University of Alberta

Physiological and Functional Outcomes in Patients with Facial Paralysis Following Facial Reanimation Surgery

by

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ABSTRACT

One treatment for chronic facial paralysis is facial reanimation surgery which restores the ability to smile in this population. This descriptive study objectively evaluated outcomes in six subjects following surgery. Several procedures were used for this evaluation. These included an oral mechanism exam, non-standardized articulation and intelligibility tests, a clinical mastication and swallowing exam, 2D kinematic analysis, EMG recordings, and EMG cross correlations. Results indicate that nerve regeneration and functional recovery of the transferred muscle had occurred. Although lip excursion on the repaired side improved following surgery, it usually did not equal that of the unaffected side. Mild problems with articulation and mastication were present following surgery; however, patients still managed to be heard and understood by unfamiliar listeners and swallowing was completely functional. Lastly, the data from this study imply that different cortical control mechanisms may be recruited for the production of individual speech tokens versus running speech.

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INTRODUCTION

Facial paralysis accompanies many diseases, syndromes, and injuries including Bell's palsy, otitis media, Mobius syndrome and traumatic brain injury. Because the facial nerve is damaged, people with facial paralysis lose normal facial expression ability. One treatment for permanent facial paralysis is facial reanimation surgery, where there is a microneurovascular transfer of the gracilis muscle from the leg to the face. The goal of surgery is to create a simulated smile and to increase oro-motor competence and coordination for function. The purpose of the current study was to compile a comprehensive evaluation of outcomes following facial reanimation surgery. Before a detailed description of the purpose and methods of this study is presented, a review of the physical and social characteristics of individuals with facial paralysis will be summarized. This will be followed by a discussion of the surgical techniques presently available for facial reanimation. The review will conclude with results of functional outcomes that have been measured in a variety of ways and reported on in the existing body of literature on this topic.

Characteristics of Those with Facial Paralysis

Facial paralysis occurs following temporary or permanent damage to the facial nerve. Subsequent loss of the voluntary action of the muscles of facial expression results in facial laxity or droopiness and a mask-like expression. There is an inability to convey emotions such as anger, delight, and sorrow as the patient with facial paralysis is unable to frown, smile or move their eyebrows.

The level of severity depends on the amount of damage to the facial nerve. Paralysis can be isolated to some regions of the face, as in unilateral facial paralysis, or paralysis can be very extensive, as in bilateral or complete facial paralysis (Dawidjan, 2001).

Lack of facial animation or emotional expression is one of the most debilitating features of facial paralysis because it negatively affects nonverbal communication. A lack of reanimation can lead to social perceptions that affected individuals are dull (Goldburg, DeLorie, Zuker, Manktelow, 2003), hostile (Bradbury, Simons & Sanders, 2006), dishonest, unfriendly or uncooperative (Dawidjan, 2001). Because people with facial paralysis have expressionless faces, as well as difficulties with speech and oral competence (i.e., drooling), they are often judged to be mentally handicapped (Meyerson & Foushee, 1978). For instance, studies often report that the incidence of mental retardation in those with Mobius syndrome is quite high even though IQ is often not assessed formally in these studies (Verzijl, van der Zwaag, Cruysberg, & Padberg (2003). In general, these perceptions may lead to altered social interactions (Bradbury, Simons, & Sanders, 2006), employment limitations, and low self esteem (Hirschenfang, Goldberg, & Benton, 1969; Neely & Neufeld, 1996). As a consequence, people with facial paralysis may become withdrawn and introverted (Gillberg, 1992; Gillberg & Winnergard, 1984).

Children and adults with facial paralysis also have a variety of physical and functional problems. Oral incompetence often leads to problems in chewing, drinking, and swallowing. For example, in congenital facial paralysis such as

Mobius syndrome, early feeding problems are often evident; breast feeding is often difficult because a tight lip seal around the nipple can not be achieved (Kahane, 1979; Meyerson & Foushee, 1978). Adults with facial paralysis also can have difficulties eating and drinking. Because the orbicularis oris cannot securely close the mouth, food, liquid and saliva may escape. Furthermore, those with facial paralysis may not be able to enclose a cup or spoon with their lips. Food also may collect in the cheeks as the buccinator cannot contract to keep food out of the buccal sulci. To offset feeding and drinking difficulties, many people with facial paralysis use compensatory strategies such as head posture, cup/spoon placement, chewing on the non-affected side (unilateral cases), and a slower rate of eating and drinking (de Swart, Verheij, and Beurskens, 2003).

People with facial paralysis may have problems with both oral and pharyngeal phases of swallowing (de Swart, Verheij, and Beurskens, 2003; Secil, Aydogdu, & Ertekin, 2002; Sjogreen, Andersson-Norinder, & Jacobsson, 2001). For instance, trapped residue may unpredictably escape into the pharyngeal cavity and a second swallow may occur (Secil, Aydogdu, & Ertekin, 2002). This may be unexpected to those with facial paralysis and coughing, laryngeal penetration and aspiration may result. Swallowing difficulties also may be due to reduced taste sensation, reduced salivary secretion, or reduced sensation in the face and mouth (Secil, Aydogdu, & Ertekin, 2002).

The facial nerve also innervates many of the muscles for articulation. Because the strength and range of the articulators is limited, the speech of those with facial paralysis is often characterized by flaccid dysarthria (Goldberg, DeLorie, Zuker, Manktelow, 2003; Meyerson & Foushee, 1978). For example, oral incompetence affects the production of labial sounds (m, b, p, w, v, and f), resulting in frequent substitutions, distortion or omissions of these sounds (Goldberg, DeLorie, Zuker, Manktelow, 2003; Sjogreen, Andersson-Norinder, & Jacobsson, 2001). Other sound production errors include t, d, n, s, sh (Goldberg, DeLorie, Zuker, Manktelow, 2003). Very often, individuals compensate for these problem sounds by placing their tongue and teeth in alternative positions to approximate the sound. For instance, bilabial sounds may be produced by placing the tongue behind, against or between the front teeth (Meyerson & Foushee, 1978; Sjogreen, Andersson-Norinder, & Jacobsson, 2001) instead of by approximating the upper and lower lips.

Because children and adults with facial paralysis suffer from a variety of emotional, physical and functional problems, interventions are routinely sought. Often, surgical management is chosen in an effort to improve function, aesthetics and quality of life.

Surgical Management for Those with Facial Paralysis

Over the past 30 years a number of different techniques have been developed for the surgical management of facial paralysis. These techniques range from simple static procedures to complex dynamic surgeries. Static procedures may be used to add support and symmetry to the face. These include, but are not limited to, gold weight lid loading, face lifts, blepharoplasty (eyelid surgery), and nasal lateralization (Aviv & Urken, 1992). These procedures will not provide movement of the facial muscles and in cases where facial reanimation is the desired outcome, dynamic procedures must be sought. When there has been no atrophy of the facial muscles (i.e. for less than year), direct repair of the facial nerve is ideal for dynamic reconstruction (Rosenwasser, Liebman, Jimenez, Buchheit, Andrews, 1991). However, it is not always the case that the facial nerve can be directly repaired and an autogenous nerve graft or transposition becomes necessary to restore function. If both ends of the nerve are accessible, an interpositional nerve graft using the sural nerve from the ankle is commonly employed. If the proximal facial nerve has been damaged beyond repair, but the distal end is still viable, then an autogeneous nerve transposition to the distal end is used. In these cases, the hypoglossal, trigeminal, or spinal accessory nerve may be used (Aronsen, Buchert, & Cummings, 1986; Conley & Gullane, 1978; Poe, Scher, & Panje, 1989; Rosenwassser, et al., 1991).

In cases where the facial paralysis is long standing or congenital, the motor end plates of the facial muscles will have degenerated and atrophy will occur (O'Brien, Franklin, Morrison, 1980). Furthermore, chronic denervation of the injured neuron and Schwann cells results in a reduced number of motorneurons that regenerate their axons (Gordon, Olawale, & Boyd, 2003). In these cases, the static and dynamic procedures described above will not be sufficient to reanimate the face. Instead, a microneurovascular muscle transfer is used. The goal of surgery is to create animation (e.g., smile) using a new motor system and to increase oro-motor competence and coordination for function (e.g., speech, drinking, mastication). Several surgical procedures are described in the literature and include the use of several different donor nerves and muscles.

Ideally, the contralateral facial nerve is used to reinnervate the paralyzed side of the face using a cross-facial nerve graft. Typically, this is a two-stage method of facial reanimation. In the first of two surgeries, an interpositional nerve graft is harvested and is subsequently sutured to the donor facial nerve of the normal hemiface. Afterward, the graft is directed over the upper lip to the paralyzed cheek. Once nerve regeneration has started, several different muscles (see below) may be used for a free microneurovascular muscle transplant. This surgery occurs approximately one year after the first was performed (Terzis & Noah, 2003).

When this nerve is not viable, other donor nerves must be utilized. The most common donor nerves are the hypoglossal, masseter, and accessory nerve (Atlas & Lowinger, 1997; Terzis & Noah, 2003; Zuker, Goldburg & Manktelow, 2000). Donor nerves are often chosen based on nerve integrity and availability. The accessory nerve is often not utilized because of its anatomical distance from the face. Moreover the actions of the sternocleidomastoid and trapezius are not compatible with movements associated with smiling (Lifchez, Matloub, Gosain, 2005; Zuker, Goldberg, Manktelow, 2000). The hypoglossal nerve is often cited as the most frequently utilized donor nerve (Lifchez, Matloub, Gosain, 2005). Although surgeons have reported encouraging outcomes using this nerve (Zuker & Manktelow, 1989), there is some evidence that the classic hypoglossal nerve procedure results in functional deficits of the tongue (Atlas & Lowinger, 1997; Hammerschlag, 1999). Several techniques have been employed to reduce these complications (Atlas & Lowinger, 1997; May, Sobol, Mester, 1991).

The use of the trigeminal nerve has been criticized because patients may not be able to smile independent of jaw movement and its use may downgrade other oral functions (Terzis & Noah, 2003). However, it is considered a viable donor option with some promising results (Lifchez, Matloub, & Gosain, 2005; Zuker, Goldburg, & Manktelow, 2000). The facial reanimation surgery which utilizes the nerve to masseter is a one stage procedure; however, if the paralysis is bilateral, each side of the face is completed separately with a period of four to seven months between surgeries (Lifchez, Matloub, & Gosain, 2005; Zuker, Goldberg, Manktelow, 2000; Zuker & Manktelow, 1999).

As is the case with the nerves that are used for facial reanimation, many different muscle donor sites have been described in the literature. The muscles most frequently selected for the muscle transfer are the gracilis, latissimus dorsi, pectoralis minor, rectus abdominus and the serratus anterior (Dellon & Mackinnon, 1985; Hata, Yano, Matsuka, Ito, Matsuda, & Hosokawa, 1990; Terzis, 1989; Whitney, Buncke, Alpert, Buncke, & Lineawerver, 1990; Zuker, Goldburg, & Manktelow, 2000). There is still considerable debate about which muscle is the best candidate for transfer to the face. Surgeons often recommend the muscle for which they have had the most experience (Bove, Chiarini, D'Andrea, Di Matteo, Lanzi, De Antoni, 1998). In general, the muscle should have: (a) a reliable vascular and nerve anatomy, (b) should induce minimal damage to the donor site, (c) should be easy to remove from the donor site, (d) should have a reliable vascular pedicle of sufficient length, (e) should have minimal bulk but ample muscle volume to allow satisfactory excursion of the face, (f) should have enough length to fit between the corner of the mouth and the zygomatic arch, and (g) should have the capability for good range of motion (Ashayeri & Karimi, 2002; Aviv & Urken, 1992). The gracilis has often been the muscle of choice as it consistently provides adequate lip elevation, has reliable vascular and nerve anatomy, is easy to dissect, and the dissection produces little donor site damage (Eppley & Zuker, 2002).

Studies have found that cross-facial nerve grafts do begin to regenerate axons which reinnervate the transferred muscle (Frey, Happak, Werner, Bittner, & Gruber, 1991; Yla-kotola, Kauhanen, Asko-Seljavaara, Haglund, Tukiainen, & Leivo, in press). Yla-kotola et al. (in press) used biopsies of transferred gracilis muscles and cross facial nerve grafts to evaluate peripheral nerve regeneration directly. Although they found viable regenerated nerve fibres at the distal end of the nerve graft to be approximately 40% of those that were found in control subjects, this did not correlate with functional outcome. They did find that the regenerated axons were thinner than that of controls and that fibrosis and invasion of inflammatory cells were present between axons.

Although axonal regeneration in humans has been reported as 1 mm/day (Fagan, 1989; Gordon, Olawale, & Boyd, 2003), muscle regeneration and activation following facial reanimation surgery is variable. While regeneration potentials can be detected by EMG about a month before the first movements are seen (Guntinas-Lichius, Streppel, & Stennert, 2006), those who have undergone facial reanimation surgery have reported that the first muscle contractions begin 6 – 48 weeks post operatively (Terzis and Noah, 1997). This variability in time course may be the result of several factors. For instance, regenerating axons may not take an efficient path across the suture site (Gordon, Olawale, & Boyd, 2003) or expression of certain neurotrophic factors/receptors may be low (Yla-kotola, Kauhanen, Asko-Seljavaara, Haglund, Tukiainen, & Leivo, in press). These factors also may contribute to poor axonal regeneration and functional recovery.

