and Westling, 1984). Essentially, the glabrous skin of the hand possesses four different major classes of functional afferents (Johansson and Vallbo, 1983, Vallbo and Johansson, 1984). Of these, two are fast adapting (FA) mechanoreceptors (i.e., FA I: Meissner corpuscles and FA II: Pacini corpuscles) and are sensitive to indentations in the skin. The other two are slow adapting (SA) mechanoreceptors (SA I: Merkel's discs and SA II: Ruffini endings) which, in addition to being dynamically sensitive to the stimulus, also signal the magnitude of the sustained indentation in the skin (Vallbo and Johansson, 1984). The density of tactile innervation is much higher in hands than in other parts of the body and these afferents are also good at extracting temporal and spatial information during mechanical events (Johansson and Westling, 1987, Westling and Johansson, 1987).

2.5 Orofacial mechanoreceptors

The neurophysiology of human orofacial mechanoreceptors have been studied on the basis of microneurographic recordings from the supraorbital, infraorbital, inferior alveolar and lingual nerve. These studies of the orofacial region have shown the presence of the same mechanoreceptive afferents as in the glabrous skin of the hand (FA I, SA I and SA II) with the exception of FA II afferents (Trulsson and Essick, 1997, Trulsson and Johansson, 2002). Moreover, the experiments indicate that mechanoreceptors in the orofacial region act as exteroceptors, which signal information to the CNS about environmental stimuli that come in

contact with the body, e.g., when the lips come in contact with food morsels. These mechanoreceptors are also believed to function as proprioceptors, which provide information about movement and position as well as information mediated from strain patterns in the skin and mucosa of the orofacial region (Johansson et al., 1988). Further, the lips, the corner of the mouth and the tip of the tongue exhibit very dense innervation with small receptive fields (Johansson et al., 1988, Trulsson and Johansson, 2002).

Several studies have shown that the proportions of slow and fast adapting receptors differ in different parts of the body. About 2/3 of all units in the tongue and on glabrous hand are fast adapting (Johansson and Vallbo, 1983, Trulsson and Essick, 1997). For comparison, 2/3 of the units in the hairy skin of the face, lip, hairy hand and arm are slow adapting (Edin and Abbs, 1991, Edin et al., 1995, Vallbo et al., 1995). These differences in the occurrence of fast and slow adapting mechanoreceptors in different parts of the body can be attributed to the functional demands of the corresponding areas. For example, the tongue and the glabrous hand are used for manipulation of objects and active touch. These active manipulative movements serve the purpose of stimulating the fast adapting receptors, and thus allowing us to feel the texture of the object's surface. Further, sensory information from the slow adapting receptors (which are usually present at the sites of joint movements) is believed to be important for proprioception and to sense passive touch (Edin, 1992, Johansson and Flanagan, 2009).

2.6 Periodontal mechanoreceptors

Periodontal mechanoreceptors (PMRs) are Ruffini-like nerve endings (stretch receptors) located among the collagen fibers connecting the roots of the teeth to the alveolar bone. When a tooth is tilted, the tension in these fibers caused by the mechanical stimulus activates the receptors (see Fig. 1) (Cash and Linden, 1982, Byers, 1985). They often are spontaneously active, exhibit weak dynamic and steady static responses. The signal recordings from the PMRs show force profiles similar to those of the Ruffini endings found in the glabrous skin of the hand and oral mucosa (Trulsson and Johansson, 1996a). The only structural difference between the Ruffini endings in the glabrous skin and those in the periodontal ligament are that the latter are not encapsulated (Byers et al., 1986, Maeda et al., 1990, Sato et al., 1992). Most of the cell bodies are situated in the trigeminal ganglion while some are also found in the trigeminal mesenchephalic nucleus in the brainstem (Gottlieb et al., 1984, Byers, 1985, Heasman and Beynon, 1986). Further, animal studies have shown that each tooth has a couple of hundred of these nerve endings, with the highest concentration near the apex.

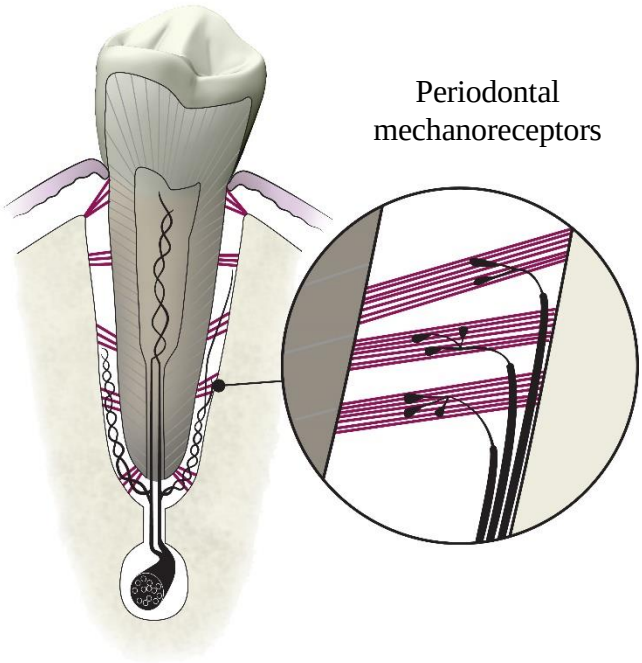

Fig. 1. Chewing displaces the tooth in the socket (less than 100 micrometers), causing movement of the root and stretching the collagen fibers. PMRs are sensory organs located among the collagen fibers around the root of a tooth and signal information about loads on that tooth. (Illustration by Lina Trulsson)

2.6.1 Characterization of the PMRs

The role of the PMRs in oral motor control has been investigated on the basis of microneurographic recordings obtained from the inferior alveolar nerve. For these recordings, a tungsten microelectrode needle with a tip of 5-10 μm is inserted near the mandibular foramen, with its tip positioned in the nerve fascicle (Johansson and Olsson, 1976, Trulsson et al., 1992, Trulsson and Johansson, 1994). These experiments suggest that PMRs often are spontaneously active, give regular static responses to force, and are extremely sensitive to force direction and force magnitude (Trulsson and Johansson, 1996a, Trulsson, 2006). Their role and properties have been discussed in detail below.

Sensitive to force direction

When a mechanical stimulus is applied on the tooth surface, the signals generated in response to the stimulus recorded from the single nerve fiber correlate with the stimulus applied (Trulsson et al., 1992). These mechanical stimuli were delivered in the form of controlled forces (250 mN) manually applied on the teeth by a probe equipped with force transducers. The direction of the force was also controlled by applying the force probe perpendicular to five free faces of a nylon cube fixed above the test tooth. The neural discharge corresponding to the horizontal forces applied in four different directions (i.e., mesial, distal, facial, lingual) and the vertical forces (up and down) were recorded. It was evident that the PMRs responded differently depending on which direction the force was applied. For example, the anterior teeth responded strongly in all directions but the posterior teeth responded more in a disto-lingual direction (Edin and Trulsson, 1992, Trulsson et al., 1992, Trulsson, 1993, Johnsen and Trulsson, 2003). Furthermore, studies have also shown that there are more PMRs in the anterior front teeth (incisors) than in the posterior (premolars and molars) (Johnsen and Trulsson, 2003).

It is hypothesized that the reason for this higher density of PMRs around the front teeth may be the need for analyzing and extracting vital information during the initial tooth-food contact. Similarly, there is a higher concentration of mechanoreceptors on the tip of the tongue compared to the back part of the tongue.

Sensitive to low forces

To determine the intensity aspects of tooth loading, "ramp-and-hold shaped" force profiles were applied to receptor bearing teeth (the teeth that gave the strongest discharge when mechanically stimulated; which most often was the incisors). The neural data obtained from these experiments helped reveal the mechanisms of how human PMRs encode information about the intensity of loads (Trulsson and Johansson, 1994, Johnsen and Trulsson, 2005). The stimulus response graphs obtained showed a hyperbolic relationship for most of the PMRs. Further, most (80%) of the periodontal afferents showed the greatest sensitivity to changes in steady state force at force levels below 1 N and gradually decreasing sensitivity as force levels increased (Fig. 2). The steep slopes of the stimulus response curves reveal that the receptors in anterior teeth are most sensitive to changes in sustained force levels below about 1 N. The posterior teeth, however, saturated at a slightly higher level of approximately 3-4 N. Further, at higher forces, the curves become almost horizontal, indicating that even though the afferents signal the presence of higher forces they do not provide any information about the magnitude of the force to the brain. These findings are also in accordance with those from early animal studies (Ness, 1954, Hannam and Farnsworth, 1977).

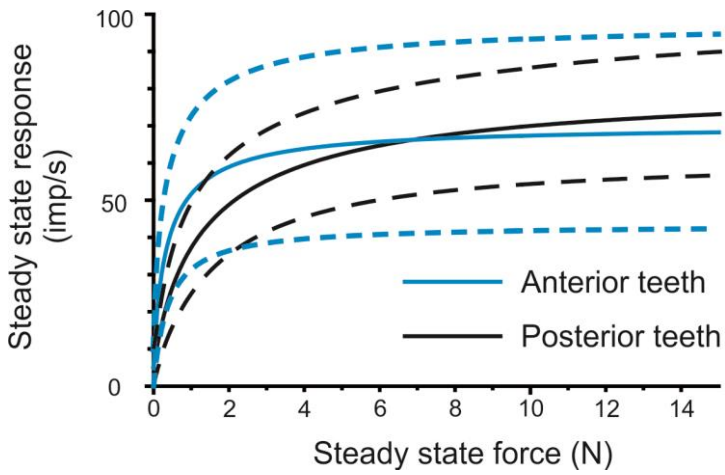

Fig. 2. Stimulus-response relationship for periodontal afferents around anterior and posterior teeth (blue lines: 19 periodontal afferents around anterior teeth; black lines: 20 periodontal afferents around posterior teeth). The solid and dashed lines represent the mean values ± 1 SD, respectively (Trulsson and Johansson 1994, Johnsen and Trulsson 2005).

Spatial control

The "hold and split" task was developed to study the natural situation of positioning and holding the food morsel and the specific regulation of these precise manipulative actions during biting. The sensitivity of the PMRs to low biting forces is put to good use for precise

manipulative actions such as during holding and manipulating food between the teeth (Trulsson and Johansson, 1996b, Trulsson and Gunne, 1998). Subsequently, when the food morsel is split (high forces, 50-70 N), the sensitivity of the PMRs decreases and they do not increase their signaling due to saturation. When the teeth are anesthetized, the magnitude of the hold forces increases (2.5 N) along with the frequency of slippage of the food morsel (Trulsson and Johansson, 1996b). Patients with various types of prostheses lacking PMRs also showed similar high hold force levels (2.5 N) and more slippage of food morsels (Trulsson and Gunne, 1998). It can be inferred that the control of low hold forces during the initial manipulating of food morsels is lost when sensory information is perturbed. This impairment of function can be attributed to decreased spatial control of the food morsels.

Previous studies describe the basic properties of PMRs in relation to simple biting tasks such as the hold and split task. However, the role of these receptors in skill acquisition and their contribution to the learning of complex motor tasks have not been investigated. Further, the consequences of impaired sensory information due to local anesthesia or complete loss of information (as in the case of dental prosthesis) on the “spatial control” of jaw actions during food biting and manipulation are not well understood. We hypothesize that PMRs are actively involved in spatial control and would thus regulate and subsequently enhance biting/chewing performance in humans.

2.7 AIMS OF THE PRESENT THESIS

2.7.1 General aim

The general aim of this thesis is to advance the analysis of sensorimotor control and spatial aspects of human jaw actions during food positioning, biting and chewing and to improve our understanding of the role of the PMRs during oral fine motor tasks using anterior and posterior teeth. A second aim was to identify specific sensorimotor impairments in patients rehabilitated with fixed prostheses supported by natural teeth or dental implants.