Outcomes Following Surgery

Overall Functional and Aesthetic Results

The value of evaluating outcomes following surgery can not be overemphasized. Numerous studies have measured outcomes following surgery and have shown significant improvement in function and aesthetics. For instance, upon clinical examination, voluntary facial movement is visually apparent following surgery (Atlas & Lowinger, 1997; Schliephake, Schmelziesen, Troger, 2000; Wang, Qi, Lin, Hu, Dong, Zhou, & Dai, 2002) and facial tone and symmetry are re-established (Atlas & Lowinger, 1997). Although many studies have tried to correlate demographic variables such as age, sex, and etiology with outcome, results have been inconclusive (O'Brien, Pederson, Khazanchi, Morrison, MacLeod, & Kumar, 1990; Terzis & Noah, 1997; Yla-Kotola, Kauhanen, & Asko-Seljavaara, 2004); however, it has been shown that those with incomplete paralysis obtain better functional results than those with complete paralysis (O'Brien, Pederson, Khazanchi, Morrison, MacLeod, & Kumar, 1990).

Patients typically report satisfaction regarding functional and aesthetic outcomes following surgery. Based on patient interviews and questionnaires, patients rate their results as excellent or good (O'Brien, Pederson, Khazanchi, Morrison, MacLeod, & Kumar, 1990), feel the surgery was worthwhile and report improved appearance and self esteem (O'Brien, Pederson, Khazanchi, Morrison, MacLeod, & Kumar, 1990; Yla-Kotola, Kauhanen, & Asko-Seljavaara, 2004; Zuker, Goldberg, Manktelow, 2000). Their quality of life and social and health-related well being also has been reported to improve following surgery (Ferreira & Marques de Faria, 2002; Schliephake, Schmelziesen, Troger, 2000; Yla-Kotola, Kauhanen, & Asko-Seljavaara, 2004).

Overall functional and aesthetic results often have been evaluated based on subjective rating or scoring systems. The most widely used measurement system is the *House-Brackmann Facial Nerve Grading System* (House & Brackmann, 1985) which was accepted as the universal standard by the American Academy of Otolaryngology-Head and Neck Surgery in 1984 (Kang, Vrabec, Giddings, & Terris, 2002). This scale is designed to assess global facial nerve function; it assigns the patient a grade from I (normal) to VI (no movement) based on symmetry, weakness, eye closure, and synkinesis (House & Brackmann, 1985). Most studies have found that patients obtain a House-Brackmann grade of III or IV following surgery (Darrouzet, Guerin, & Bebear, 1999; Hammerschlag, 1999; Magliulo, D'Amico, & Forion, 2001; Manni, Beurskens, van de Velde, & Stokroos, 2001; Yla-kotola, Kauhanen, & Asko-Seljavaara, 2004).

Although this scale is widely used, it has been criticized because it is a gross motor scale; it does not consider fine motor movements and is vague in regards to secondary facial deficits (Kang, Vrabec, Giddings, & Terris, 2002). As such, many researchers have developed their own Likert-type rating scales designed to assess specific outcomes (e.g., smaller movements such as spontaneous and posed smiling, muscle bulk, synkinesis). In general, ratings from these scales indicate that outcomes based on these traits are moderately good to excellent following surgery (Ferreira & Marques de Faria, 2002; O'Brien, Pederson, Khazanchi, Morrison, MacLeod, & Kumar, 1990; Terzis and Noah, 1997). Although these scales measure specific outcomes, they are still subjective in nature and none have become widely used.

Although these clinical studies have shown that overall functional and aesthetic outcomes following surgery are promising, they are all subjective in nature and may not give a complete picture of outcomes following facial reanimation. To thoroughly describe clinical and physiological outcomes following surgery, many studies have begun to look at post-operative results using objective measures.

Mastication, Swallowing, and Speech

Recently, researchers have begun to assess oral competence, mastication and speech following surgery. Several studies have reported that patients often describe improved post-operative oral competence. Specifically, these patients report less drooling, an increased ability to contain liquids while drinking (Goldberg, DeLorie, Zuker, & Manktelow, 2003), and an improved ability to eat (O'Brien, Pederson, Khazanchi, Morrison, MacLeod, & Kumar, 1990). To the best of my knowledge, no investigation has formally evaluated mastication and swallowing following facial reanimation surgery.

Based on formal assessment of speech following facial reanimation surgery, studies have shown that articulation problems resulting from bilabial insufficiency resolve or improve following surgery in many patients (Goldberg, DeLorie, Zuker, & Manktelow, 2003; Zuker, Goldburg, & Manktelow, 2000). Patients and their families often report that intelligibility improves following surgery. This observation has been confirmed when formally assessed by an unblinded observer (Goldberg, DeLorie, Zuker, & Manktelow, 2003).

Movement

The main goal of facial reanimation surgery is to increase movement on the paralyzed side of the face. Several researchers have begun to assess facial movement in those with facial paralysis using more objective measurement systems. The simplest measurement systems of this kind involve the direct measurement of movement on the skin of the patient using a simple ruler (Paletz, Manktelow, Chaban, 1994) or a hand held caliper (Burres, 1985; Frey, Jenny, Giovanoli, & Stussi, 1994). Studies that have used this method to measure facial movement following facial animation have found that commissure excursion and symmetry during smiling improve following surgery (Erni, Lieger, & Banic, 1999; Yong-Chan, Zuker, Manktelow, & Wade, 2006; Zuker, Goldberg, & Manktelow, 2000). In a study conducted by Erni, Lieger, and Banic (1999), range of movement of the oral commissure on smiling was on average 3.6 – 5.5 mm, approximately 14 – 71% of those excursions seen on the non-affected side.

Some researchers (Zuker, Goldberg, & Manktelow, 2000) have reported excursions on the surgically-repaired side to be anywhere from 10 mm to 3.7 cm, with most having movements in the 10 - 15 mm range.

Recently, several promising computer programs have been created to assess facial movement using pictures or video recordings. Some of these systems assess the movement of regional surfaces of the face by measuring differences in luminance or light reflectance between images of the face at rest and during movement (Meier-Gallati, Scriba, & Fisch, 1998; Scriba, Stoeckli, Veraguth, Pollak, & Fisch 1999), pixel subtraction (Neely, Cheung, Wood, Byers, & Rogerson, 1992), and moire topography which uses optical strips to produce a facial contour map that measures facial movement in three dimensions (Yuen, Inokuchi, Maeta, Kawakami, & Masuda, 1997). Other measurement systems use computer software to measure specific facial points during one or more of the following: maximal eyebrow lifting, closing of the eyes, maximal showing of the teeth, smiling with showing the teeth, smiling with closed lips, pursing the lips, pulling the corners of the lips downwards, and clenching the teeth (Frey, Jenny, Giovanoli, Stussi, 1994; Johnson, Brown, Kuzon, Balliet, Garrison & Campbell, 1994; Linstrom, 2002; Linstrom, Silverman, & Susman, 2000; Sargent, Fadhli, & Cohen, 1998; Tomat & Manktelow, 2005; Watchman, Cohn, VanSwearingen, & Manders, 2001). Although there is a plethora of quantitative measurement systems, each has its own limitations and none has become widely accepted.

Several studies have used computer programs to assess facial movement following facial reanimation surgery. For instance, Johnson, Bajaj-

Luthra, Llull, and Johnson (1997) used a system called the Maximum Static Response Assay to assess the direction and magnitude of selected facial points using digitized photographs. It was determined that following surgery, the direction and magnitude of the vector on the paralyzed subject's face became similar to that of the non paralyzed side and also was similar to that of controls. Prior to surgery, the muscles on the non paralyzed side of the face pulled on the muscles of the paretic side. As a result, the paretic side of the face was in a non anatomical, asymmetrical position. Following surgery, the muscles on the paralyzed side of the face could withstand the forces of the muscles on the non paralyzed side. Schliephake, Schmelziesen, and Troger (2000) used a measurement system similar to that of Johnson et al. and determined that on average, the surgically-repaired side of the face moved approximately 63.7% of the non-paralyzed side in the vertical direction and 65.5% of the non-paralyzed side in the horizontal direction.

Researchers have published results which indicate that many of these facial movement systems are reliable (Frey, Giovanoli, Gerber, Slameczka, & Stussi, 1999; Ghoddousi, Edler, Haers, Wertheim, & Greenhill, 2007; Hontanilla & Auba, 2008; Tomat, & Manktelow, 2005; Wachtman, Cohn, VanSwearingen, Manders, 2001) and it appears that they are sensitive enough to pick up even small changes in movement.

Muscle Activation Using Electromyography

In order to get an overall view of facial motor function it also is necessary to objectively assess peripheral changes in muscle activation using electromyography (EMG). Several researchers have combined EMG findings (i.e., general statements such 'EMG demonstrating high amplitudes' or 'low action potentials in the EMG') and clinical outcomes such as symmetry, tone and naturalness of facial expression to create Likert-type rating scales that assess function (Harii, Asato, Yoshimura, Sugawara, Nakatsuka, & Ueda, 1998; Schliephake, Schmelziesen, & Troger, 2000; Takushima, Harii, Asato, Ueda, & Yamada, 2004). Other researchers have conducted studies that focus on detailed changes in muscle activation following surgery. These studies have shown that there are a considerable number of voluntarily activated motor units which may indicate that the transferred muscle has obtained good functional recovery (Sassoon, Poole, & Rushworth, 1991; Schliephake, Schmelziesen & Troger, 2000; Terzis & Noah, 1997; Ueda, Harii, Yamada, 1995).

For instance, Ueda, Harri, and Yamada (1995) used concentric needle electrodes to assess the functional recovery of the gracilis muscle following facial reanimation surgery. In the long term, it was found that spontaneous action potentials decreased, amplitude increased, and duration of the action potential and distal latency first increased and then decreased over time. Results from this study indicate that the number of regenerated muscle fibres and synchronization of these fibres increases over time. Although these results were not correlated with functional recovery in terms of movement, several trends were evident. When fasciculation potentials were present soon after the gracilis was transferred, muscle recovery (i.e., strength of the muscle) tended to be good. Additionally, when voluntary action potentials occurred earlier, muscle recovery also tended to be good. Other studies using concentric needle electrodes also have shown similar results (Sassoon, Poole, & Rushworth, 1991). A few studies also have shown that the velocity of the nerve fibres in the sural nerve used in cross facial nerve grafts increased over time (Sassoon, Poole, & Rushworth, 1991; Ueda, Harii, and Yamada, 1994).

Central Nervous System Changes

Coherence analysis can be used to compare two EMG signals in the frequency domain. From this analysis, it is possible to interpret the common neural drive to two different muscles (Nielsen, 2002). Root and Stephens (2003) used EMG coherence values to determine if co-contraction of facial muscles during a variety of facial expressions was controlled by a common cortical control in the normal population. Although coherence was found in several muscle pairs, it was the largest between the orbicularis oculi and zygomatic major during smiling. It was concluded that in at least some of the facial muscles during some facial expressions, a common cortical control was present.

To date, studies have not used protocols such as the one proposed to look at cortical adaptation in humans following facial reanimation surgery. As such, the cortical controller of different motor plans is unknown in the paralyzed face. It is also uncertain if this cortical control changes following facial reanimation surgery.

Purpose

It is difficult to evaluate and compare functional outcomes reported in the literature for facial reanimation surgery for two main reasons. First, there are many clinical case presentations in this population, representing numerous and differing surgical techniques. Second, there have been a myriad of subjective and objective assessment tools used to measure function.

Many studies use ambiguous subjective scales like the House Brackmann scale to evaluate facial function. Studies that have begun to objectively assess functional outcomes related to speech, mastication, movement and muscle physiology, show promising results. However, these studies have not examined the effects of surgery on facial muscles other than the transferred muscle. Moreover, no study to date has compiled a systematic and comprehensive evaluation of all outcomes in this population. Movement and muscle physiology data have not been related to functional activities (e.g., puckering, chewing, speech) other than smiling.

As such, the purpose of the current study was to collect a comprehensive evaluation of mastication, speech, movement and muscle physiology not only in the new transferred muscle, but in several muscles across the face. Data were collected not only during smiling, but during a variety of functional activities which included both speech (i.e., individual speech sounds and running speech) and non-speech tasks (i.e., chewing, smiling, puckering). Outcomes following surgery were then used to analyze: (1) overall face activation and movement; (2) asymmetries between the two sides of the face; (3) differences in activation and movement between tasks (specifically differences between speech and non-speech tasks); (4) relationships between movement and EMG motor recruitment;

and (5) the common synaptic drive to the motorneurons of the facial muscles.

Systematic physiological and behavioural measurements during recovery, habilitation, and rehabilitation will contribute to our understanding of outcomes in this population and neuromuscular adaptation in relation to function (e.g., facial movement, mastication, drooling, and speech). This understanding eventually will lead to better pre- and post-surgical evaluations, more effective intervention protocols and more accurate predictions of outcomes in this population.