2.7.2 Specific aims

Study I

- To examine if short-term training of subjects with natural dentition in an oral fine motor task involving repeated splitting of food morsels, would improve performance and also lead to optimization of jaw movements, in terms of reduced duration of various phases of jaw movements.

Study II

- To investigate if reduction of afferent inputs from the PMRs by local anesthesia, in subjects with natural dentition, perturbs fine oral motor control and related jaw movements during intraoral manipulation of food morsels.

Study III

- To investigate the role of PMRs in motor performance during a "manipulation and split task", and to compare the motor performance of subjects with natural teeth and subjects with fixed prostheses supported by natural teeth or dental implants.

Study IV

- To describe and compare motor behavior during the first chewing cycle of a natural chewing task in individuals with natural dentition or subjects with bimaxillary fixed tooth- or implant-supported prostheses.

3 MATERIAL AND METHODS

The subjects participating in all four studies were in good general health and were visiting their dentists and dental hygienists on a regular basis. The participants did not report any orofacial pain, associated disturbance in jaw function or any neurological problem related to biting and chewing. Studies I, II and part of study III were performed in normal healthy individuals with natural dentition, healthy periodontium with normal occlusion without any malocclusion related to overjet and overbite. The natural dentate participants were young staff and students at the Department of Dental Medicine, Karolinska Institutet, who were invited to participate in the study, and did so voluntarily. The participants in Studies III and IV comprised also prosthodontic patients with bimaxillary fixed tooth-supported prostheses or bimaxillary fixed implant-supported prostheses. They were recruited from the Department of Dental Medicine, Karolinska Institutet, private and public dental service clinics specializing in oral rehabilitation in and around the greater Stockholm area, Sweden.

3.1 Study participants and protocol

Study I

Thirty healthy young natural dentate volunteers (16 female) in the age range of 21-32 years (mean: 27 years) participated in a single experiment session of approximately one hour. The volunteers were comfortably seated on an office chair in an upright position and were asked to do a “manipulation and split” task, wherein they performed 3 series of 10 trials before and after a short-term training session (a total of 60 repetitions). During the training session, the participants were asked to perform the same behavioral task for approximately 30 minutes or to split 100 chocolate candies (whichever occurred the first) without any recordings being made. Occasionally, the examiner gave feedback to the participants during the training on the performance of the splits. The participants were not allowed to perform any practice trials prior to the start of the experiment. However, the participants wore the measurement contraption during the entire experiment.

Study II

Thirty healthy young volunteers with sound natural teeth in both upper and lower jaws, who also had participated in Study I, were enrolled for the second study. These volunteers participated in a single experimental session of approximately 40 minutes and were equally divided into an experimental (10 women; 23-32 years of age, mean: 27 years) and a control group (6 women; 21-29 years of age, mean: 25 years). The participants were seated on an office chair in an upright position without any head support, and their jaw movements recorded while

performing a “manipulation and split” task. The participants repeated this task 30 times each before (baseline) and after the intervention (a total of 60 repetitions). Following 30 repetitions of the behavioral task, the experimental group were injected into the buccal sulcus around the upper and lower central/lateral incisors with local anesthetic solution (approximately 2 x 1.8 ml Citanest® Dental Octapressin® (1.8 ml cartridge); Prilocain-hydrocloride (30 mg/ml) and Felypressin (0.54 mg/ml), Dentsply Ltd, Umeå, Sweden). No injection was made in the control group. Subjective symptoms related to anesthesia were confirmed in the experimental group prior to recording the post-intervention session.

Study III

Ten healthy age-matched volunteers with bimaxillary natural teeth (4 women; 61-72 years of age, mean: 66 years), 10 healthy volunteers with bimaxillary fixed tooth-supported prostheses (5 women; 61-83 years of age, mean: 70 years) and 10 healthy volunteers with bimaxillary fixed implant-supported prostheses (3 women; 67-77 years of age, mean: 72 years) participated in a single experimental session of approximately one hour. The participants were comfortably seated on a dental chair and were asked to perform a “manipulation and split” task 15 times. Prior to start of the experiment all the participants were allowed at least five practice trials.

The participants with tooth-supported fixed prostheses (metal-ceramic) had a range of 10-13 prosthetic units (mean: 11 units), supported by 4-9 abutment teeth (mean: 7 abutment) in each jaw; the prostheses had been in use for a range of 8-246 months (mean 53 months). The marginal bone support (from the margin of the metal-ceramic bridge to the apex of the root) was calculated from their available radiographs using a Schei ruler and exhibited a range of 66-89% (mean: 79%) bone height left (Schei et al., 1959). The participants with fixed implant-supported prostheses (metal-acrylic, except for one individual who had a metal-ceramic prosthesis in the upper jaw) had a range of 4-6 dental implants (mean: 5 implants) in each jaw extending to the premolar/molar region and their prostheses had been in use for a range of 1-240 months (mean: 77 months).

Study IV

Ten healthy age-matched volunteers with bimaxillary natural teeth (4 women; 61-72 years of age, mean: 66 years); 11 healthy volunteers with bimaxillary fixed tooth-supported prostheses (5 women; 61-83 years of age, mean: 70 years) and 10 healthy volunteers with bimaxillary fixed implant-supported prostheses (4 women; 68-77 years of age, mean: 72 years) participated in a single experimental session of approximately one hour. The participants were comfortably seated on a dental chair and were asked to perform a “chewing” task 5 times. The participants

were not allowed to perform any practice trials prior to the start of the experiment.

All subjects with natural dentition had at least 24 occluding teeth and some of the premolars and molars had been subjected to endodontic and/or restorative treatment such as fully covering crowns. The participants with tooth-supported fixed prostheses (metal-ceramic) had a range of 9-14 units (mean: 11 units) supported by 4-9 abutment teeth (mean: 7 abutment teeth) in each jaw; the prostheses had been in use for a range of 8-246 months (mean 82 months) and some of the abutment teeth had undergone endodontic treatment. The marginal bone support (from the margin of the metal-ceramic bridge to the apex of the root) was calculated from their available radiographs using a Schei ruler and exhibited a range of 54-90% (mean: 80%) bone height left (Schei et al., 1959). The participants with fixed implant-supported prostheses (metal-acrylic, except for one individual who had a metal-ceramic prosthesis in the upper jaw) had a range of 4-6 dental implants (mean: 5 implants) in each jaw extending to the premolar/molar region, which had been in use for a range of 1-240 months (mean: 82 months).

3.2 Equipment

In all four studies, vertical and lateral movements of the lower jaw in relation to the upper jaw were measured with the help of a customized 3D jaw-tracker. Electromyographic activity (EMG) of the masseter muscle and sound pertaining to the fracture of the food morsel during the behavioral tasks were also recorded. The accuracy of the task performance during the "manipulation and split" behavioral task along with the corresponding duration of jaw movements were measured in study I-III. The amplitude of vertical and lateral mandibular movement during a natural chewing task was investigated in study IV. A detailed account of the equipment and methods used is given below.

3.2.1 3D - Jaw tracker

The vertical and lateral movements of the lower mandible were monitored with the help of headgear equipment and a small magnet (10 x 5 x 10 mm; Neodymium Iron Boron) attached to the lower central incisor. The jaw movements were recorded in all three dimensions (Study I-IV) using this custom-built 3D jaw tracking device (Physiology Section, IMB, Umeå University, Umeå, Sweden). The light-weight device (approximately 220 grams) was worn by resting it on the bridge of the nose like a pair of spectacles and anchored to the head with adjustable straps. The device was designed to allow free movement of the head and minimize interference with oral function. Eight magnetic sensors (four on each side) were attached to monitor the position of the magnet attached to the incisor independently of the posture of the head (see Fig. 3A).

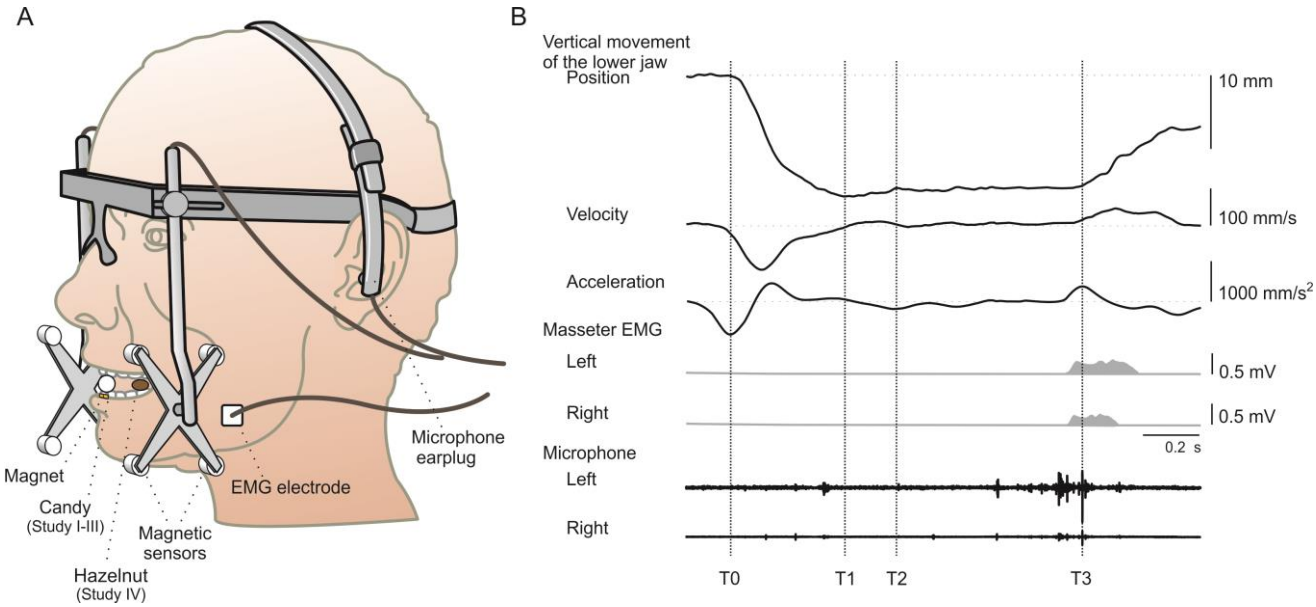

Fig. 3. (A) The device custom built to monitor movement of the lower jaw relative to the upper jaw during different behavioral tasks by tracking a small magnet attached with dental composite to the lower central incisors. Magnetic sensors (four on each side) located on arms projecting down from the frame track the position of a magnet attached to the labial surface of the lower incisors. EMG activity was recorded bilaterally from the masseter muscles using bipolar surface electrodes. Sounds pertaining to fracture of the food morsel were recorded bilaterally by microphones secured in an earpiece on a headgear. **(B)** Representative recordings made during the "manipulation and split" task performed by a single participant. From top to bottom the curves depict: jaw position; vertical velocity and acceleration of the jaw; muscle activity (the r.m.s.-processed EMG) from the left and right masseter muscles; and sound recordings from the left and right ear microphones. The events of interest are the following: onset of the *jaw opening phase* (T0); end of the opening phase, and start of the *contact-establishing phase* (T1); end of the contact-establishing phase, and start of the *contact phase* (T2); end of the contact phase, and start of the *jaw closing phase* (T3). The fracture of the candy was detected as rapid closing of the jaw that coincided with both a clear sound and increased EMG activity.

3.2.2 Electromyography

Electromyographic activity (EMG) was recorded (Study I-IV) by attaching a pair of bipolar surface electrodes (2 mm in diameter and 12 mm apart, custom built at Physiology Section, IMB, Umeå University, Umeå, Sweden) which rested on shielded pre-amplifiers (bandwidth: 6 Hz - 2.5 kHz) (see Fig. 3A). The most prominent part of the masseter muscle was identified by asking the participants to clench their teeth and palpating the muscle. The muscle was cleansed with alcoholic wipes (99.5% ethanol) and the electrodes were placed perpendicular to the direction of the muscle fibers. Prior to the attachment the electrodes were coated with conductive gel and they were secured on the masseter muscle with doubled-sided adhesive tape.