METHODS

Subjects

A convenience sample of 6 subjects (4 females and 2 males) was recruited for this study from patients who underwent or who were scheduled to undergo facial reanimation surgery at the University of Alberta Hospital. Potential subjects were sent recruitment letters (see Appendix A) and were asked to contact the investigators if they were interested in participating. Subjects who participated gave informed consent (see Appendix B and C). All study procedures were approved by the University of Alberta Ethics Committee. The current study measured outcomes following surgery specific to the procedures associated with transfer of the gracilis muscle from the leg and reinnervation using the motor nerve to the masseter (innervated by the mandibular division of the trigeminal nerve) or the contralateral facial nerve depending on the specific clinical situation of each patient. Subjects were between the ages of 5 and 49 and presented with a number of different etiologies. Table 1.1 shows the general demographic data for the subjects in the study. The specific characteristics of each participant are described in the results section of this paper.

Operative Technique

Those subjects with unilateral facial paralysis underwent a two-stage facial reanimation surgery which utilized the contralateral facial nerve. In the first of the two surgeries, an 18 – 20 cm long sural nerve graft was harvested and subsequently sutured to the donor facial nerve of the normal hemi-face. Following this procedure, the graft was directed over the upper lip to the paralyzed cheek. Once nerve regeneration had started, the second surgery took place. At this time, the gracilis muscle was transferred to the face and coapted to the new interpositional nerve graft (Terzis & Noah, 2003).

In cases where facial paralysis was bilateral, the gracilis muscle was transferred to the face and reinnervated by the masseteric branch of the trigeminal nerve. Surgery to each side of the face was completed separately with a period of four to seven months between surgeries (Goldberg, Delorie, Zuker, Manktelow, 2003). In this operation, the face was first dissected and the masseter nerve was exposed and divided. Simultaneously, the gracilis transplant along with its motor nerve and vascular pedicle were dissected from the upper thigh. The muscle was then sutured to the corner of the upper lip and zygomata, vascular repairs took place and the masseteric nerve was anastomosed to the transferred muscle (Goldberg, Delorie, Zuker, Manktelow, 2003; Zuker, Goldberg, Manktelow, 2000; Zuker & Manktelow, 1999).

Table 1.1: Demographic information for all subjects

Subject	Age	Gender	Etiology	Duration of Paralysis Prior to Initial Surgical Intervention	Bilateral or Unilateral	Nerve Utilized	Time Elapsed Between 1st & 2nd Surgeries	Time between the Last Surgical Intervention Completed and Study Participation
1	47	F	Bell's Palsy	15 yrs 2 mo	Unilateral	Facial	SSFNS occurred 5 mo following FSFNS	9 mos
2	49	F	Pleomorphic Adenoma	1 yr 10 mos	Unilateral	Facial	FSFNS had occurred, but SSFNS had not	3 mos
3	5	F	Mobius Syndrome	5 yrs	Bilateral	Trigeminal	FMNS occurred 9 mo before SMNS	3 mos
4	19	M	Mobius Syndrome	19 yrs	Bilateral	Trigeminal	FMNS had occurred, but SMNS had not	1 yr
5	11	M	Trauma (R. occipital skull fracture)	7 yrs	Unilateral	Facial	SSFNS occurred 7 mo following FSFNS	1 yr 5 mos
6	17	F	Congenital	17 yrs	Unilateral	Facial	SSFNS occurred 10 mo following FSFNS	2 yrs 11 mos

FSFNS = First stage facial nerve surgery
SSFNS = Second stage facial nerve surgery
FMNS = First masseter nerve surgery
SMNS = Second masseter nerve surgery

Data Collection

Several measures were used to evaluate functional outcomes and peripheral and central nervous system changes. Functional outcomes for oral competence, mastication, articulation and speech intelligibility were assessed using a modified oral mechanism exam, a clinical mastication and swallowing assessment, and non-standardized articulation and speech intelligibility tests. Peripheral changes in muscle activation were assessed using peak EMG recordings while video motion analysis was employed to assess the maximum excursion of facial movement. Central nervous system changes were inferred from EMG coherence analysis.

The order of presentation of each of the tasks within each evaluation was randomized for each subject. The specific procedures associated with each evaluation are described below. With the exception of one subject (S3) who completed the testing procedures twice, once after the first masseter nerve surgery (FMNS) and once after the second masseter nerve surgery (SMNS), each subject was examined once following facial reanimation. While S1, S5, and S6 were all tested after the second stage of the facial nerve surgery (SSFNS), S2 was tested after the first stage of the facial nerve surgery (FSFNS). S4, who had congenital bilateral facial paralysis, was tested after only one side of his face had been surgically repaired via masseter nerve surgery.

Oral Mechanism Exam

In order to evaluate orofacial morphology and function, the investigator administered a modified version of the Dworkin-Culatta Oral Mechanism Examination to each subject (Appendix D). Tasks within this examination included, but were not limited to: puckering the lips, smiling, grasping a tongue depressor with the lips, smacking the lips, puffing out the cheeks, blowing up a balloon, whistling, and demonstrating vertical and horizontal movements of mandible. In addition, notation of breathing, nasality, drooling, and diadochokinetic rates was made. Video recordings of this exam were made using a Canon ZR-60 digital video camera (Canon Canada Inc., Mississauga, On.) (video format of 60 fps; 1/6” 680,000 pixel CCD).

Mastication and Swallowing Exam

Problems with eating and drinking and compensatory behaviours were noted using a checklist adapted from de Swart et al. (2003) (Appendix E). Prior to examination of these functions, participants were asked if there were any medical reasons, such as allergies, that would prevent them from completing the task. If able, subjects were required to drink a coloured liquid (i.e., raspberry juice) from a Styrofoam cup, chew a solid food (i.e., a standard size winegum) and consume a semi-solid (i.e., pudding). The examiner noted any occurrences of: coughing, oral incompetence, rate of mastication and swallowing, extent of mouth opening and/or deviation, residue left in the oral cavity after the subject indicated they had swallowed a bolus, and various other adjustments related to the process of consuming each bolus (e.g., cup/spoon positioning, decreased rate of mastication, etc.). The examiner also noted whether the size of bolus that the subject consumed appeared appropriate for their age. Again, this exam was recorded using the digital video camera.

Articulation

In order to evaluate articulation, a protocol similar to that of Nelson and Hodge (2000) was used. Each subject was required to say 11 consonants (/p/, /b/, /m/, /t/, /d/, /n/, /f/, /v/, /s/, /ʃ/, and /w/) in a consonant-vowel (CV) framework where V included two different vowels: /i/ and /u/. Each of the CVs was embedded in the carrier phrase, “I can say __ today.” One production of each test syllable was produced so that a total of 22 carrier phrases were recorded (11 consonants x 2 vowels). In some cases, subjects made more than one production of the carrier phrase for various circumstantial reasons (e.g., extraneous noise etc.). Five seconds was given between each production. To elicit the productions, the investigator provided a spoken model of the CV in isolation. The participant was then instructed to say the carrier phrase aloud including the CV in their regular conversational voice. Audio recordings of the productions were made using a digital audio tape (DAT) recording unit (TASCAM DA-P1, Mississauga, On.) and a directional over-the-head microphone.

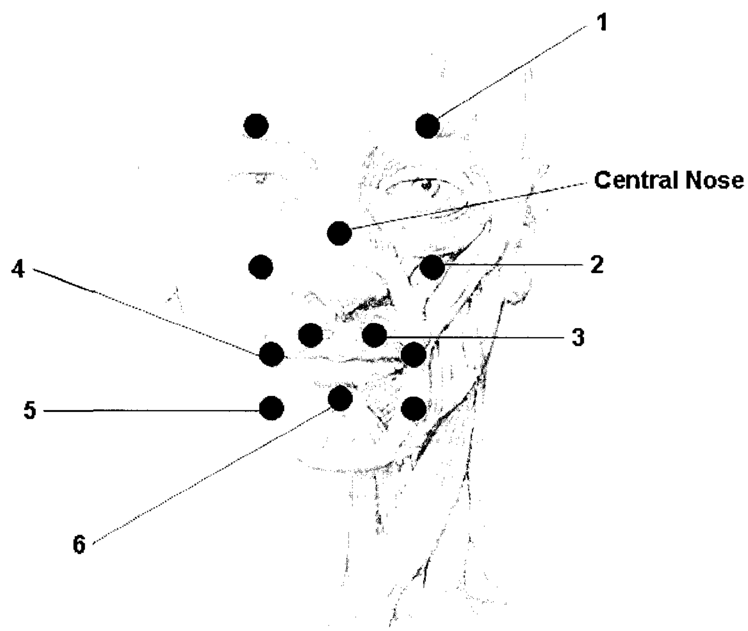
Intelligibility

Intelligibility was assessed using a non-standardized test. In order to collect a five minute speech sample, the investigator presented each participant with a series of open ended questions (see Appendix F). Answers were recorded using the DAT recorder. If an utterance was not understood by the investigator at the time of recording, the subject was asked to clarify any unknown words.

Kinematics

In order to track movement in two-dimensional space, small circles (approximately 1 cm in diameter) were drawn at 6 anatomically reproducible points on each subject's face using an eyeliner pencil (see Figure 1.1). These circles were drawn by the same investigator each time.

Figure 1.1: Placement of markers for kinematic measures. Diagram is adapted from http://www.mydr2.com/cgi-bin/english/fetch2.pl?refnum=498, accessed on March 6, 2008.



Points were drawn: (1) above the midpoint of each eyebrow (straight above the pupil) (2) on each of the cheeks (straight below the pupil at the horizontal projection from the ala of the nose) (3) on each side of the upper lip (between the philtrum and lip corner along the upper lip border) (4) at each lip corner (5) at each side of the lower lip (between the chin edge and the corner of the lip) and (6) at the midpoint of the lower lip (at the vertical projection of the philtrum along the lower lip border). To ensure that head motion did not confound measurement of facial movement during the tasks, a mark also was made at a stationary point. Based on previous research, the central nose was chosen as the most appropriate (Frey, Jenny, Giovanoli, & Stussi, 1994). In order to maximally define each marker, subjects were positioned in front of a white background and a spotlight was directed onto the face. During the exam, the subjects were seated upright in a comfortable chair facing the digital video camera which recorded the subject completing each of the following tasks: (1) maximum muscle contraction tasks (2) mastication and (3) speech. Two trials of each task were performed with time given to relax between activities (approximately five seconds).

Maximum Muscle Contraction Tasks

Subjects were asked to exert maximum contraction of relevant muscles for each of five tasks: clenching, smiling, frowning, lip puckering, and lip pressing. To elicit each task, the investigator provided the subject with a verbal explanation (e.g., put your teeth together and bite down as much as you can) and a model. Verbal reminders to relax completely between tasks also were given.

Mastication

In order to evaluate muscle activity and facial movement during mastication, subjects were prompted to take successive sips of juice for approximately 10 seconds, to eat 2 spoonfuls of pudding and to chew 2 standard sized winegums.

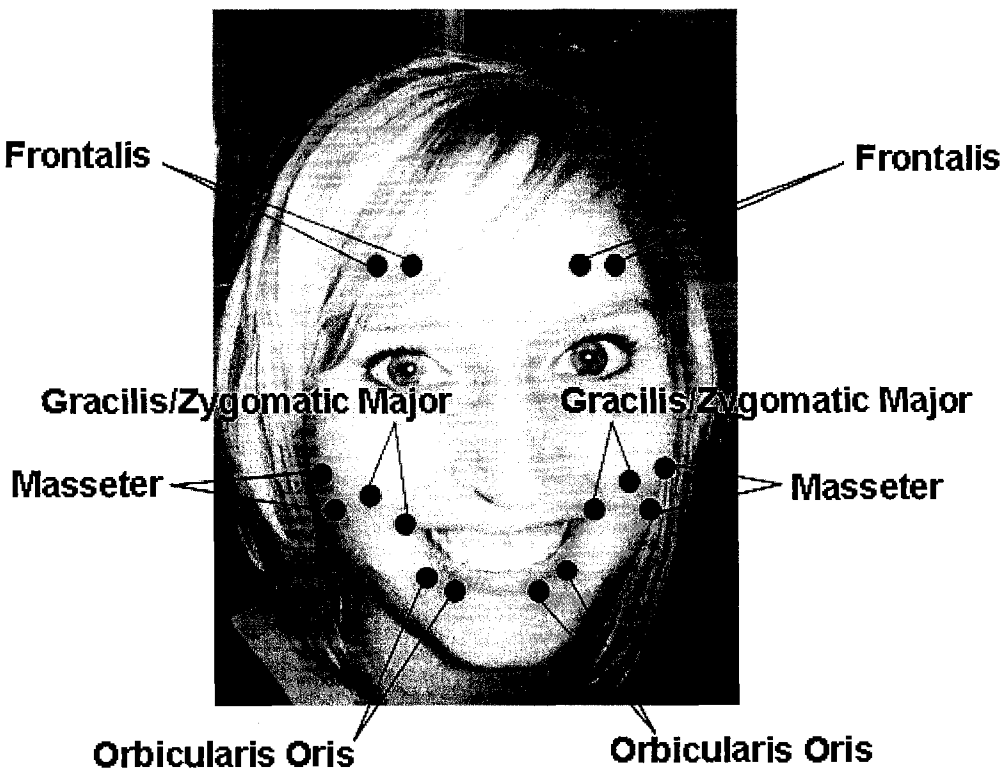
Speech Tasks

The subjects also performed the articulation tasks outlined above with the following modifications. Subjects again produced eleven consonants (/p/, /b/, /m/, /t/, /d/, /n/, /f/, /v/, /s/, / ʃ /, and /w/) in a consonant-vowel (CV) framework where V was only one vowel, /i/. Each CV syllable was produced in isolation. To elicit the productions, the investigator provided a spoken model of the CV and subjects were instructed to use their everyday conversational voice throughout the task. Subjects were also required to produce a spontaneous nursery rhyme (i.e., Jack and Jill).