3.2.3 Ear microphones

The sound created by the fracture of the food morsels during the behavioral tasks was recorded (Study I-IV) using custom-built microphones. The earpiece was attached to the headgear described above (Physiology Section, IMB, Umeå University, Umeå, Sweden) and placed in the external auditory meatus of the ears. Prior to start of the experiment, the microphones were positioned firmly in the ears and then calibrated individually for each subject (see Fig. 3A).

3.3 Behavioral tasks and model food

In the present thesis, the intraoral fine motor control of the subjects was primarily assessed on the basis of their motor behavior and performance of the "manipulation and split" task (Study I-III). Similarly, on the basis of their performance of the chewing task, spatial control and motor skills were assessed (Study IV). The examiner demonstrated the behavioral tasks prior to start of each experiment.

3.3.1 Manipulation and split task

The participants were comfortably seated in a quiet room on an office chair (Study I-II) or a dental chair (Study III) in an upright position with the Frankfort horizontal plane approximately parallel to the floor. Prior to the start of each recording, when instructed, the participants placed a spherical sugar-coated piece of chocolate candy (10 mm in diameter, 0.84 g; Fazer Marianne chocolate dragees, Fazer konfektyr AB, Stockholm, Sweden) between the midsection of the palate and the tongue then positioned their teeth in maximum intercuspation. Shortly thereafter, when they had had the candy in the mouth no more than 2-3 seconds, at the examiner's signal, they moved the candy in between the anterior incisors and attempted to split it into two equal halves, then spat out the pieces in a plastic cup held by the examiner. The examiner instructed the participants to split the candy into two equal parts, but gave no instructions concerning how quickly this task should be performed.

3.3.2 The chewing task

The participants (Study IV) were comfortably seated in a quiet room on a dental chair in an upright position with the Frankfort horizontal plane approximately parallel to the floor. Prior to the start of each recording, when instructed, the participants placed a shelled medium sized hazelnut between the tongue and mid-section of the hard palate, then positioned their teeth in maximum intercuspation. The instruction they received was to eat the hazelnut, but they were given no instructions concerning how quickly this task should be performed. After receiving verbal instructions, but no training, each participant performed the "chewing" task five times.

3.4 Data analysis

Data regarding jaw movements (Study I-IV) were recorded with computer-based data acquisition and analysis software (WinSc/WinZoom v1.54; Umeå University, Physiology Section, IMB, Umeå, Sweden) at a frequency of 800 Hz. The EMG signals were sampled at 3.2 kHz and sound pertaining to the crushing of the food morsel was recorded at a frequency of 25.6 kHz. The velocity and acceleration of jaw movement were obtained through symmetrical numerical time differentiation (±20 points) of the position and velocity. The EMG signals were processed as root-mean-squares (r.m.s.) during a moving time window corresponding to ±100 samples.

3.4.1 Manipulation and split task

Performance of the split

Performance of the "manipulation and split" task (Study I-III) was assessed by comparing the weight of the largest piece resulting from the split to half the weight of the candy (ideal split = 0.42 g (Study I-II) and 0.40 g (Study III-IV)), with a precision of ±0.01 g (Fino Balance Mini; Fino GmbH, Bad Blocket, Germany). The smaller the deviation from the ideal split, the better the performance. A deviation of 0% was characterized as "*ideal*"; a deviation of <5% as "*perfect*"; a deviation of >50% as "*unsuccessful*"; and a deviation of >75% as a "*failed*" split.

Motor behavior

The points of interests during the individual trials were identified by the software and checked manually for errors. These points of interests were the *onset of jaw opening* (i.e., T0), defined as the time-point at which vertical acceleration at the *beginning of jaw opening* was maximal (i.e., the first peak negative value), the *end of the jaw opening phase* (T1), when the vertical velocity exceeded zero for the first time *(beginning of the contact-establishing phase*); and continued to exceed zero thereafter, assessed as the *end of* the *contact-establishing phase* (T2) (and subsequent *beginning of contact phase*) (see Fig. 3B). Splitting of the candy, i.e., the *end of the contact phase* and *beginning of the jaw-closing phase* (T3), was determined from a characteristic rapid increase in the vertical jaw movement (jaw closing) which coincided with both a clear sound (≥30% of the loudest signal) and enhanced EMG activity of the masseter muscles (Fig. 3B).

3.4.2 The chewing task

Data collected during the first cycle of chewing in each trial were analyzed. The first cycle was defined as the period from the beginning of jaw opening until initial fracture

of the hazelnut.

Motor behavior

The points of interest during the individual trials were identified by the software and checked manually for errors. These points of interest were the *onset of jaw opening* (i.e., M1), defined as the time-point at which vertical acceleration at the *beginning of jaw opening* was maximal (i.e., the first peak negative value), the *end of the jaw opening phase* (M2), when the vertical velocity exceeded zero for the first time (*beginning of the contact-establishing phase*); and continued to exceed zero thereafter (see Fig. 4A). Fracture of the hazelnut (M4), was determined from a characteristic rapid increase in the vertical jaw movement (jaw closing) which coincided with both a clear sound (≥30% of the loudest signal) and enhanced EMG activity of the masseter muscles (Fig. 4A).

In cases where the participants made several attempts to crush the hazelnut, the end of the last jaw opening (M3) prior to the fracture of the hazelnut was defined as the last time at which the vertical velocity exceeded zero prior to M4. In cases where the hazelnut was fractured at the first attempt, M2 and M3 were the same.

In order to quantify the range of motion, the mandibular movement (lateral and vertical) during the first chewing cycle (M1 to M4) was plotted from a frontal view (by WinZOOM). This was done for every trial by every participant. The plot was then imported into image-processing software (CorelDraw® Graphics Suite version 12.0, Corel Corp., Ottawa, Canada) where the cycle was "enclosed" utilizing the "Auto-closed curve" tool. Once the line from M4 (corresponding to the point of fracture) had been drawn to M1 (corresponding to the start of jaw opening), all figures were imported into a second software program as a JPEG file (Adobe Photoshop CS4 version 11.0, Adobe Systems Inc., San Jose, USA) and the number of pixels within the enclosed cycle was counted (see Fig. 4B).

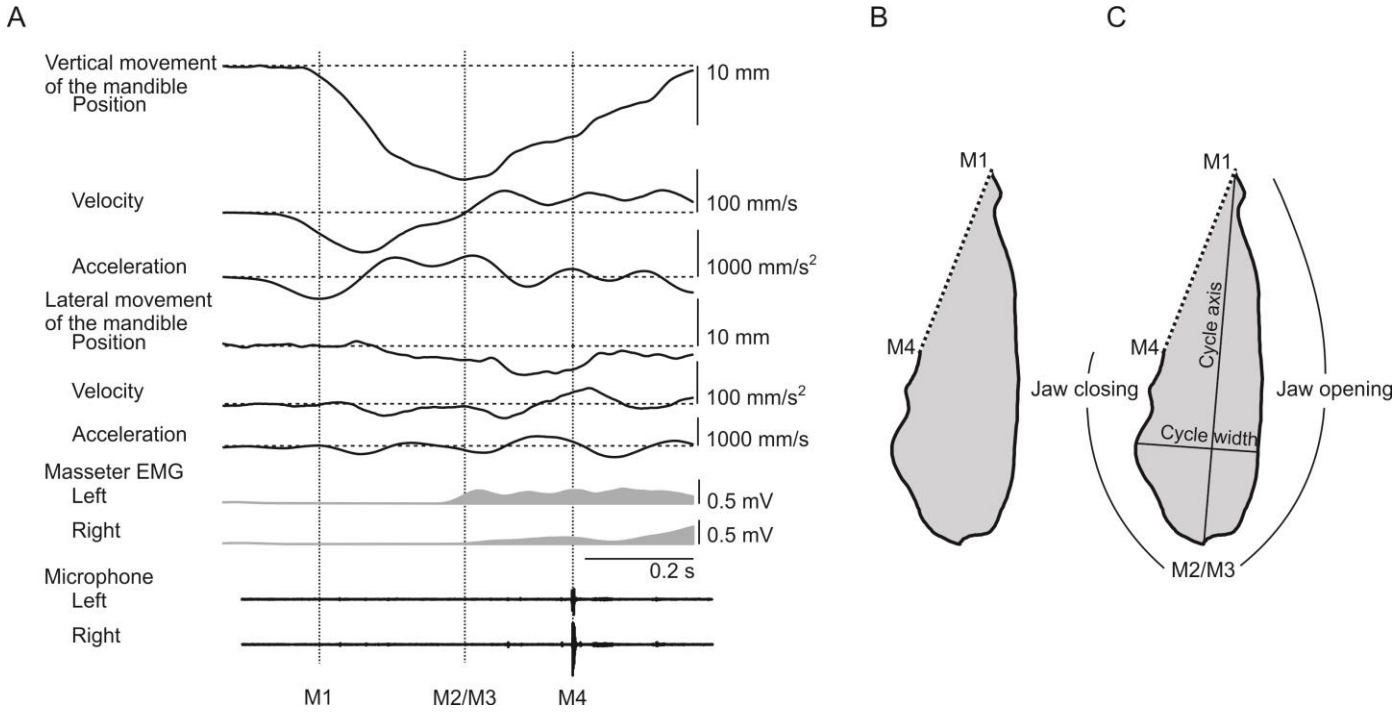

Fig. 4. (A) Representative recordings from the first chewing cycle of a participant with a natural dentition. These curves illustrate vertical and lateral movements: position, velocity, and acceleration of the mandible; EMG-activity of the left and right masseter muscles; and sound recordings from the left and right microphones. **(B)** Mandibular movement of every participant trial was imported into image-processing software and the chewing cycle "enclosed" with a dashed line from the point of fracture (M4) to the start of jaw opening (M1). This made it possible to count the number of pixels within the enclosed area. **(C)** Here, a "cycle axis" has been plotted, i.e., a line connecting the start of jaw opening (M1) to the time-point of peak vertical movement (M2 or M3) along with a "cycle width", i.e., the longest line that can be drawn perpendicular to the "cycle axis".

Further, a line was drawn from start of jaw opening (M1) to the peak vertical jaw movement (M2/M3) creating a "cycle axis" and perpendicular to that a second line creating a "cycle width", in an additional approach to quantify the lateral component of mandibular movement (Piancino et al., 2005, Piancino et al., 2008) (see Fig. 4C). The ratio of cycle axis/cycle width was then calculated for each chewing cycle.

3.5 Statistical analysis

The level of statistical significance was set at $P<0.05$, across studies I, II and IV and a P-value of less than 0.10 was considered significant in study III (the limit was set higher than the conventional level of 0.05 to reduce the risk of obtaining false negative findings since it was an explorative study). Study I was analyzed with STATISTICA 6.x (StatSoft INC., Dell, Tulsa, OK, USA) and the analysis of study II-IV was done with SAS 9.x software (SAS Institute INC., Cary, NC, USA).

Study I

The outcome parameters of performance and jaw movements from the mean of ten trials were calculated and series mean was obtained. The data thus obtained were subjected to two-way analysis of variance (ANOVA) with repeated measures model and in this way the outcome parameters were evaluated. The factors in ANOVA were condition (2 levels; before and after training) and series (3 levels; first to third series). Post-hoc tests were performed with Tukey Honestly Significant Difference test with corrections for multiple comparisons. The variation in performance (SEM) was again calculated across the thirty participants (participant means of SEM from all thirty trials). The data pertaining to occurrence of "failed splits" was analyzed with Chi-square test.

Study II-IV

Normal probability plots were used in the linear mixed models analyses to evaluate the assumption of normally distributed residuals (Study II-IV). In cases of significant interaction, simple main effects were examined and if these exhibited a significant P-value, pairwise comparisons were carried out (Study II-IV). Data from all trials were combined to obtain mean values, which were then used to calculate group means and standard deviations. However, when the data were skewed to the right, they were transformed logarithmically and the results presented as medians and 25-75 percentiles. Split performance was analyzed with a general estimating equation for repeated measures. The numbers of "ideal", "perfect", "unsuccessful" and "failed" splits per 30 trials (Study II); per 15 trials (Study III) and per 5 trials (Study IV) were determined. The link function and outcome distribution were expressed as logarithmic and negative binomials, respectively and the chosen covariance was unstructured. Jaw movements (i.e., peak vertical velocity, positions at the different time-points T1-T3; total duration and duration of the jaw-opening, contact-establishing and contact phases) were analyzed employing a mixed-effects model for repeated measures.

Split performance and jaw movements were further investigated by calculating the relative changes (Study II). This relative change expressed as a percentage within the group was calculated as the mean difference between the baseline and intervention values divided by the mean deviation at baseline and was subjected to ordinary least squares analysis taking into consideration the heterogeneity of variance across groups.

3.6 Ethical approval

All four studies were approved by the regional ethical review board in Stockholm and were performed in accordance with the Declaration of Helsinki. Participation in the study was voluntary and the participants were informed about their rights to discontinue the experiment if they wanted. Informed consent was obtained from all participants prior to the start of the experiment.

- *Study I* and *II* were approved by the regional ethical review board in Stockholm, Sweden (Dnr: 2012/1562-31/1).
- *Study III* and *IV* were approved by the regional ethical review board in Stockholm, Sweden (Dnr: 04-715/4).

4 RESULTS

All participants performed the tasks in a reliable manner, similarly, and completed the experiment without any difficulties (Study I-IV). However, several noteworthy differences were seen within the different studies. The most important findings regarding performance and motor behavior (duration and position of jaw movements) resulting from the participants during the behavioral tasks (Study I-IV) are presented below.

4.1 Study I

Split performance

When split performance was evaluated by weighing the larger piece of candy produced by the split (the lower the deviation, the better the performance), we found that the precision of the task improved significantly after training (22.2 ± 2.1% deviation) compared to before training (31.1 ± 2.1% deviation) (P<0.001) (Fig. 5). It may also be noted that the mean variation was significantly reduced (21%) after training compared to before training, 3.3 ± 0.2 and 4.2 ± 0.2, respectively (P<0.001). The occurrence of failed splits was also significantly lower after training (28) than before training (70) (P=0.005).

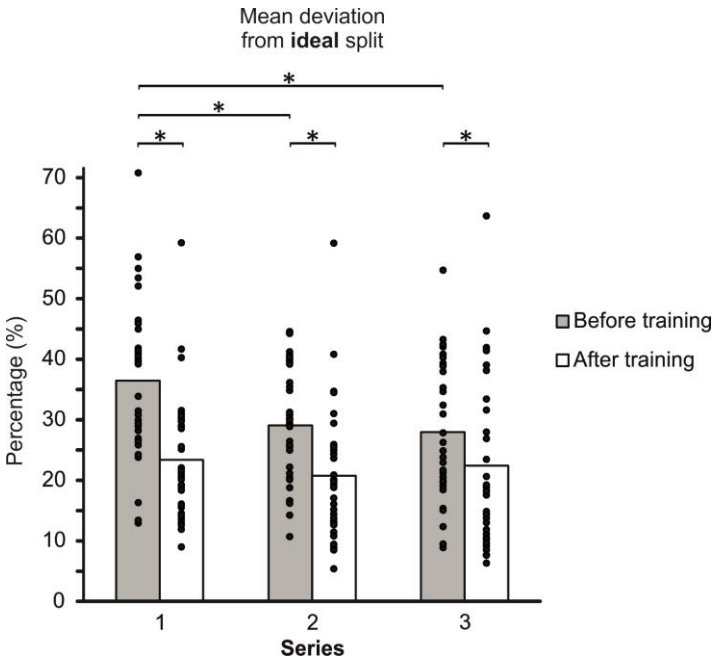

Fig. 5. Performance of the "manipulation and split" task presented as mean deviation (in percentage) from ideal split during the three series before and after training. The filled circles represent individual means and bars represent the group mean of the conditions. Asterisk (*) denotes significant difference.

Duration and individual jaw movement phases

The total duration of the jaw movement phases (T0-T3; see Fig. 3B for detail information regarding the individual phases) was significantly shorter after training than before training (1.21 ± 0.08 s and 1.56 ± 0.10 s, respectively) (P=0.001). Further, when the jaw movements where divided into different phases it was observed that the contact phase was the longest and

the duration of this phase decreased significantly after training compared to before training (0.71 ± 0.07 s and 0.99 ± 0.08 s, respectively) (P<0.0002). The mean variation of the total duration of the task and the duration of the contact phase decreased by 25% and 23%, respectively, after training as compared to before training (P=0.001, P=0.001).

4.2 Study II

Split performance

As in Study I, split performance was evaluated by weighing the larger piece of candy produced by the split, and the lower the deviation, the better the performance. We observed that (Ane) when the experimental group was anesthetized the performance decreased (deviation from ideal split) significantly compared to baseline (P<0.001) (Fig. 6A). However, there was no significant difference in performance between the baseline and during intervention (nAne) in the control group (P=0.567). Consequently, the relative change from baseline to intervention was significantly higher (+48%) for the experimental group than for the control group (-4%) (P<0.001).

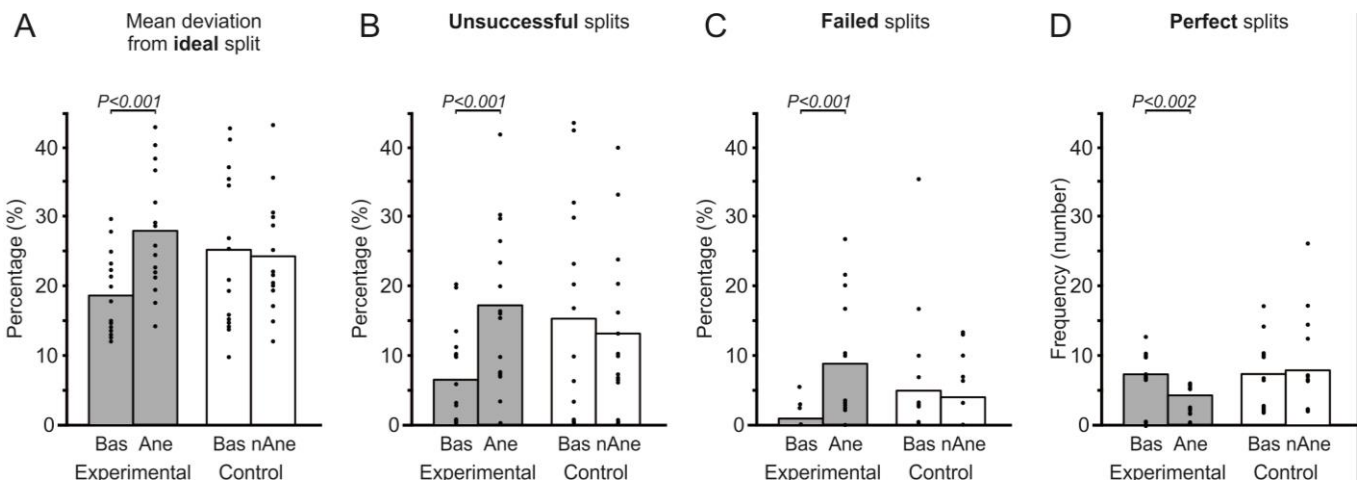

Fig. 6. A-D Effects of anesthetization on split performance (as assessed by deviation in from the "ideal" split) by participants of the Experimental and Control groups at baseline (Bas) and during the intervention (Ane and nAne, respectively). **(A)** Mean deviation from the "ideal" split. **(B)** Percentage of "unsuccessful" splits (i.e., with a deviation of >50% from the "ideal" split). **(C)** Percentage of "failed" splits (i.e., with a deviation of >75%). **(D)** Mean number of "perfect" splits (i.e., with a deviation of <5%). The height of each bar indicates the mean value for all of the subjects in each group and the filled circles show individual mean values.

It may also be noted that for the experimental group, the percentages of unsuccessful splits (P<0.001) (Fig. 6B) and of failed splits were significantly higher (P<0.001) (Fig. 6C) and the number (frequency) of perfect splits lower during the intervention than at baseline (P<0.002) (Fig. 6D) with no significant changes in the case of the control group (P=0.138, 0.244 and

0.342, respectively). Again, this pattern was reflected in the relative changes (P<0.001 in all three cases).

In addition, during the baseline trials, almost no slippage of candy (100% deviation from the ideal split) was observed in either the experimental or the control group. However, following anesthetization, nine of those in the experimental group exhibited at least one slippage versus none in the control group.

Duration and individual jaw movement phases

The total duration of the jaw movement phases (T0-T3) was not significantly changed due to anesthesia in the experimental group or during intervention in the control group (Bas: 1.53 s, Ane: 1.42 s; Bas: 0.95 s, nAne: 0.90 s, respectively) (P=0.357) (see Fig. 7A). In addition, when the jaw movements were divided into different phases it was observed that the contact phase was the longest and the duration of this phase showed as well no significant effect of condition (e.g., T2-T3; P=0.546; see Fig. 7D), as well significant difference between groups in the relative changes (P=0.384).

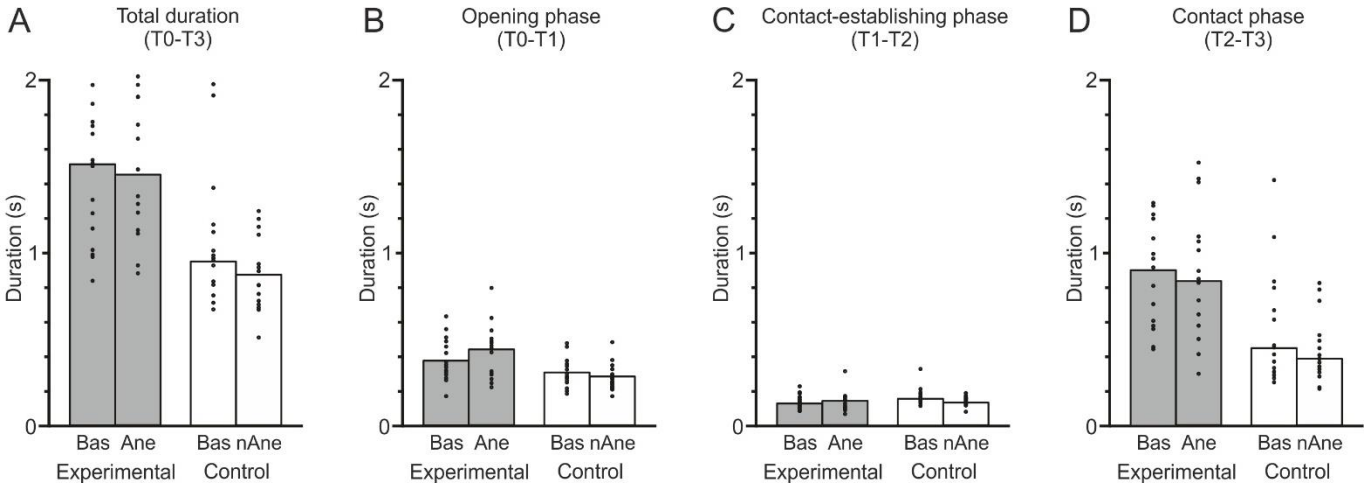

Fig. 7. A-D Duration of jaw movement phases of the participants in the *Experimental* (n=15) and *Control* (n=15) groups (at baseline (*Bas*) and during the intervention (Ane and nAne, respectively)). Total duration of the task (T0-T3) and durations of the opening (T0-T1), contact-establishing (T1-T2), and contact phases (T2-T3), are shown. The height of each bar indicates the median value for all the participants as a group, and the filled circles show the individual mean values.