EMG

While performing the above tasks, surface EMG recordings also were obtained using bipolar silver/silver chloride electrodes (1 cm diameter, 1-2 cm interelectrode distance) immersed in conductive gel and attached to the skin with double-sided adhesive circles. Electrodes were arranged on top of, and in parallel with, the most superficial facial muscle in each region. Amplitude and frequency of muscle activation were obtained from 4 different facial muscles bilaterally (see Figure 1.2).

Figure 1.2: Placement of electrodes for EMG measures.



To monitor frontalis muscle activation, electrodes were placed approximately 3 cm above the eyebrow directly above the pupil. In order to determine the position of the masseter muscle, subjects were asked to clench their teeth and electrodes were then placed over the belly of the flexed muscle. Electrodes for the gracilis/zygomatic major were placed on an imaginary line connecting the corner of the mouth to the tragus. To record over the region of the lower orbicularis oris, electrodes were placed bilaterally just inferior to the lower lip. A ground electrode was placed on the mastoid bone of each subject while a directional microphone recorded simultaneous acoustic data.

ANALYSIS

Oral Mechanism, Mastication and Swallowing Examination

Clinical judgement was used to complete the forms and checklists related to the oral mechanism, mastication, and swallowing examinations by the investigator at the time of testing. Results tabulated during the clinical examination were then verified post-hoc by the investigator using video recordings of all examinations.

Articulation and Intelligibility

Data Preparation

Articulation and intelligibility recordings were edited and played back to a group of three naïve listeners. In preparation for the listening task, articulation and intelligibly data were first edited. When multiple productions of a carrier phase were elicited during the articulation portion of the testing, those with the clearest productions and the least extraneous noise were used for further analysis. To measure intra-listener reliability, 10 CV pairs (~50%) were randomly selected and repeated for each listener (5 pairs with the vowel /i/ and 5 with the vowel /u/). A two-way mixed effects model was used to calculate inter and intra-rater reliability. For inter-rater reliability, the intraclass correlation was 0.890 ($df = 6$, $p < 0.0001$, single measures). For intra-rater reliability, intraclass correlations were between 0.843 ($df = 6$; $p < 0.006$, single measures) and 1.000.

In order to create sentences for the intelligibility portion of the listening task, speech samples were transcribed and reviewed. Problematic phrases or sentences were excluded from further analysis. For instance, sentences with less than four words or more than fifteen were omitted. If possible, sentences with more than fifteen words were broken up into sensible, shorter phrases. As well, sentences with extraneous noise were removed. The total number of sentences varied across subjects; some contained as few as 2 while others had as many as 50. Mean length of utterance and complexity also varied; younger subjects tended to use shorter and simpler sentences when compared to the adult subjects. From the edited transcripts, fifteen sentences were randomly selected to be played back to the judges. To measure reliability, five of those sentences (33%) were selected to be replayed to the each listener. Again, a two-way mixed effects model was used to calculate inter and intra-rater reliability. For inter-rater reliability, the intraclass correlation was 0.991 ($df = 6$; $p < 0.0001$, single measures). For intra-rater reliability, intraclass correlations were between 0.795 ($df = 6$; $p < .009$, single measures) and 0.916 ($df = 6$; $p < 0.0001$, single measures).

Selected carrier phrases and sentences were then edited and digitized using Computerized Speech Laboratory (CSL), Model 4500 software (KayPENTAX, Lincoln Park, NJ.). Extraneous background noise was removed from the acoustic waveform and each phrase/sentence was saved as an individual wave file. Sentences/phrases for each subject were then grouped together in play lists on a 10 GB Apple iPod (Markham, Ontario, Canada). Titles, introducing each sentence/carrier phrase, and a space of approximately 2 seconds were placed between each sentence/phrase. The order of presentation of sentences and phrases was randomized for each subject as was the presentation of each subject to each listener.

Listener Task

A listening task with a group of three naïve listeners was conducted. Selection criteria for the listeners included: (1) Hearing that was within normal limits (2) English as a first language (3) The cognitive ability to perform the listening protocol. At the time of testing, listeners were seated comfortably in a chair at a desk in a quiet room with noise levels of less than 10 dB as measured by a digital sound level meter. Each judge listened to the sentences/carrier phrases on an iPod using factory in-the-ear head phones. When listening to the sentences, judges were instructed to write what they thought the subject had said. When listening to the carrier phrases, they were asked to note the syllable (e.g., /bi/) they heard embedded in the phrase.

Listeners were allowed to adjust the volume control on the iPod to a loudness level that was comfortable for each subject. Once the volume control was set for a given subject, it did not change at anytime during the listening task for that subject. Listeners were allowed to listen to the sentences/phrases twice prior to making their decisions. Additionally, they were allowed to take breaks between play lists (i.e., the full set of sentences or phrases for a subject). The listening task took approximately 4 hours for each judge to complete.

In order to get an objective measure of articulation, the percent of correct consonants (PCC) was calculated and averaged between the three judges. For intelligibility measures, transcriptions were compared to the investigator's transcription and percent intelligibility (naïve listener words correct/total words) was derived and averaged between three judges. In order to obtain a complexity measure for each of the sentences, rate (syllables per second) and number of words was recorded.

2D Kinematics

2D facial kinematics were used to calculate the maximum excursion produced at each of the face markers during several of the tasks: */bi/*, */pi/*, */fi/*, */wi/*, *Jack and Jill*, *chewing the winegum*, *smiling* and *puckering*. Those trials with the best movement (e.g., largest movement based on subjective evaluation, least extraneous head movement) were selected for further analysis. Video was edited using the Pinnacle Studio Plus version 10.7 (Pinnacle Systems, Mountainview, CA.) and each trial was individually saved as an avi. file. Approximately one second of motionless video was saved before and after the subject performed the task. Edited video clips were then converted to Windows avi. files using Adobe Premier version 3.0 (Adobe Systems Incorporated, San Jose, CA.).

Video clips (video format of 60 fps (DV): resolution, 720 x 480) were then analyzed using Motion Tracker 2D (Dr. D. Webber, University of Pittsburgh, Pittsburgh, PA), a Matlab application that can digitize the position of 1 – 18 markers within a Cartesian plane that has an origin (0,0 coordinate) in the upper left hand corner of the screen. The position of each marker is calculated in pixels, but these values can be converted into centimeters (see below). In this program, video clips are played in the viewing screen of the software. The user specifies the marker positions at the beginning of the video clip by clicking the center of each marker with the cursor. Individual markers are then automatically tracked by the program using a "search box"; the program detects contrast between adjacent pixels (i.e., the facial marker) and tracks its position within the Cartesian plane. As such, the x and y position of each marker is determined for each frame of the video. When the program is unable to capture the position of a marker (i.e., can not detect where the marker is or it begins to track an inappropriate target), the user must stop the program, re-specify the location of the marker, and re-start the tracking.

To calculate maximum excursions, the co-ordinates of the markers were further analyzed using custom written programs (Dr. J. A. Norton, University of Alberta, Edmonton, AB) for Matlab v.7.1 (The Mathworks, Inc., Natick, MA). Again, in order to ensure that head motion did not confound measurement of facial movement during the tasks, the following formula was used to calculate the distance of each marker from the central nose:

$$D = |x_1 - x_2| + |y_1 - y_2|$$

where x_1 is the horizontal co-ordinate of the central nose in pixels, x_2 is the horizontal co-ordinate of the other marker in pixels, y_1 is the vertical co-ordinate of the central nose in pixels, and y_2 is the vertical co-ordinate of the other marker in pixels. As such, D represents the absolute sum of the horizontal and vertical distances of each marker from the central nose. Using the distance between the subject's pupils as a reference, the Motion Tracker 2D program was able to establish the number of pixels in one centimeter. This ratio was then used to convert distances in pixels to distances in centimeters. In order to calculate the maximum excursion produced at each marker, the frame with the smallest D was subtracted from the frame with the largest D.

EMG

Peak EMG Amplitudes

EMG signals using bipolar surface electrodes (8mm diameter, 5mm inter-electrode distance) were amplified (Grass Telefactor IPS 600, Quincy, Mass., USA), filtered (band pass 10-1000 Hz) and acquired using Powerlab at a 10,000 Hz sampling rate. The raw EMG records for all of the tasks were analyzed using custom-made software for Matlab V.7.1. Peak EMG amplitudes were clinically determined by largest voltage/deflection from baseline (at least 500 ms prior to an activity).

In order to further analyze 2D kinematics and EMG peak amplitudes, figures 2.1 – 6.9 were visually inspected for trends related to: (1) overall face activation and movement; (2) asymmetries between the two sides of the face; (3) differences in activation and movement between tasks; and (4) connections between maximum excursions and EMG motor recruitment. To determine if a relationship existed between movement and peak EMG amplitudes, maximum excursions at each of the face markers were visually compared to the EMG peak amplitudes of the muscle most likely responsible for those movements: frontalis to eyebrows, gracilis to lip corners, masseter to central lip, and orbicularis oris to lower lip. This comparison was difficult for several reasons. In most cases, there was not a 1:1 correspondence between movement and EMG activity level and overall trends in movement did not correspond to overall trends in peak amplitudes.

Coherence

EMG analysis similar to those of Norton and Gorassini (2006) were used to determine if there was a common cortical control to the muscles of interest during running speech (i.e., *Jack and Jill*) and the individual speech tokens (i.e., */bi/, /pi/, /fi/, /wi/*). This process yields coherence values between 0 and 1 where 0 indicates that the two muscles being compared are independently controlled at a given frequency and a value of 1 indicates that the muscles are driven by a common control at a given frequency.

To determine the EMG window where coherence was measured from, the period of muscle co-contraction was identified. EMG signals for shorter tasks (i.e., the individual speech tokens) were replicated and then placed adjacent to one another to form a longer waveform which was used for further analysis. EMG signals were then passed through a Tukey window and were rectified. Coherence values were then calculated in Matlab using programs based on those developed by Neurospec (www.neurospec.org). These programs utilized a formula previously used by Halliday, Rosenberg, Amjad, Breeze, Conway, & Farmer (1995). A 95% confidence interval was used to assess the significance of these values (Amjad, Halliday, Rosenberg, & Conway, 1997).

To support coherence data, phase relationships in the frequency bands in which coherence was statistically significant also were calculated using the Neurospec software. The slope of the phase spectrum can be used to calculate the lag time between muscles in a particular frequency band. The phase spectrum can also determine the stability of coherence above the 95 percent confidence interval.

RESULTS

Case Report S1

Case Information and History

S1 was a 43-year-old woman diagnosed with unilateral Bell's palsy 14 years prior to her facial reanimation surgery. Nerve transposition of the contralateral facial nerve occurred 6 months prior to the transfer of the gracilis muscle to the face. Evaluation for the present investigation took place 9 months following the transfer of the gracilis muscle.

Oral Mechanism Exam

At rest, mild flaccidity of facial muscles and ptosis of the eye were noted on the affected side of the subject's face. Bulkiness in the area of the transferred muscle also was detected. While facial expression was observed to be typical on the non-paralyzed side (NPS) of the face during spontaneous speech, both the eyebrows and lips moved minimally on the surgically-repaired paralyzed side (SRPS). Drooling did not occur at any point during testing. Mild asymmetry in lip excursion was noticed when the subject smiled and puckered her lips, with less excursion occurring on the SRPS. Lip strength was noted to be moderately impaired on the SRPS while the subject smacked her lips and when she was asked to hold a tongue depressor between her lips on that side in opposition to the clinician pulling on the depressor. As well, a small amount of air was released on the SRPS while the subject puffed out her cheeks. Based on clinical judgment, jaw strength (as measured by resistance to mild force applied by the clinician's hand) and range of motion for opening and closing and side-to-side movement appeared adequate. Respiration for speech and voice were within normal limits and tissues of the palate and oral cavity appeared healthy.