4.3 Study III

Split performance

When split performance was evaluated by weighing the larger piece of candy produced by the split, we observed that the group with natural dentition (NAT) achieved a significantly lower mean deviation from ideal split compared to the groups with fixed tooth-supported prostheses

(TSP) and fixed implant-supported prostheses (ISP) (NAT: 14% (13-20) (median (25-75 percentile)); TSP: 30% (20-35) (P=0.005); and ISP: 28% (23-33) (P=0.034)) (Fig. 8A). Moreover, it should be noted that for the natural group, the percentages of unsuccessful splits (9% (0-16)) were significantly lower than for the TSP (30% (8-40)) and ISP (24% (14-33)) groups (P=0.002 and 0.015, respectively) (Fig. 8B). Similarly, the natural group exhibited no failed split (0%) compared to the TSP and ISP groups (18% and 8%, respectively) (Fig. 8C).

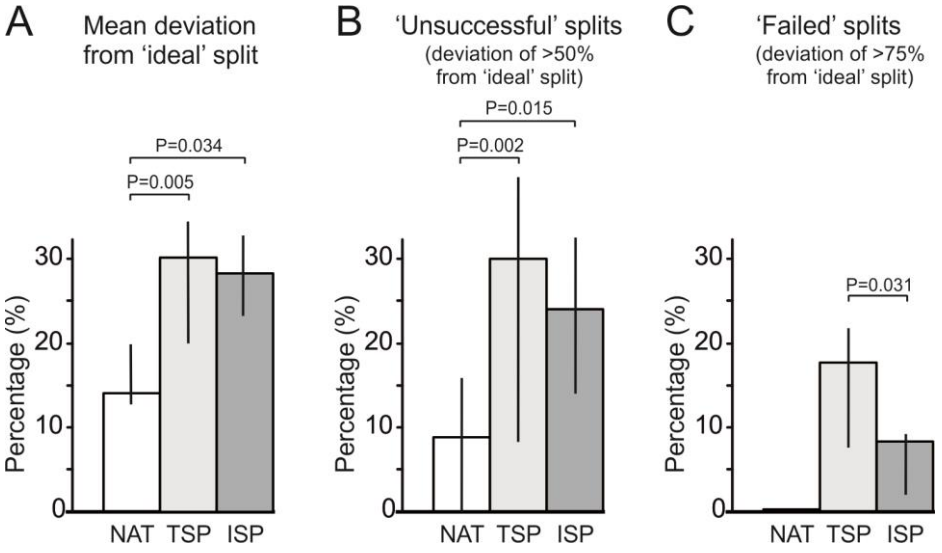

Fig. 8. A-C Split performance (assessed by deviation in from the "ideal" split) by participants in the NAT, TSP and ISP groups. The height of each bar indicates the median values for all subjects in a group and the vertical lines 25-75 percentiles.

In addition, the natural group had a slippage rate of 8% in all trials, compared to 9.2% and 12.4% for the TSP and ISP group, respectively. However, we observed that three subjects in the natural group, three in the TSP group and four in the ISP group exhibited no slips at all.

Duration and individual jaw movement phases

The total duration of the jaw movement phases (T0-T3) was significantly shorter for the TSP (1.16 s (0.33), P=0.053) and ISP (1.08 s (0.42), P=0.018) groups compared to the natural group (1.47 s (0.27)); however, there was no significant difference between TSP and ISP groups (P=0.617) (Fig. 9A). In addition, when the jaw movements were divided into different phases no significant difference was seen in the duration of jaw opening and contact-establishing phase between any of the groups (P=0.471 and P=0.629) (Fig. 9B-C). However, the duration of the contact phase (T2 to T3) was significantly shorter for the TSP (0.65 s (0.29)) and ISP (0.51 s (0.31)) groups compared with the natural group (0.89 s (0.22)) (Fig. 9D). Further analysis revealed that the natural and TSP groups differed in this respect by 0.24 s (P=0.063); the natural and ISP groups by 0.38 s (P=0.004); and the TSP and ISP groups by only 0.15 s (P=0.248).

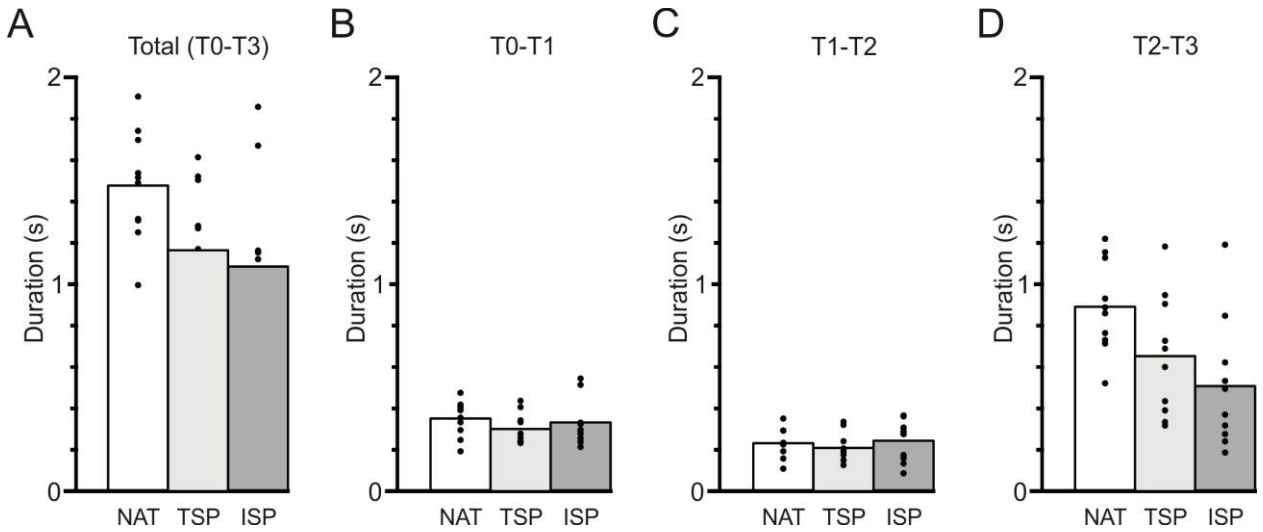

Fig. 9. A-D Duration of the jaw movements phases of the participants in the NAT, TSP and ISP groups during the manipulation and split task. **(A)** Total duration of the task (from start until fracture of the candy, T0-T3). **(B)** Duration of the opening phase (T0-T1). **(C)** Duration of contact-establishing phase (T1-T2). **(D)** Duration of the contact phase (T2-T3). The height of each bar indicates the mean values for all subjects in a group and the filled circles show mean values for individual participants.

4.4 Study IV

Split performance

In this study, the hazelnut slipped and did not fracture during the subject's first attempt to close the jaw, necessitating additional attempts to crush the nut. The subjects in the natural group (30%) exhibited fewer failed splits (in a total of five trials) compared to TSP (82%) and ISP group (70%) (P=0.006 and P=0.038, respectively).

Duration and individual jaw movement phases

The total duration of the jaw movement phases (M1-M4; see Fig. 4A for detail information regarding the individual phases) was significantly longer for the TSP group (0.57 s (0.39-0.74) (median (25-75 percentile), P=0.109) and the ISP group (0.58 s (0.39-0.92), P=0.017) compared to the natural group (0.44 s (0.34-0.58)). However, when viewed in relation to jaw movements and the average durations of different phases such as jaw opening (M1-M2) and the last jaw closing movement before fracture of the hazelnut (M3-M4) there were no significant differences between groups (NAT/TSP, P=0.469; NAT/ISP, P=0.343).

Mandibular movements

Visual analysis of the range of motion of the mandible during the first chewing cycle revealed a narrower pattern of movement for the TSP and ISP groups. In addition, the trajectory of the

mandibular movement was obviously more hesitant and probing for the TSP and ISP group compared the smooth jaw movements of natural group (see Fig. 10).

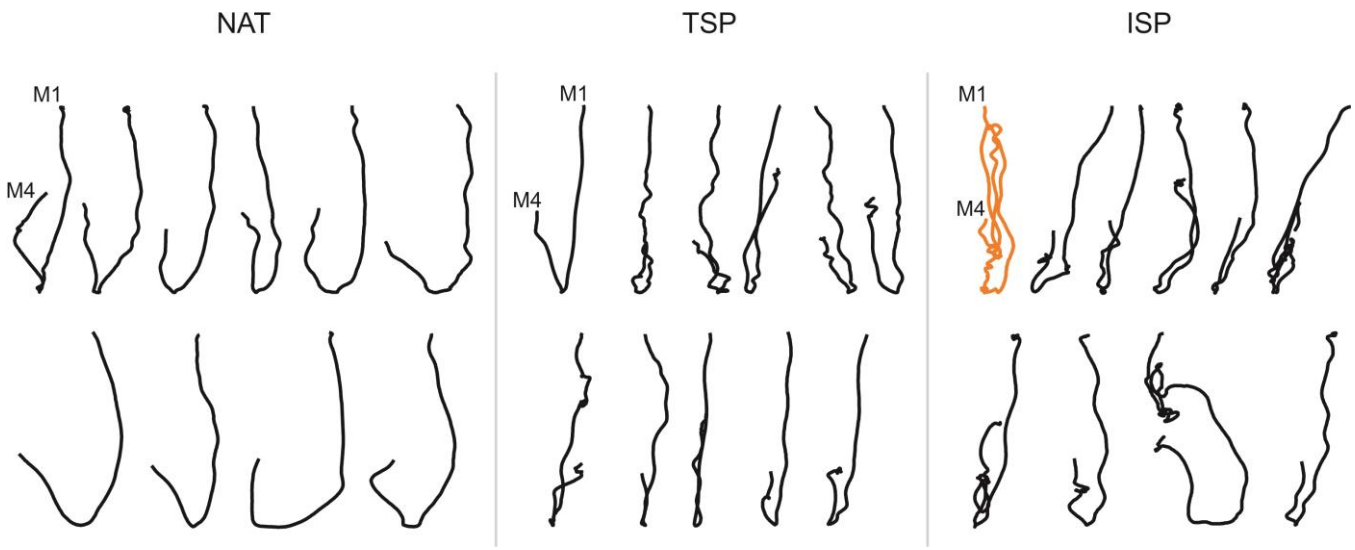

Fig. 10. The mandibular movements (plotted from a frontal view) from the start of jaw opening (M1) to fracture of the hazelnut (M4) during a representative "first chewing cycle" by each individual with natural dentition (NAT) or a fixed tooth- (TSP) or implant-supported prosthesis (ISP). All movements have been normalized in the vertical plane and some have been mirrored to facilitate comparison. The orange jaw movement recording at the top left in the ISP group originates from a subject whose hazelnut slipped, and who therefore required more than one attempt to crush the hazelnut. Note also the wider and smoother mandibular movement of the individuals in the natural group.

The observations above were quantified by plotting the mandibular movement (M1 to M4), closing the loop, and counting the number of pixels enclosed. Subjects in the natural group (94.8×10^3 (38.7×10^3)) (mean (SD)) clearly displayed a wider range of movement compared to the TSP (68.6×10^3 (44.8×10^3)) and ISP group (63.2×10^3 (25.3×10^3)) (P=0.049 and P=0.024, respectively) (Fig. 11A). Further, the natural group exhibited fewer passages (2.55 (2.25-3.15) (median (25-75 percentile))) than the TSP (4.0 (3.52-5.25), P=0.0004) and ISP group (3.6 (2.4-4.5), P=0.040) as shown by the number of times the value for acceleration of the vertical movement passed through zero in trials without slips (i.e., when M2=M3).

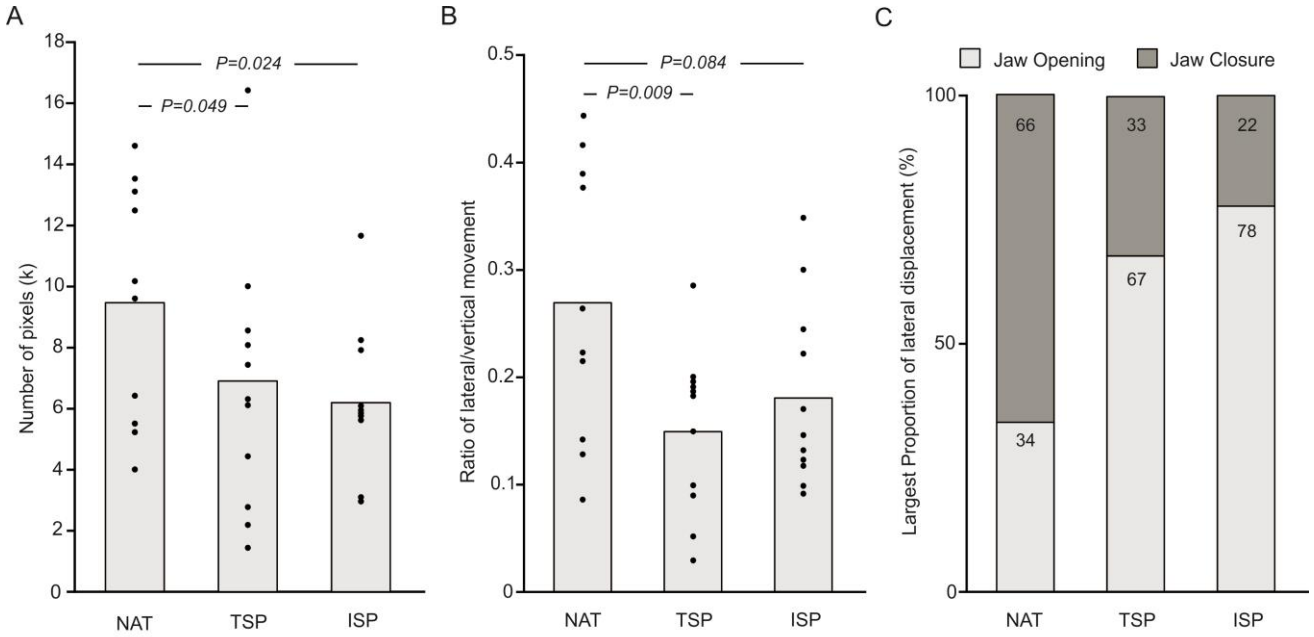

Fig. 11. (A) Total number of pixels in the figures created by plotting mandibular movement during the first chewing cycle. Filled circles represent mean values for individual participants, bars denote group means. **(B)** The ratio of lateral to vertical movement of the mandible (calculated as cycle width /cycle axis) during the first chewing cycle. Filled circles represents mean values for individual participants, bars denote group means. **(C)** Relative lateral mandibular displacement associated with jaw opening or closure during the first chewing cycle.

The ratio of lateral/vertical displacement (cycle width/cycle axis) was significantly higher for the natural group (0.27 (0.13)) (mean (SD)) compared to the TSP (0.15 (0.08)) and ISP group (0.19 (0.09)), P=0.009 and P=0.084 respectively (Fig. 11B). In addition, in the natural group, 66% of the maximum lateral displacement occurred during *jaw opening*, whereas maximum displacement occurred during *jaw closure* in the TSP (67%) and ISP (78%) groups (P=0.00002 and P=0.00001, respectively) (Fig. 11C).

5 DISCUSSION

The studies in this thesis emphasize the importance of orofacial motor skill acquisition and behavioral changes associated with short-term training and transient (local anesthesia), impaired (ISP) and complete (TSP) deprivation of sensory inputs from the PMRs. The results indicate that individuals can increase their motor performance through short-term training (Study I), and that performance is impaired by alteration or loss of sensory inputs from the PMRs during complex biting (Study II-III) and chewing tasks (Study IV). These findings may be important in improving our understanding of how humans learn orofacial motor tasks and in identifying specific sensorimotor impairments in patients rehabilitated with fixed prostheses supported by dental implants or natural teeth. The specific results obtained from the four studies included in the present thesis are discussed below.

5.1 Motor performance

This thesis showed that repeated splitting of food morsels during a short-term training resulted in increased accuracy of the task performance and decreased the occurrence of failed splits (Study I). However, transient deprivation of the sensory inputs from the PMRs due to local anesthesia decreased the accuracy of the task performance and increased the percentage of failed splits (Study II). Further, the accuracy was significantly lower in subjects with prostheses (i.e., the TSP and ISP groups) than in subjects with natural dentition (Study III). Subjects with prostheses also exhibited a higher number of slips in an attempt to crush a food morsel (hazelnut) than those with natural dentition (Study IV).

5.1.1 Improved performance due to short term training

It was previously reported that repeated splitting of food morsels during a simple “hold and split” task did not lead to optimization of jaw movements in participants with a natural dentition (Kumar et al., 2014). It was proposed that training-related optimization could perhaps be induced by challenging the system with a more complex task. Previously, it has been suggested that training-induced cortical plasticity would be dependent on the complexity of the task, training time and the muscle group being trained (Duchateau et al., 2006, Tyc and Boyadjian, 2006, Kothari et al., 2012). Hence, in the present thesis, a complex manipulation and split task was used to test the effects of short-term training on behavior learning and skill acquisition by participants with natural dentition.

The manipulation and split task is highly demanding, and requires precise sensorimotor control. Accordingly, repeated splitting of food morsels into two equal parts resulted in an

almost 50% increase in the accuracy of task performance after training (22% compared to 31% deviation before training) (Study I). Likewise, the participants exhibited significantly fewer slips after training, which would indicate improved spatial control (Study I). Presumably, due to training and the complexity of the task, the participants attained greater ability to place the spherical candy between the front teeth and fine-tune the direction of the bite force vector in order to split it into two almost equal parts. Additionally, by having an intact periodontium and therefore normal sensory signaling, the participants most probably gain vital spatial information from the PMRs resulting in enhanced motor skill performance (Trulsson et al., 1992, Johnsen and Trulsson, 2003).

5.1.2 Perturbed performance due to anesthesia

The masticatory system is heavily dependent on sensory information from various mechanoreceptors (PMRs included) around the oral cavity in order to adapt the motor output program during biting and chewing (Lund, 1991, Trulsson, 2006, Woda et al., 2006). During the work on this thesis, we demonstrated that maneuvering a light-weight spherical sugar-coated candy and splitting it into two equal halves was a useful tool for measuring oral fine motor control. Previous studies in dexterous manipulation tasks have emphasized the importance of the fingertips coming in contact with the objects at the same time as the fingertip force vectors are summed to zero. This would particularly be important during initial contact with light-weight objects that otherwise might slip out of the fingers (Burstedt et al., 1997, Flanagan et al., 1999, Reilmann et al., 2001). PMRs have previously been shown to play a pivotal role in controlling and directing the forces required to hold a food morsel; it has also been shown that periodontal anesthesia disrupts this control (Trulsson and Johansson, 1996a, 1996b). Hence, in study II we explored the impact of transient deprivation of sensory information from the PMRs due to anesthesia on spatial oral motor control in natural dentate subjects. As expected, anesthetizing the incisors significantly decreased the accuracy of the task performance by almost 30% (28% compared to 19% deviation from ideal split during baseline) in individuals in the experimental group. Furthermore, anesthetizing the teeth resulted in increased slippage of the candy as evident from the increased percentage of failed splits (1% before and 9% after anesthesia). These findings confirm previous reports that loss or reduction of input from the PMRs (due to local anesthesia of the upper and lower incisors) cannot be fully compensated by inputs from other orofacial mechanoreceptors (e.g., mechanoreceptors in the oral mucosa, muscle spindles or temporomandibular joint, etc.) (Trulsson and Johansson, 1996a, 1996b, Johnsen et al., 2007). Clearly, such a lack of peripheral afferent input to the CNS

attenuates fine motor control of the jaws, as also previously demonstrated in connection with a simple “hold and split” task (Trulsson and Johansson, 1996a, 1996b, Johnsen et al., 2007).

5.1.3 Altered performance due to dental prostheses

Previous studies have shown impaired oral motor control in subjects with dental prostheses during simple biting tasks (Trulsson and Gunne, 1998, Svensson and Trulsson, 2011). These studies demonstrate increase in the intensive aspect of force control during the simple hold and split task (higher hold forces compared with the natural dentate individuals). In the present thesis, we investigated the spatial aspect of oral motor control in subjects with dental prostheses (TSP and ISP) in comparison to individuals with normal intact periodontium (NAT). The subjects in the TSP and ISP groups exhibited a higher mean deviation from the ideal split (30% and 28%, respectively) compared to the individuals in the NAT group (14%) (Study III). Correspondingly, the percentages of failed splits were higher for the subjects in the TSP (18%) and ISP (8%) groups compared to those in the NAT (0%) group (Study III). Further, during the chewing task, the TSP (81%) and ISP (70%) groups had inferior spatial control as manifested in more frequent slippage compared to the individuals in the NAT group (30%) during the first attempt to crush the hazelnut (Study IV). The poorer biting performance demonstrated by these subjects (TSP and ISP groups) supports the importance of intact sensory information, signaled from the PMRs, regarding spatial location and direction of forces applied to the teeth for successful biting (Trulsson et al., 1992, Trulsson, 1993, Johnsen and Trulsson, 2003). The natural dentate subjects clearly demonstrated a superior ability to position the sugar-coated spherical candy between the central incisors and split it into equal parts (Study III) and to successfully fracture the hazelnut (Study IV). Even though subjects in the TSP group have some teeth with intact periodontium, the rigid nature of the coupling between the prostheses and the abutment teeth probably alters the pattern of PMR signaling and attenuates the possibility of determining the exact location of forces applied to the tooth. However, it is suggested that subjects in the ISP group, most likely due to lack of periodontium, rely on less competent sensory inputs from adjacent mechanoreceptors, even though these do not fully compensate for the absence of PMRs (Trulsson and Gunne, 1998, Svensson and Trulsson, 2011). It was also suggested that the impaired biting behavior exhibited by ISP and TSP groups is similar in some respects impairment seen in individuals with intact periodontium under acute periodontal anesthesia (Trulsson and Johansson, 1996b). Unimpaired sensory information from the PMRs has been proven to be important in several orofacial motor tasks (Johnsen et al., 2007, Grigoriadis et al., 2011, 2014, Kumar et al., 2016, Zhang et al., 2016). We suggest that the perturbed and altered oral motor performance exhibited by the anesthetized individuals in

the NAT group and individuals in the TSP and ISP groups in the present thesis reflects the importance of spatial information provided by the PMRs.

5.2 Duration of jaw movement phases

The behavioral task performed by the participants in the present thesis showed that independent of their condition (anesthetized or not) and their dental status (NAT, TSP or ISP), they could efficiently transport the light-weight spherical candy/hazelnut from the midsection of the palate to between the teeth in order to split it into two equal parts (Study I-III) or crush it (Study IV). The velocity with which the participants moved their mandible downwards and the jaw orientations at all predefined positions were more or less identical and did not differ in any of the groups across the studies (Study I-IV). However, there were interesting differences between the groups with respect to the time taken to complete the tasks (Study I-IV). When the jaw movements were divided into individual phases it was observed that the contact phase was the longest; this was also the phase when profound differences between groups could be seen (Study I-III). Further, we also observed some interesting differences between the groups in the attempts to crush a hazelnut during the chewing task (Study IV).