Mastication and Swallowing Exam

Prior to surgery, the subject complained of some drooling, dribbling of food, and biting her inner lip while eating. The mastication and swallowing exam revealed mild oral phase dysphagia characterized by a slow rate of mastication while chewing the winegum and consuming the pudding, and mild leakage of semi-solids and liquids from the oral cavity with residue on the lips and inside the oral cavity of the SRPS. The subject did remove the semi-solid found on her lips with her tongue. In order to compensate for these difficulties, the subject made the following adaptations. Food was masticated on the NPS and adapted cup and spoon positions were used. For instance, while drinking from a cup the subject's head was tipped slightly forward; while drinking from a bottle, her head was tipped slightly backward. When consuming the pudding, the subject tipped the spoon slightly upward. Coughing or choking on the food bolus did not occur while eating or drinking.

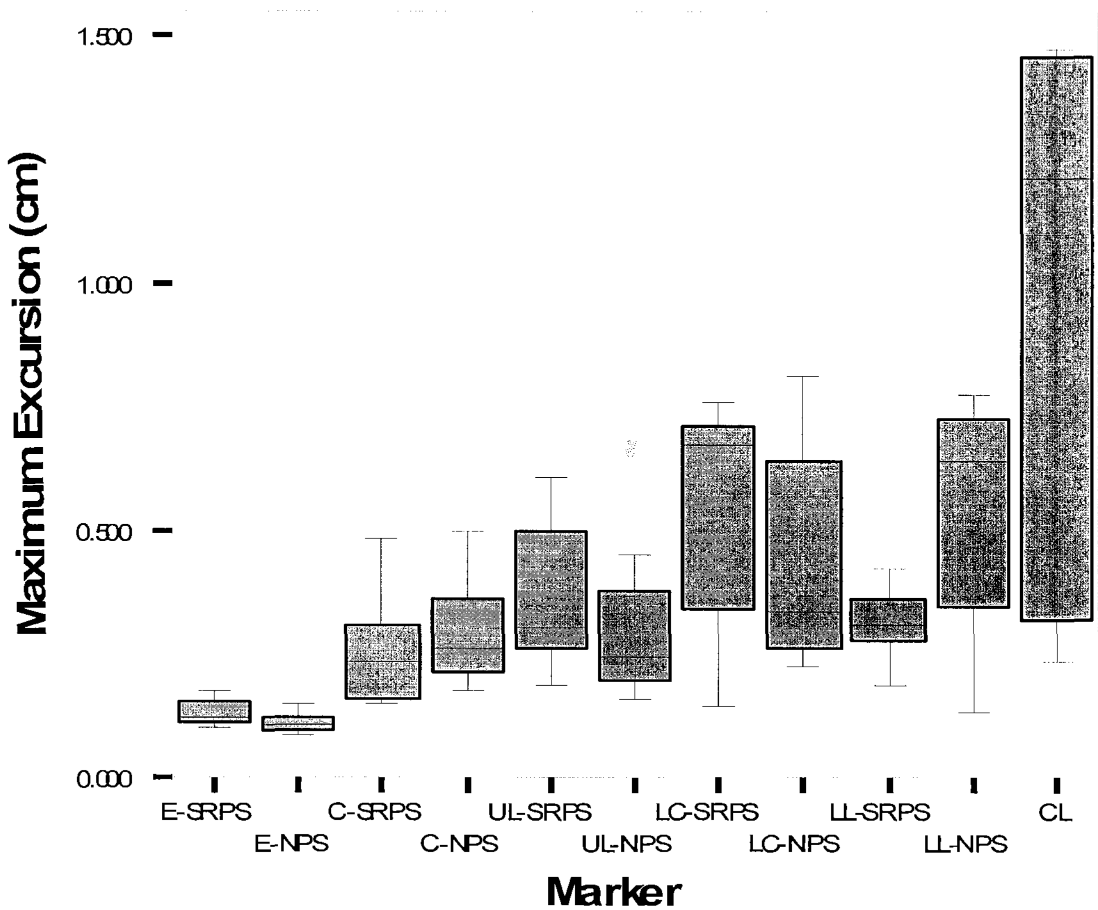
Speech Measures - Articulation and Speech Intelligibility

The subject voiced no concerns regarding speech articulation preceding surgery. On the whole, scores on articulation and intelligibility measures were high and difficulties in speech were not observed during testing. The average PCC across listeners was 100%; errors were not reported by any of the listeners. The average intelligibility rating from listeners was 96%. Furthermore, the investigator was able to understand everything the subject said during face-to-face conversation.

2D Kinematic Measures

Maximum excursions produced at each marker are shown in Figure 2.1 and Figure 2.2. It is apparent that movement was variable across markers, side of the face and task. An overall summary of kinematic data is presented below while summary tables for each individual marker are reported in Appendix G.

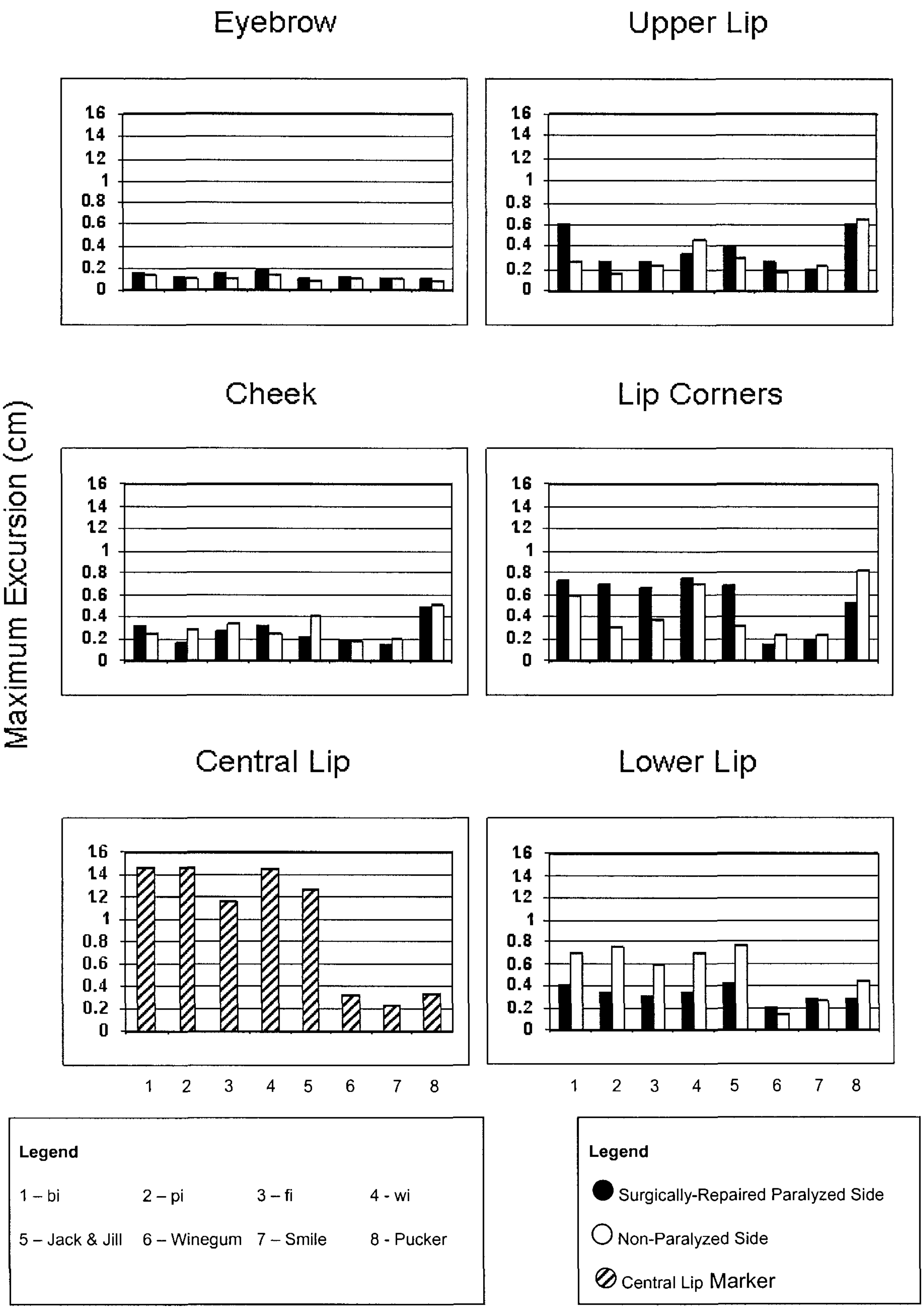
Figure 2.1: Maximum excursions at each marker with tasks collapsed.



Legend	
E-NPS – Eyebrow - Non-Paralyzed Side	E-SRPS – Eyebrow - Surgically-Repaired Paralyzed Side
C-NPS – Cheek - Non-Paralyzed Side	C-SRPS – Cheek - Surgically-Repaired Paralyzed Side
UL-NPS – Upper Lip - Non-Paralyzed Side	UL-SRPS – Upper Lip - Surgically-Repaired Paralyzed Side
LC-NPS – Lip Corner - Non-Paralyzed Side	LP-SRPS – Lip Corner - Surgically-Repaired Paralyzed Side
LL-NPS – Lower Lip - Non-Paralyzed Side	LL-SRPS – Lower Lip - Surgically-Repaired Paralyzed Side
CL – Central Lip	

In this and subsequent graphs, o indicates a mild outlier, while * indicates an extreme outlier

Figure 2.2: Maximum excursions produced at each marker



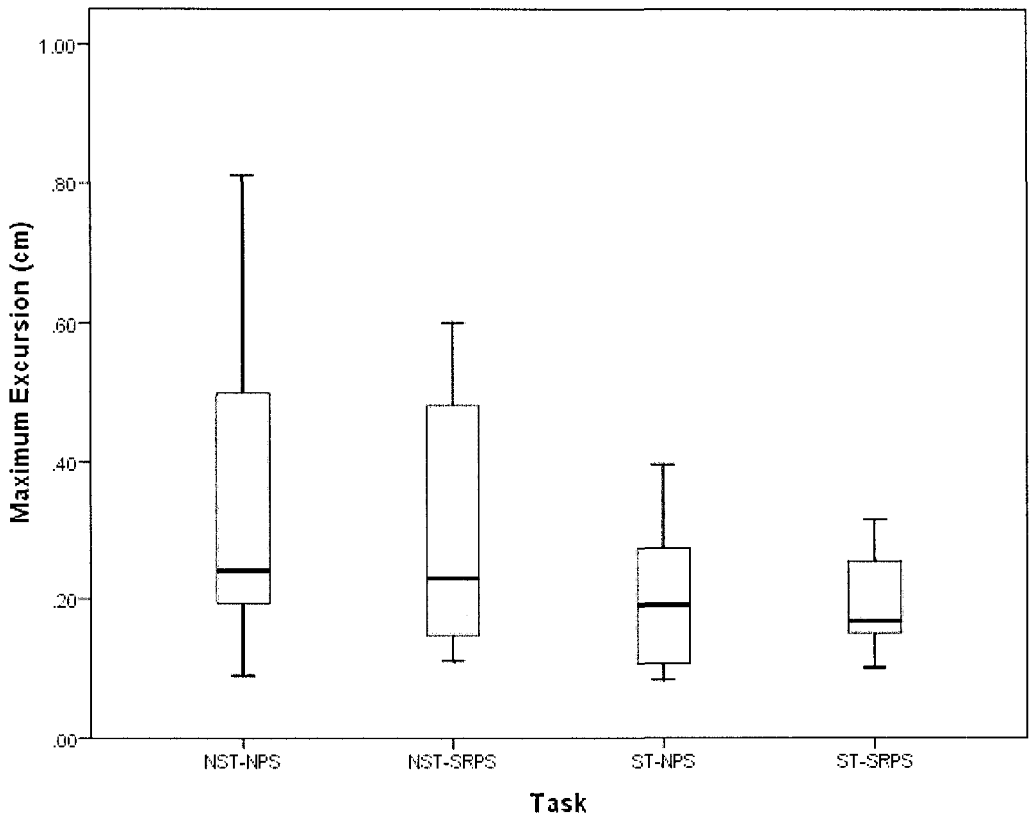
Figures 2.1 and 2.2 were used to review maximum excursions produced at each marker. Several general trends are apparent. The upper face (i.e., eyebrows and cheeks) tended to move less than the lower face (i.e., the lower lips and chin). Movements produced at the eyebrows on both sides of the face were the smallest and least variable when compared to the other markers. Overall, the central chin marker produced the largest and most variable maximum excursions when compared to the other markers. However, when visually inspecting the markers placed bilaterally, the lip corner produced the largest maximum displacements on the SRPS while the lower lip produced the largest movements on the NPS. When comparing each of the lip markers, the upper lips tended to move the least.

When comparing maximum excursions across the face, the side that produced the largest movements varied across tasks and markers (see Tables 3.1 – 3.11 in Appendix G for a summary). In general, the SRPS produced larger and more variable maximum excursions than did the NPS. The exception to this trend was at the cheeks and lower lips where the NPS produced larger movements.

A summary of the activities that produced the largest and smallest maximum excursions is listed in Appendix G. Although these tasks varied across marker, */bi/* and */wi/* tended to produce some of the largest maximum excursions on the SRPS, and */wi/* and *pucker* produced some of the largest movements on the NPS. *Chewing the winegum* and *smiling* produced the smallest maximum excursions on both sides of the face.

Maximum excursions produced during non-speech tasks (i.e., *smiling* and *puckering*) and speech tasks (i.e., */bi/*, */pi/*, /fi/, /wi/, and *Jack and Jill*) also were compared (see Figure 2.3). Generally, the non-speech tasks produced slightly larger and more variable maximum excursions than did the speech tasks. With respect to the speech tasks, maximum excursions tended to be larger and more variable during connected speech (i.e., *Jack and Jill*) than during the production of isolated speech tokens (see Figure 2.4).

Figure 2.3: Maximum excursions collapsed across non-speech and speech tasks



Legend

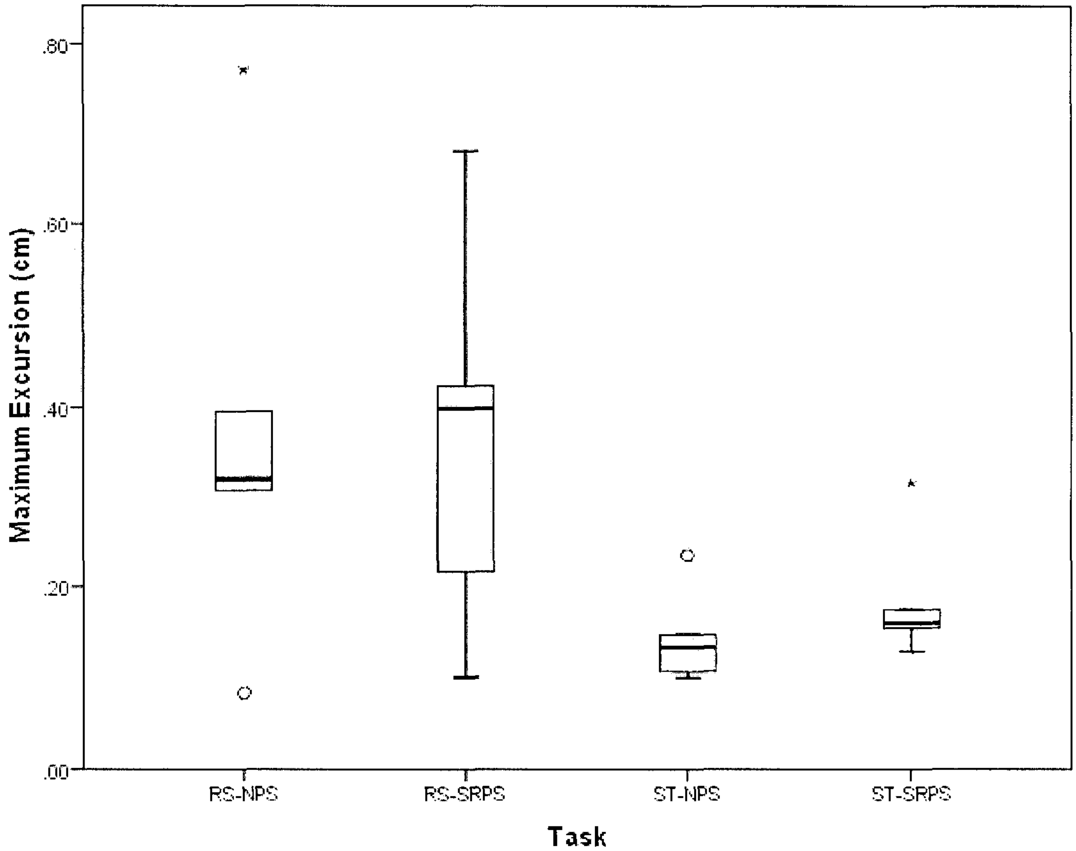
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 2.4: Maximum excursions collapsed across running speech and the speech tokens

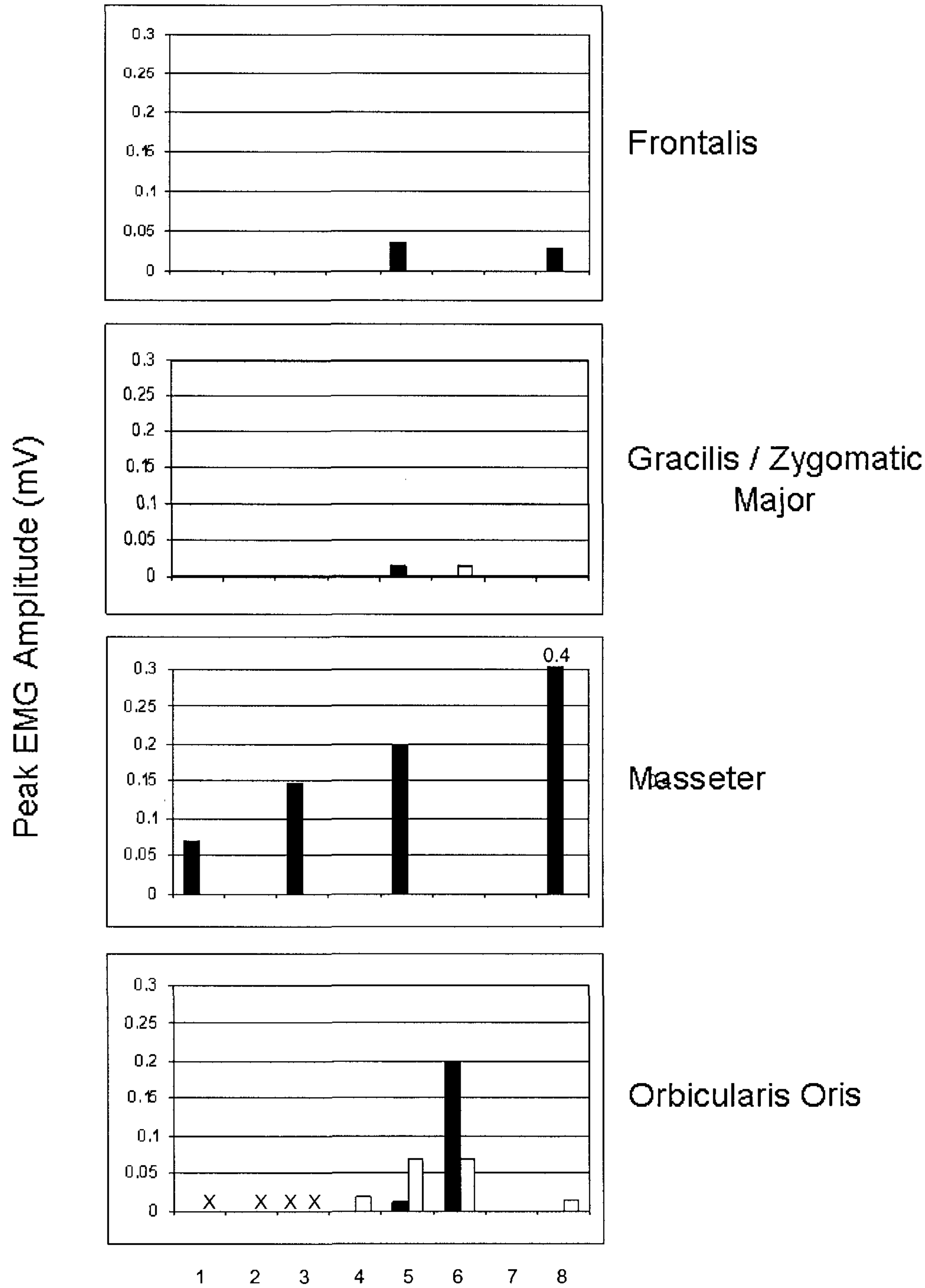


Legend
RS-NPS – Running Speech--Non-Paralyzed Side
RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side
ST-NPS – Speech Tokens--Non-Paralyzed Side
ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

EMG

Peak EMG amplitudes by facial marker and task are shown in Figure 2.5 and 2.6. Like the kinematic data, peak amplitudes varied across muscles, side of the face, and task. An overall impression of EMG measures follows while summary tables for each individual muscle are presented in Appendix G.