Accordingly, it was observed that repeated splitting of food morsels during the short-term training resulted in a shorter duration of the jaw movement phases, especially with respect to the contact phase, after training as compared to before training (Study I). However, transient deprivation of the sensory inputs due to local anesthesia did not affect the duration of the jaw movement phases or the contact phase (Study II). Further, the total duration for subjects in the TSP and ISP groups was significantly shorter than for those with natural dentition, whereas the contact phase - which was the longest jaw movement phase - was significantly shorter for subjects with prostheses than for those with natural dentition (Study III). The subjects in the TSP and ISP groups also exhibited a significantly longer total duration of the jaw movement phases compared to the individuals in the NAT group when attempting to crush the food morsel (hazelnut) (Study IV).

Like most manual dexterity tasks, the “manipulation and split” task studied in the present thesis involves a sequence of actions that rely on discrete signals from the peripheral receptors for successful task completion. The events of interest during the manipulation and split task used in the present thesis are the jaw opening phase, contact-establishing phase and the contact phase. Similarly, the events of interest for the chewing task are the jaw opening phase and the last jaw closing phase prior to split. These different action phases involve certain points of mechanical events (Study I-III: T1-T3; Study IV: M1-M4): these critical points may serve as sensorimotor control points defining the task sub-goals, similar to what has been shown in

previous dexterity studies (Johansson and Flanagan, 2009, Säfström et al., 2014). The participants started a cycle by moving their jaw downwards, and movement continued throughout the jaw opening phase, in order to accommodate the food morsel. During the next period (contact-establishing phase) the food morsel is transported with the help of the tongue and lips and placed in between the front teeth to obtain a stable clasp. During the last period (contact phase) the subjects probably collect vital information by maneuvering the food morsel prior to splitting (Study I-III).

As we expected, the natural dentate participants required 25% shorter time to complete the task after approximately half an hour of training (1.21 s) than before training (1.51 s) (Study I). Consequently, the duration of the contact phase also reduced by 28% after training (0.71 s) compared to before training (0.99 s) (Study I). Successful completion of the task sub-goals would not only be dependent on sensory information, but would also require successful execution of muscle commands in anticipation of an upcoming movement (Flanagan et al., 2003, Flanagan et al., 2006). The CNS predicts an outcome of the movement and identifies the commands required for optimal achievement of the task. Such predictions can be aided and refined by previous experience (learning) and may also aid in optimizing motor performance (Reilmann et al., 2001, Flanagan et al., 2003, Wolpert et al., 2011). The interpretation of our findings is that, prior to training, participants with a natural dentition take longer time to collect spatial information provided by the PMRs and other mechanoreceptors in the tongue and lips, during the contact phase. The CNS processes this information to parameterize the correct motor program and then sends efferent signals to activate the jaw closing muscles, moving the mandible upwards and with the right force-vector to split the food morsel without slipping. Further, as a result of short-term training, this efferent motor output program could be optimized, leading to a shorter duration of the contact phase, as seen in our findings. Indeed, as stated above, it has been suggested that skill learning in object manipulation tasks involves optimization and linking of action phases (Säfström et al., 2013). Hence, we believe that decrease in total duration of task after training (Study I) indicates optimization and linking of action phases relevant to the task: that training enabled the jaw muscles to achieve the desired outcome faster and perform the task more efficiently and skillfully.

Surprisingly, subjects with prostheses (TSP and ISP) take less time than individuals with natural dentition to split the food morsel (although they also exhibit poorer overall performance) (Study III). These findings suggest that perhaps these participants do not depend on sensory inputs from the PMRs and hence exhibit a shorter contact phase than those with natural dentition. Thus, it may be anticipated that deprivation of sensory inputs in natural

dentate subjects by anesthesia may significantly alter the total duration of the task and specifically affect the contact phase. However, the results of study II showed no significant effect of anesthesia on the total duration of the task (0.95 s before and 0.90 s after anesthesia for the experimental group) and the contact phase. These results reveal that transient deprivation of sensory inputs does not alter the duration of either the jaw movements or the contact phase, contrary to our hypothesis. The total duration of the overall task and of the individual phases of jaw movements did not differ between groups and conditions (anesthesia or control). However, it may be noted that these participants had been trained for about half an hour (Study I) prior to their participation in study II. Since the training improved task performance and optimized jaw movements, these individuals may have auto-regulated the motor commands which triggered the sequential events for optimized performance, despite the decreased sensory input due to sudden transient deprivation.

Our findings on oral motor control do not corroborate the reported observations on general motor control (Cole and Sedgwick, 1992, Hager-Ross and Johansson, 1996). Those studies showed that finger grip forces were reduced and automatic triggering of movements by other sensory inputs was lost (Cole and Sedgwick, 1992, Hager-Ross and Johansson, 1996). It has been proposed that in the absence of sensory inputs, greater mental attention is required to complete the specified task, thereby prolonging the duration of the task (Cole and Sedgwick, 1992). However, in the present study we did not observe any increase in task duration due to local anesthesia (Study II). We suggest that one inherent difference between the trigeminal and spinal systems is that visual feedback is available for motor tasks performed by the hands or digits, but not during oral tasks (van Steenberghe et al., 1991). Previous studies have emphasized the role of visual feedback in optimizing performance (Iida et al., 2013, Pavlova et al., 2015), e.g., anesthesia dramatically impairs digital motor control only in the absence of visual feedback (Jenmalm and Johansson, 1997, Jenmalm et al., 1999, Jenmalm et al., 2000, Pavlova et al., 2015). Accordingly, we suggest that the differences between our findings (Study II) and those of others may perhaps be attributed to inherent differences between the two motor systems involved. Further studies will be needed to investigate these differences.

In contrast to the findings in study I, subjects in the TSP and ISP groups in study III displayed a significantly shorter total duration of task performance (1.16 s and 1.08 s, respectively) during the manipulation and split task compared to those in the NAT group (1.47 s). Similarly, the contact phase for the subjects in the TSP (0.65 s) and ISP (0.51 s) groups were 24% and 41% shorter, respectively, compared to the duration for those in the NAT group (0.86 s) (Study III). It is suggested that during tooth-food contact, sensory information from

the PMRs is used in a predictive feed-forward manner to select appropriate pre-existing motor commands in order to split the food morsels effectively (Svensson and Trulsson, 2009, 2011). Therefore, when manipulating a spherical candy with natural front teeth, we assume that the natural dentate individuals subconsciously have a "prolonged" contact phase (in comparison with the subjects in the TSP and ISP groups) which allows them to collect necessary spatial information from the PMRs regarding the tooth-food contact (see Fig. 12). In line with our above-mentioned hypothesis, other studies have shown that prior to splitting a peanut with the front teeth, in almost 50% of the attempts, individuals with natural dentition briefly held the peanut (similar to our prolonged contact phase) with intentionally low forces, probably to collect sensory information from the PMRs (Trulsson and Johansson, 1996b). However, when their teeth were anesthetized, this brief delay could be seen in just 14% of the trials (Trulsson and Johansson, 1996b).

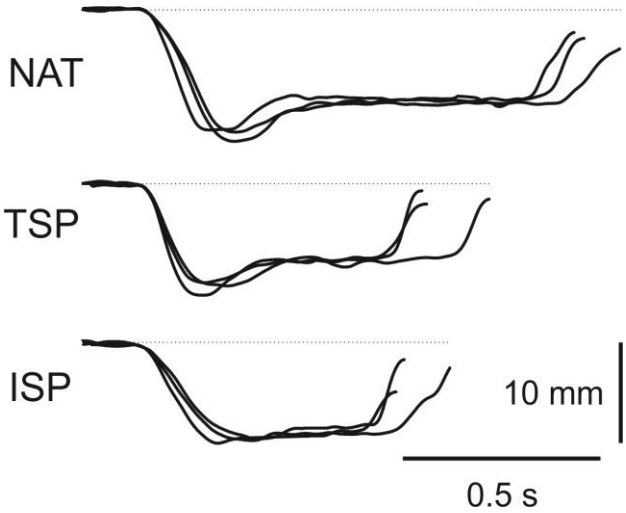

Fig. 12. Representative recordings of vertical jaw movement during performance of the manipulation and split task by subjects with a natural dentition (NAT) and fixed tooth- (TSP) or implant-supported prostheses (ISP). The lines depict three superimposed trials for each subject. Notice the shorter contact phase for the TSP and ISP groups in comparison with the subjects in the NAT group.

Experimental studies have previously shown that the lack of sensory information from the finger-object contact (due to anesthesia) delayed initiation of the appropriate motor commands, resulting in prolonged manipulation time during the task. Nevertheless, the individuals were able to perform the task, albeit with poorer performance (Johansson and Westling, 1984, Westling and Johansson, 1984). Findings in study III, in contrast to the studies by Johansson and Westling, revealed that the individuals in the TSP and ISP groups had a shorter contact phase, probably because they did not receive any additional sensory input by staying longer in that phase. Earlier it was suggested that in the TSP group, the PMRs might have received spatial information about initial contact despite the rigid coupling between the prostheses and the supporting intact teeth (Svensson and Trulsson, 2011). Subjects in the TSP group have an intact periodontium and the PMRs should still be able to transmit sensory information, although the results from the present thesis suggest that these subjects have reduced sensory input. Nonetheless, they are able to initiate the motor commands required to

split the morsel, probably with assistance from either the PMRs or other mechanoreceptors in the orofacial region. Individuals in the ISP group, who have osseointegrated implants in the jaw, lack intact periodontium and must therefore function without sensory information from the PMRs. Nevertheless, we believe that these subjects sense the initial tooth-food contact through vibrations transmitted via the jawbone to nearby receptors, the phenomenon of osseoperception, thus providing relevant information (Klineberg et al., 2005, Jacobs and Van Steenberghe, 2006, Van Steenberghe and Jacobs, 2006). Therefore, in the present study it is suggested that in the absence of sensory information from the PMRs, these subjects (TSP and ISP) tend to proceed directly from the contact phase without prolonging the duration of the task.

5.2.1 Regulation of the contact phase

A detailed observation of the vertical jaw movements during the contact phase reveals presence of oscillations representing the cyclic activation and deactivation of the jaw muscles with a specific frequency (Jaberzadeh et al., 2003a). This is probably because jaw muscles react to small motor commands (pulses), causing changes in force and direction which in turn activate PMRs to retrieve sensory information. We hypothesize that the most critical part of the contact phase is the first part when oscillations are present, which activate/deactivate the PMRs in a cyclic manner (Jaberzadeh et al., 2003b). When individuals with natural dentition are trained for half an hour during the manipulation and split task, the duration of the contact phase clearly decreases (0.71 s); a similar decrease is seen subjects in the TSP (0.65 s) and ISP (0.51 s) groups. However, although the performance of all individuals improves with training, the improvement is smaller among subjects in the TSP and ISP groups than in those with natural dentition. After training, one would probably need fewer oscillations in order to extract vital spatial information. The motor system is preprogrammed and adjusted and therefore probably recognizes the morsel earlier and can initiate the attempt to split it. Similar reasoning has been put forward in literature pertaining to urinary bladder control. These studies have suggested that the spontaneous phasic contractions of the bladder reflect local smooth muscle contractions observed both during increased bladder volume and during micturition contraction; during non-micturition, they are believed to contribute to sensations that signal bladder filling state (Gillespie et al., 2012, Vahabi and Drake, 2015).