Figure 2.5: Peak EMG amplitudes by facial marker and task



Legend

1 – bi 2 – pi 3 – fi 4 - wi

5 – Jack & Jill 6 – Winegum 7 – Smile 8 - Pucker

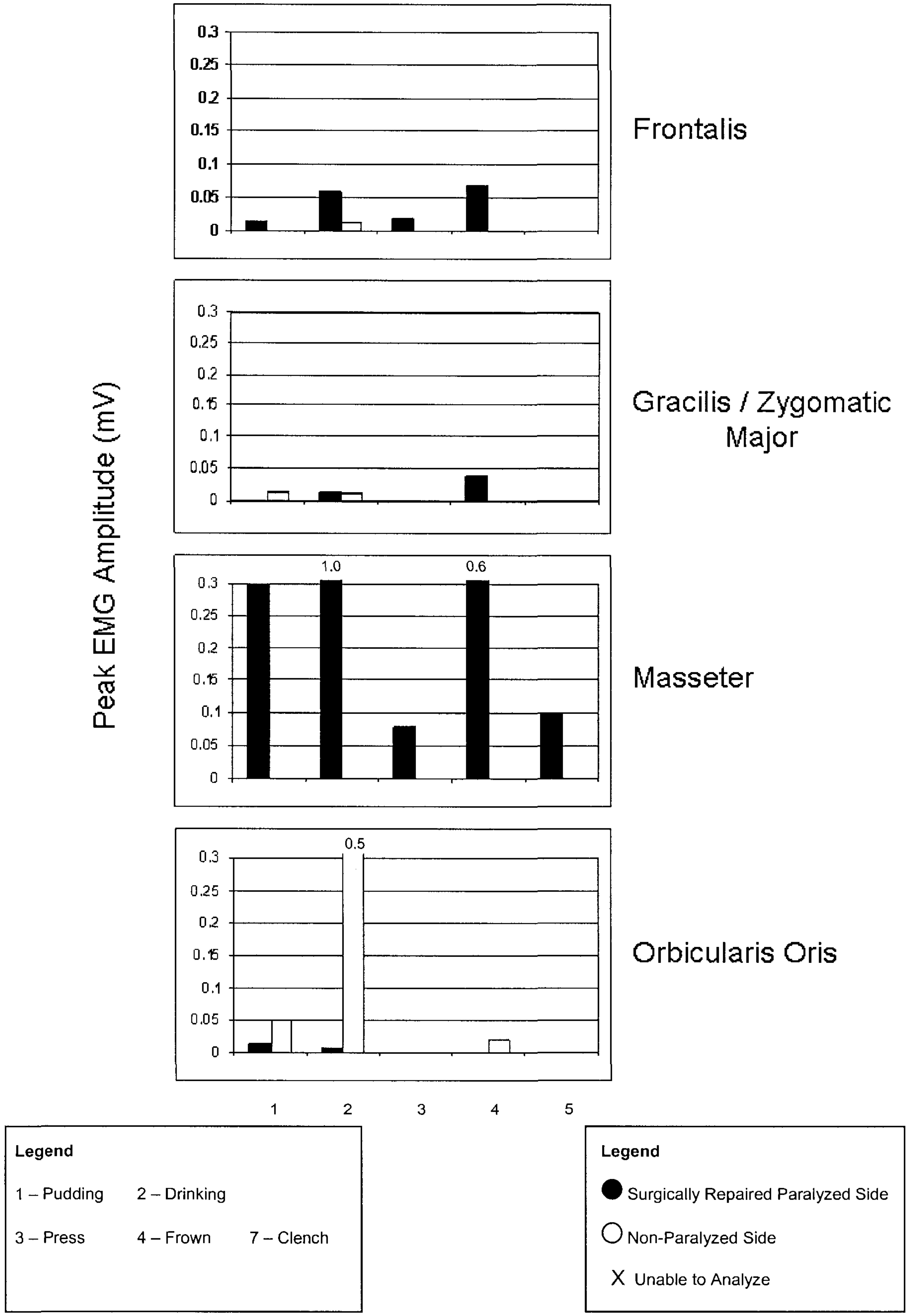
Legend

● Surgically-Repaired Paralyzed Side

○ Non-Paralyzed Side

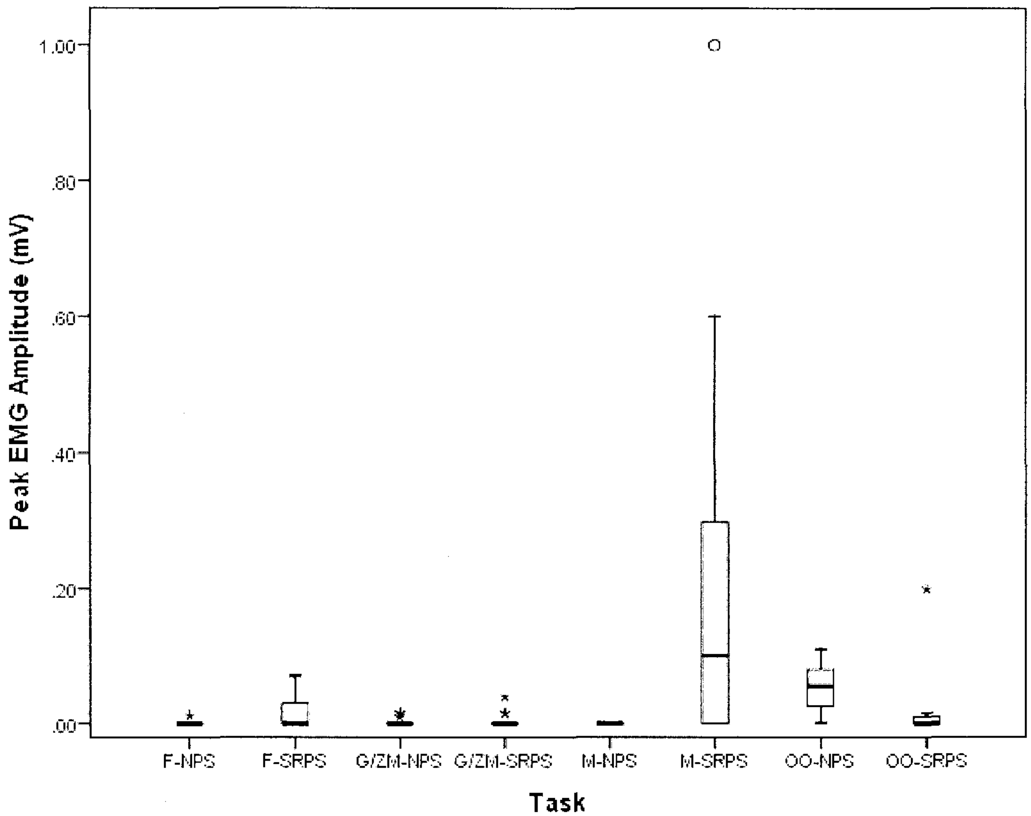
⊘ Central Lip Marker

Figure 2.6: Peak EMG amplitudes by facial marker and task



Box plots shown in Figure 2.7, present EMG data for each muscle collapsed across tasks. Overall, the peak EMG amplitudes recorded at each muscle were small (ranging from 0.008 to 1.00 mV) and many activities produced barely detectable signals (<0.008 mV) (see Tables 3.14 – 3.21 in Appendix G for a summary). However, the masseter produced the largest and most variable peak amplitudes on the SRPS while the orbicularis oris produced the largest and most variable EMG activity levels on the NPS.

Figure 2.7: Peak EMG amplitudes for each muscle collapsed across tasks



Legend

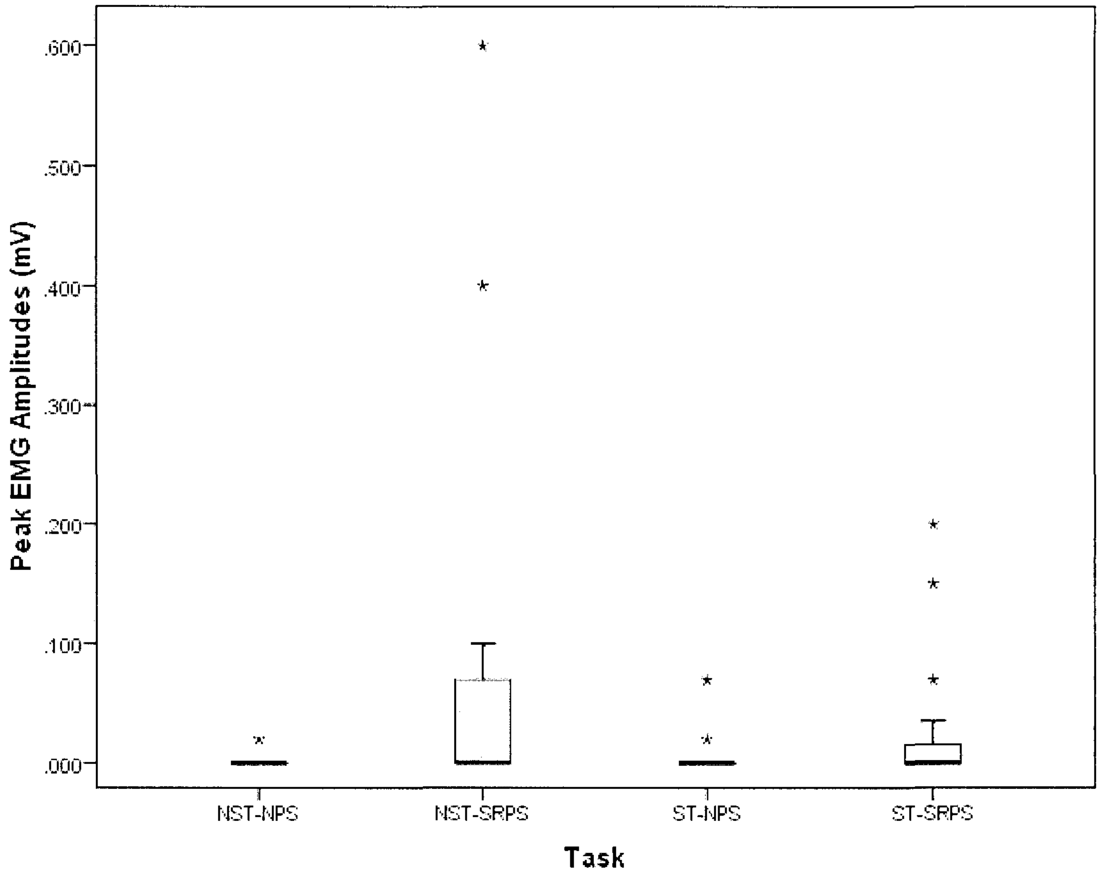
F-NPS – Frontalis Non-Paralyzed Side
F-SRPS – Frontalis Surgically-Repaired Paralyzed Side
G/ZM-NPS – Gracilis/Zygomatic Major Non-Paralyzed Side
G/Z-SRPS – Gracilis/Zygomatic Major Surgically-Repaired Paralyzed Side
M-NPS – Masseter Non-Paralyzed Side
M-SRPS – Masseter Surgically-Repaired Paralyzed Side
OO-NPS – Orbicularis Oris Non-Paralyzed Side
OO-SRPS – Orbicularis Oris Surgically-Repaired Paralyzed Side

It is apparent from Figures 2.5, 2.6, and 2.7 that asymmetries in peak EMG amplitudes existed. With the exception of the orbicularis oris muscles, larger and more variable peak EMG amplitudes were produced on the SRPS. The NPS tended to produce larger EMG amplitudes during the chewing and drinking tasks.

Several activities generated relatively large peak EMG amplitudes (see summary in Appendix G). In particular, *drinking* and *frowning* produced some of the largest EMG signals on SRPS whereas *drinking* and *chewing the winegum* produced some of the largest signals on the NPS. Peak EMG amplitudes were especially large (i.e., greater than 0.2 mV) in the masseter on the SRPS during *puckering*, *consuming the pudding*, *drinking* and *frowning* and in the orbicularis oris while *chewing the winegum* on the SRPS and while *drinking* on the NPS.

Average peak EMG amplitudes remained small when collapsed into speech and non-speech tasks (see Figure 2.8). The non-speech tasks tended to produce larger peak amplitudes than the speech tasks on the SRPS. Peak amplitudes also were compared across the speech tokens and running speech (see Figure 2.9). Running speech produced larger and more variable maximum excursions when compared to the speech tokens.

Figure 2.8: Peak EMG amplitudes collapsed across non-speech and speech tasks



Legend

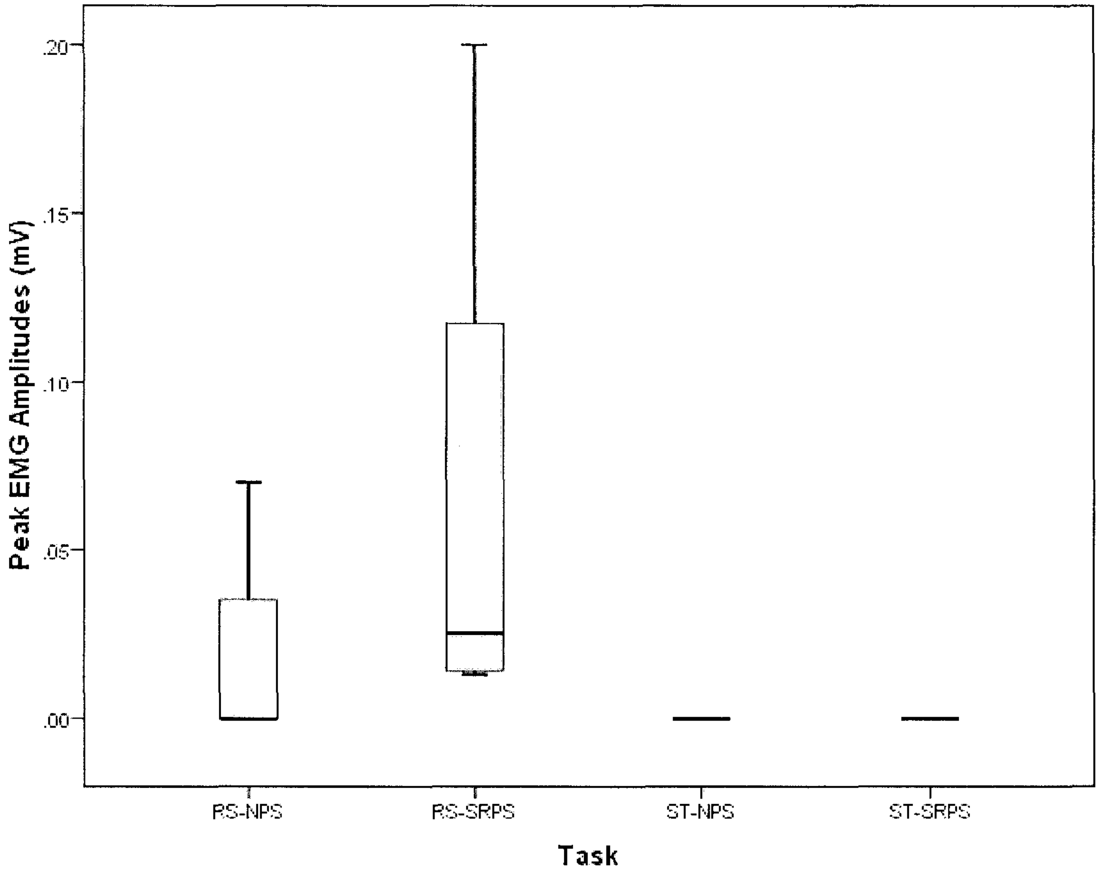
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 2.9: Peak EMG amplitudes collapsed across running speech and speech tokens.



Legend

RS-NPS – Running Speech - Non-Paralyzed Side

RS-SRPS – Running Speech - Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tokens - Non-Paralyzed Side

ST-SRPS – Speech Tokens - Surgically-Repaired Paralyzed Side

Relationship Between Kinematic Measures and EMG Peak Amplitudes

Visual comparison of kinematic and EMG data was difficult to complete in this subject. Maximum excursions and peak EMG amplitudes varied across muscles/markers, side of the face, and task, and although movements were recorded at all of the markers during each of the tasks, peak amplitudes recorded during many of the tasks were very small (< 0.008 mV). Despite these difficulties several general trends were evident.

As a whole, the lower face (i.e., lip markers, orbicularis oris and masseter) showed more movement and EMG activity than the upper face (i.e., eyebrow and cheek markers, and frontalis). When comparing each side of the face, some asymmetries in movement corresponded to asymmetries in EMG amplitudes. For instance, the SRPS showed more activity (i.e., larger maximum excursions and peak EMG amplitudes) than the NPS in the frontalis/eyebrows, and the NPS showed larger maximum excursions and peak EMG amplitudes in the orbicularis oris/lower lip.

The relationship between movement and EMG amplitude also was compared across tasks. Some weak positive and negative relationships were apparent. Puckering produced some of the largest movements and peak EMG amplitudes on both sides of the face. On the other hand, smiling produced some of the smallest peak amplitudes and excursions on both sides of the face. Although the speech tokens (especially */bi/* and */wi/*) produced some of the largest maximum excursions, small EMG amplitudes were recorded at all of the muscles during theses activities. Although chewing produced some of the smallest movements on both sides of the face, large EMG amplitudes were produced during many of the mastication tasks including chewing the winegum, drinking the juice and consuming the pudding.

S1 Summary

As a result of Bell's palsy, the first subject suffered from permanent unilateral facial paralysis. Speech difficulties were not observed; the subject was completely intelligible and listeners did not report articulation errors. Mild oral incompetence was noted during mastication and drinking; however, the subject was able to compensate for these difficulties. Clinically, mild weakness and flaccidity of the facial muscles were indicated on the SRPS. Some residual function and/or recovery was present following facial reanimation surgery as evidenced by movement and some EMG activity being recorded on the SRPS during many tasks including smiling, puckering, running speech and chewing. When reviewing overall facial activation and movement, it is apparent that this subject's lower face (i.e., masseter, orbicularis oris, and the lips) tended to exhibit larger maximum excursions and EMG amplitudes than did the upper face (i.e., frontalis and the eyebrows).