5.2.2 Motor behavior during chewing task

When mandibular movements were plotted from a frontal view during a representative first chewing cycle of subjects attempting to crush a hazelnut, differences between the groups were clearly visible (see Fig. 10). One of the most obvious differences was that subjects in the TSP

and ISP groups had a narrower pattern of movement, and more hesitation and probing in comparison with those in the NAT group (Study IV). Conversely, the individuals with natural dentition clearly displayed a wider range of movement in the mandibular movement plots, with a significantly higher ratio of lateral displacement occurring during jaw closure, compared with subjects in the TSP and ISP groups (Study IV).

Motor behavior during the first chewing cycle, which is often disregarded in analyses of jaw kinematics during mastication, has been analyzed in detail (Study IV). When subjects were told to crush the hazelnut, they started by moving their jaw downwards, transported the hazelnut with help from the tongue and cheeks and positioned it between the upper and lower posterior teeth prior to crushing it. This chain of events was similar to that seen in the manipulation and split task. The total duration of the task was significantly longer among subjects in the TSP (0.57 s) and ISP (0.58 s) groups compared to those with natural dentition (0.44 s), due to more frequent slippage of the hazelnut (Study IV). The first chewing cycle of the subjects in the TSP and ISP groups also had a narrower, more chopping-like pattern as demonstrated by the mandibular movement plots enclosing 28% and 33% fewer pixels than those in the NAT group (Study IV). Further, the TSP and ISP groups also exhibited a smaller lateral displacement, where lateral movements were only 15% and 19%, respectively, of the vertical movement (Study IV). However, the subjects in the NAT group demonstrated a lateral movement (27% of the vertical movement) which was in agreement with the previous findings of approximately 20-30% during chewing (Pröschel and Hofmann, 1988, Shiga et al., 2003, Piancino et al., 2008). Subjects with fixed dental prostheses seem to have a different pattern of movement during the first bite, which cannot be entirely explained by the shorter dental arch in comparison with the natural dentate (Hashii et al., 2009). Subjects with removable dental prostheses have previously demonstrated, similar to our findings, more chopping-like mandibular movements during chewing (Tallgren et al., 1989, Postic et al., 1992). For fractionation of tough material, a wider lateral approach of the mandible during occlusal contact is suggested to be preferable for maximal chewing efficiency (Suit et al., 1976, Yamashita et al., 1999, Rilo et al., 2009). In line with results from previous studies, our findings show that the natural dentate individuals exhibited 66% of their largest lateral displacement during jaw closure compared to 33% in those in the TSP group and 22% in the ISP group. Probably the “safest” way of eating, for those who are unable to perceive sensory information from the PMRs, is by opening the jaw and transporting the food morsel to between the upper and lower teeth with help from the tongue and cheeks, securing the food morsel so it will not slip when the subject attempts to bite or crush it. The increased evidence of slippage, and the altered jaw movement pattern exhibited by these subjects is due to lack

of appropriate information from the PMRs. SA II mechanoreceptors found in the skin, PMRs included, have been proposed to be part of a general proprioceptive system that provides kinesthetic information to the CNS regarding the position of our body in space, but also to let us know or feel where our teeth are in relation to our body (Birznieks et al., 2009, Trulsson and Essick, 2010, Trulsson et al., 2010). In order for individuals in the TSP and ISP groups to bite or crush a food morsel they must first know where their teeth are. Therefore, on the basis on these findings, we believe that the lack of sensory information and of the reference point provided by the teeth leads to difficulties in achieving an efficient chewing stroke without slipping.

6 CRITICAL REMARKS

Methodological concerns are typically evident in clinical and experimental studies and must be acknowledged. One such concerns is in Study II, where baseline differences in split performance between the experimental and control groups were observed. However, previous studies have shown large variations in motor performance in the general population and therefore such intergroup differences may be attributable to individual factors (Kumar et al., 2015, Zhang et al., 2016). Further clarification of such inter-individual differences is required but in our study we circumvented the problem by evaluating the relative changes in performance in each individual.

Prior to start of the experiment we did not inspect our participants for obvious differences with respect to dental surface structure or if they had any teeth/prostheses with a large angulation (Study III). Previous studies have shown that the surface structure influences the friction between teeth/prostheses and objects, and that new porcelain prostheses (although having higher friction than acrylic) have a lower friction coefficient than enamel (Study IV) (Tillitson et al., 1971, Koran et al., 1972, Schuh et al., 2005). Nor did we calculate the posterior bucco-lingual width of the prostheses, even though we know from clinical experience that these are made narrower (reduced occlusal area) in order to minimize the force load acting on the abutment teeth/implant during biting or chewing (Study IV) (Becker and Kaldahl, 2005, Klineberg et al., 2007). However, we believe that differences of that kind are negligible and might not have affected our findings (Study III-IV).

7 SUMMARY OF MAJOR FINDINGS

Study I

In study I we observed that repeated splitting of food morsels during a short-term training resulted in an increase in the accuracy of the task performance and decrease in the occurrence of failed splits in natural dentate participants. Additionally, we observed that repeated splitting of food morsels resulted in a decreased total duration of the jaw movement phases, especially the contact phase. We believe that decrease in total duration of task after training indicates optimization in the linking of action phases relevant to the task, during which the motor programs related to the jaw movements were learned and the participants were able to achieve the functional goal of the behavioral task faster and more skillfully without slipping.

Study II

In study II we observed that transient deprivation of sensory inputs in individuals with natural dentition due to local anesthesia decreases the accuracy of the "hold and split" task performance and increases the percentage of failed splits. Similarly, transient deprivation also results in an increase in the percentage of unsuccessful splits and a decrease in the occurrence of perfect splits. However, transient deprivation of the sensory inputs does not affect the total duration of the task performance or of the contact phase. We suggest that the perturbed oral motor performance exhibited after anesthetization by those with a natural dentition reflects the importance of spatial information provided by the PMRs. It is apparent that lack of peripheral afferent input to the CNS attenuates fine motor control of the jaws.

Study III

In study III it was observed that the accuracy of "manipulation and split" task performance was significantly lower in subjects with TSP and ISP in comparison to those with natural dentition (see Fig. 13A). Additionally, the total duration (including the contact phase) of the task was significantly shorter in subjects with TSP and ISP than in those with natural dentition. Therefore, we assume that when individuals with natural dentition were manipulating a spherical candy, they subconsciously "prolonged" the contact phase (in comparison to the TSP and ISP groups) in order to collect the necessary spatial information from the PMRs regarding the tooth-food contact and therefore demonstrate both greater accuracy of task performance and longer total duration of the task.

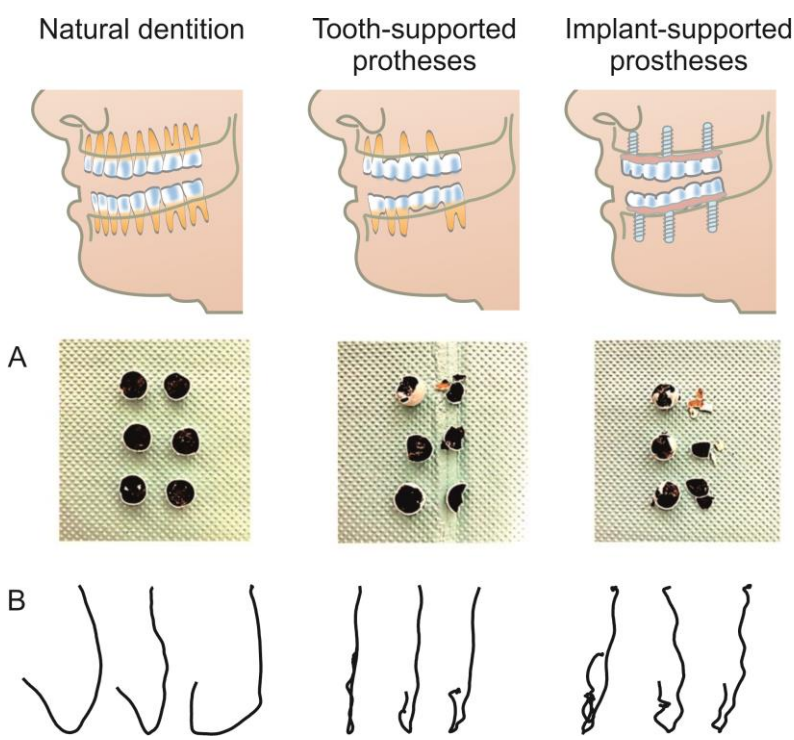

Fig. 13. Performance of the manipulation and split task (Study III) and mandibular movements (Study IV) performed by subjects in the NAT, TSP and ISP groups. **(A)** The outcome of three manipulation and split attempts and their outcome by one individual from each group. **(B)** The mandibular movements (plotted from a frontal view) from the start of jaw opening (M1) to fracture of the hazelnut (M4) during a representative "first chewing cycle" from 3 different individuals in each group (A-B: Modified with permission (Svensson and Trulsson, 2016)).

Study IV

In study IV, we observed that subjects with fixed tooth- or implant-supported prostheses exhibited a larger number of slips in an attempt to crush the food morsel (hazelnut) than the natural dentate group. Subjects in the TSP and ISP groups also exhibited a significantly longer total duration of the task, with narrower and more probing jaw movements compared to the individuals in the NAT group (Fig. 13B). On the basis on these findings we believe that a lack of sensory information and decreased spatial control by the teeth leads to difficulties in achieving an efficient chewing stroke without slipping.

8 CLINICAL RELEVANCE AND FUTURE PERSPECTIVES

The findings from the present thesis emphasize the importance of the sensory information provided by the PMRs with respect to spatial and temporal control during food positioning for biting. Lack of peripheral afferent input to the CNS attenuates fine motor control of the jaws. In the clinic, different prosthetic rehabilitation procedures generally aim at restoring normal occlusion and lost anatomical structures. Subjects with tooth- or implant-supported prostheses have, during different behavioral tasks, exhibited poorer performance and impaired motor behavior. Although subjects with fixed tooth-supported prostheses have intact periodontium, the rigid coupling of the teeth inhibits the mobility of individual teeth, resulting in an altered and decreased motor performance. Therefore, we propose that whenever possible, connecting teeth in rigid constructions should be avoided and, instead, missing teeth should perhaps be replaced with implants.

Some preliminary findings resulted from subjective comments from the subjects with dental prostheses who participated in these studies revealed that most subjects in the TSP group did not feel that their teeth belonged to their body. Conversely, almost all of the subjects in the ISP and NAT groups strongly associated their prostheses with their own body. However, all participants, regardless of group, were more or less equally satisfied with their teeth/prostheses. It has been suggested that the individuals with ISP rely on the sensory information provided by the vibrations transmitted from the implant to the adjoining alveolar bone - a phenomenon known as osseoperception (Klineberg et al., 2005). Although the subjects in the TSP group were very satisfied with their prostheses, the rigid constructions uniting their natural teeth and the prosthesis may dampen the effect of these vibrations and provide a “cushioning” experience which makes the subjects feel that their teeth are not part of their body. However, most individuals in the ISP group have gone from being edentulous, probably using a removable prostheses with poor retention, to using a substantially better prosthesis that is mechanically secured. Future studies are also needed in order to understand why some perceive their teeth as belonging to them more than others do.

Sensorimotor relearning is important in neurorehabilitation; it involves improvement, through practice, in the performance of sensory-guided motor behaviors (Krakauer and Mazzoni, 2011, Wolpert et al., 2011). We and others have observed training-induced learning of oral motor skills in healthy individuals with natural dentition. Therefore, future studies should analyze how rehabilitation influences the sensorimotor mechanisms, relearning and adaptation of motor function after alterations of the oral environment. We aim to improve masticatory performance and sensorimotor functions in various groups of patients whose

sensory input is perturbed with the goal to increase their quality of life. We should also consider that the current treatment evaluation is to some extent subjective and relies on experience of the clinicians, because of a lack of objective indicators. Hence, our long-term goal is also to develop clinical indicators of optimum rehabilitation and improve the oral motor skills of patients through different treatment rehabilitation protocols.

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