Although movement and muscle activity were observed on the SRPS, asymmetries in maximum excursions and peak amplitudes were still evident between that side of the face and the NPS. The SRPS produced larger and more variable maximum excursions and peak EMG amplitudes overall; however, the exception to this trend was found at the cheek and lower lip where the NPS produced larger movements during most activities. Specifically at the lip corners, the SRPS produced larger peak EMG amplitudes during the speech tasks (i.e., */bi/, /pi/, /fi/, /wi/,* and *Jack and Jill*) while the NPS produced larger peak amplitudes during the non-speech tasks (i.e., *chewing*, *smiling*, and *puckering*).

For smiling, the largest discrepancy in movement between the two sides occurred at lip corners where movement on the NPS was approximately 25% greater than that at the SRPS. For puckering, the largest difference in movement occurred at the lip corners where the NPS movement was approximately 37% larger than the SRPS. Although the same pattern was observed at the lip corners while *chewing the winegum*, the SRPS produced larger maximum excursions during running speech (i.e., *Jack and Jill*).

Asymmetries in EMG peak amplitudes also were observed between the two sides of the face. With the exception of the orbicularis oris muscles, larger and more variable peak EMG amplitudes were produced on the SRPS. Overall, the transferred gracilis produced barely detectable signals (< 0.008 mV) during most of the activities. It did, however, produce peak amplitudes that were larger than those produced on the NPS during running speech (i.e., *Jack and Jill*), *drinking* and *frowning*. The NPS produced higher peak amplitudes while *chewing the winegum* and *consuming the pudding*. Interestingly, barely detectable signals (< 0.008 mV) were recorded at all of the muscles during *smiling*.

Finally, the relationship between maximum movement excursions and peak EMG amplitudes varied across muscles/markers, side of the face, and task. As such, determining relationships between peak amplitudes and maximum excursions was difficult to ascertain. Despite this, some conclusive positive and negative relationships were evident. For example, a positive relationship was observed in the movement and peak EMG amplitude data generated during the non-speech tasks (i.e., *puckering* and *smiling*). A negative relationship was observed in the movement and peak EMG amplitude data generated during the mastication tasks. Although chewing the winegum produced some of the smallest movements on both sides of the face, large EMG amplitudes were produced during many of the mastication tasks (i.e., *chewing the winegum*, *consuming the pudding* and *drinking*).

Case Report S2

Case Information and History

This 49 year-old female suffered unilateral facial palsy post excision of a pleomorphic adenoma. Cross-facial nerve grafting took place a year and a half after the removal the tumor. Testing for the present study occurred 3 months following this initial nerve transposition. At that time, the transfer of the gracilis had not yet occurred.

Oral Mechanism Exam

Although no ptosis was noted, flaccidity of the facial muscles and a moderately drooped lip corner were observed on the non-repaired paralyzed side (NRPS) of the face. The subject's cheek appeared sunken in the area where the tumor was removed. During spontaneous speech, both of the subject's eyebrows remained relatively unanimated. Moreover, the NRPS of the mouth moved little during conversation and it was often pulled by the non-paralyzed side (NPS). Drooling was not noted during the exam. Although lip strength was within normal limits on the NPS, very little strength was noted on the NRPS when the subject smacked her lips and when she was asked to hold a tongue depressor between her lips on that side in opposition to the clinician pulling on the depressor. When the subject puckered her lips and smiled, lip excursion on the NPS was noted to be within normal limits; however, movement was not visible on the NRPS during these activities. Jaw ROM was adequate for opening and closing and side-to-side movement. Jaw strength in opposition to resistance from the clinician's hand appeared sufficient. Respiration and voice were within normal limits and tissues of the palate and oral cavity appeared healthy.

Mastication and Swallowing Examination

Moderate difficulties with oral competence and mastication were noted during this exam. For instance, rate of mastication and swallowing were noted to be slow while the subject ate and drank. She also was observed to take small sips while drinking and small spoonfuls of pudding. While chewing the winegum, the affected side of the subject's mouth occasionally remained opened. Moderate amounts of residue were noted on the cup and on the subject's lips after drinking and on the lips and in the oral cavity after consuming the pudding. Although these difficulties arose, the subject did not cough or choke during the exam. Furthermore, the subject was able to compensate for her difficulties by masticating on the non-affected side and by using spoon and cup adaptations; her spoon was turned towards the affected side and she leaned forward while drinking.

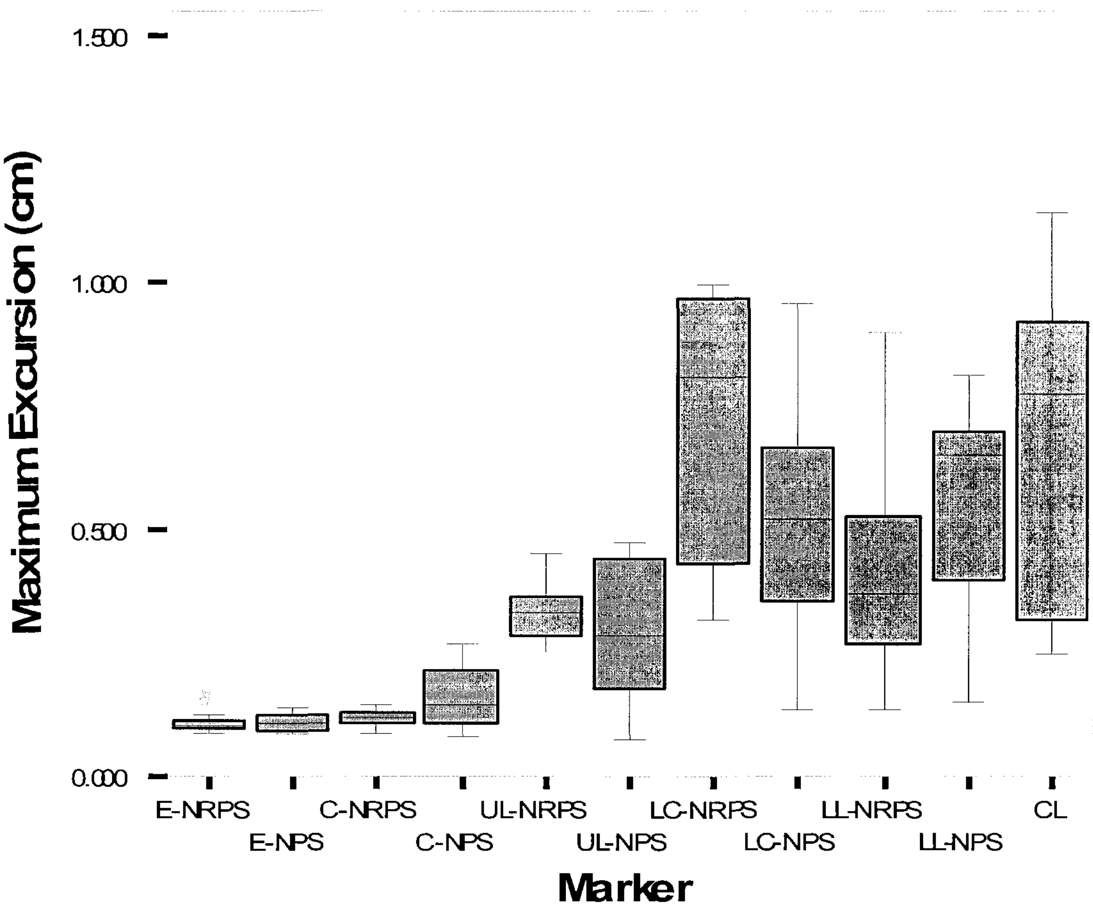
Speech Measures – Articulation and Speech Intelligibility

Although the subject noted that she had difficulty pronouncing the /p/, /b/, and /f/ sounds prior to surgery, listeners reported few articulation errors. The average PCC across listeners was 98%. Two articulation errors were reported: /thi/ for /fi/ and /mi/ for /ni/. Both errors occurred when the syllable contained the vowel /i/. The average intelligibility rating from listeners was 98%. Face-to-face conversation was easy to comprehend; the investigator could understand all of the subject's speech.

2D Kinematic Measures

While a general overview of kinematic data is reported next, summary data for each individual marker can be found in Appendix H. When visually analyzing Figures 3.1 and 3.2 for general trends in movement, several patterns are evident.

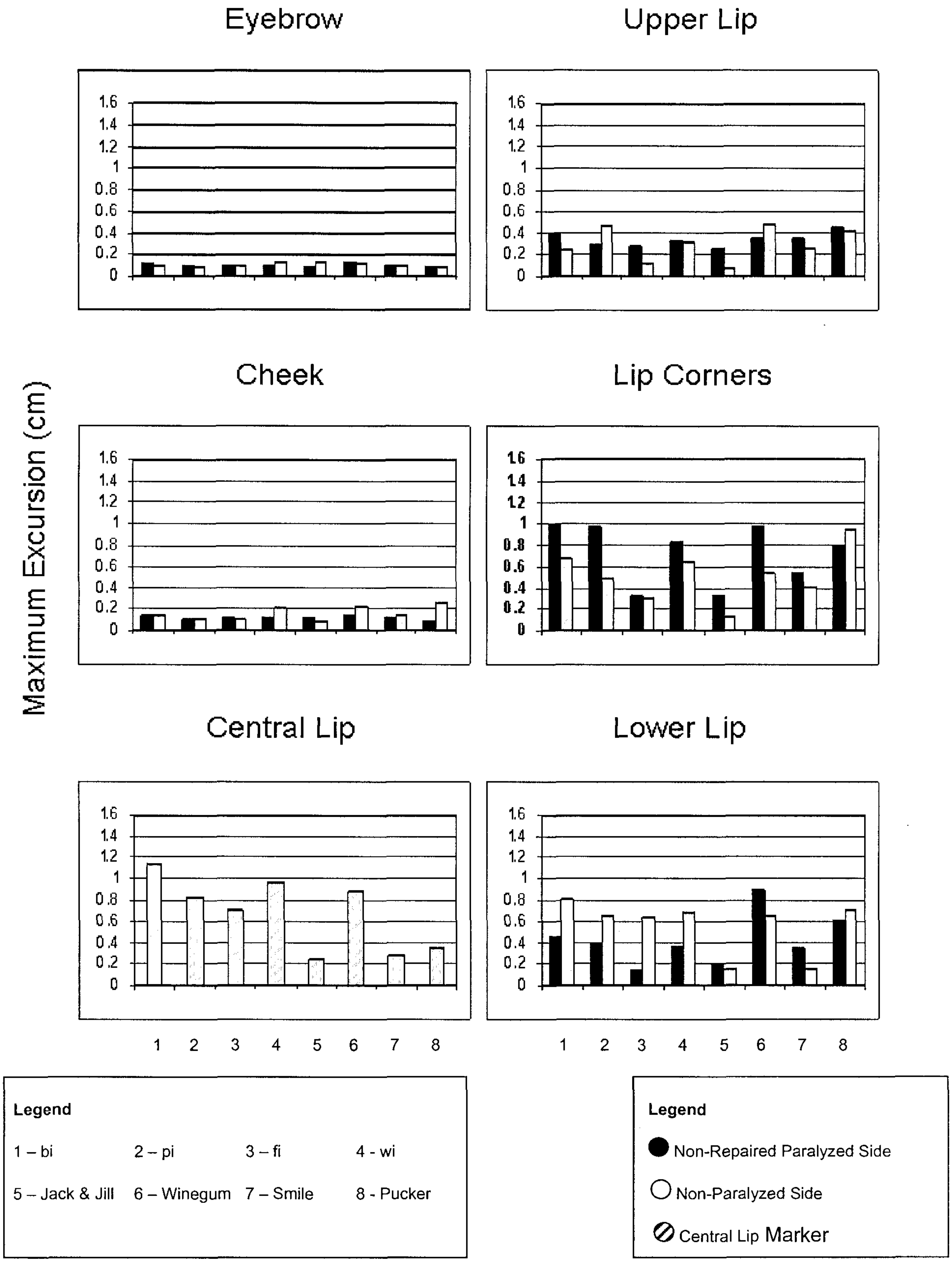
Figure 3.1: Maximum excursions at each marker with tasks collapsed.



Legend

E-NRPS – Eyebrow - Non-Repaired Paralyzed Side	E-NPS – Eyebrow – Non-Paralyzed Side
C-NRPS – Cheek - Non-Repaired Paralyzed Side	C-NPS – Cheek – Non-Paralyzed Side
UL-NRPS – Upper Lip - Non-Repaired Paralyzed Side	UL-NPS – Upper Lip – Non-Paralyzed Side
LC-NRPS – Lip Corner - Non-Repaired Paralyzed Side	LP-NPS – Lip Corner – Non-Paralyzed Side
LL-NRPS – Lower Lip - Non-Repaired Paralyzed Side	LL-NPS – Lower Lip – Non-Paralyzed Side
CL – Central Lip	

Figure 3.2: Maximum excursions produced at each marker



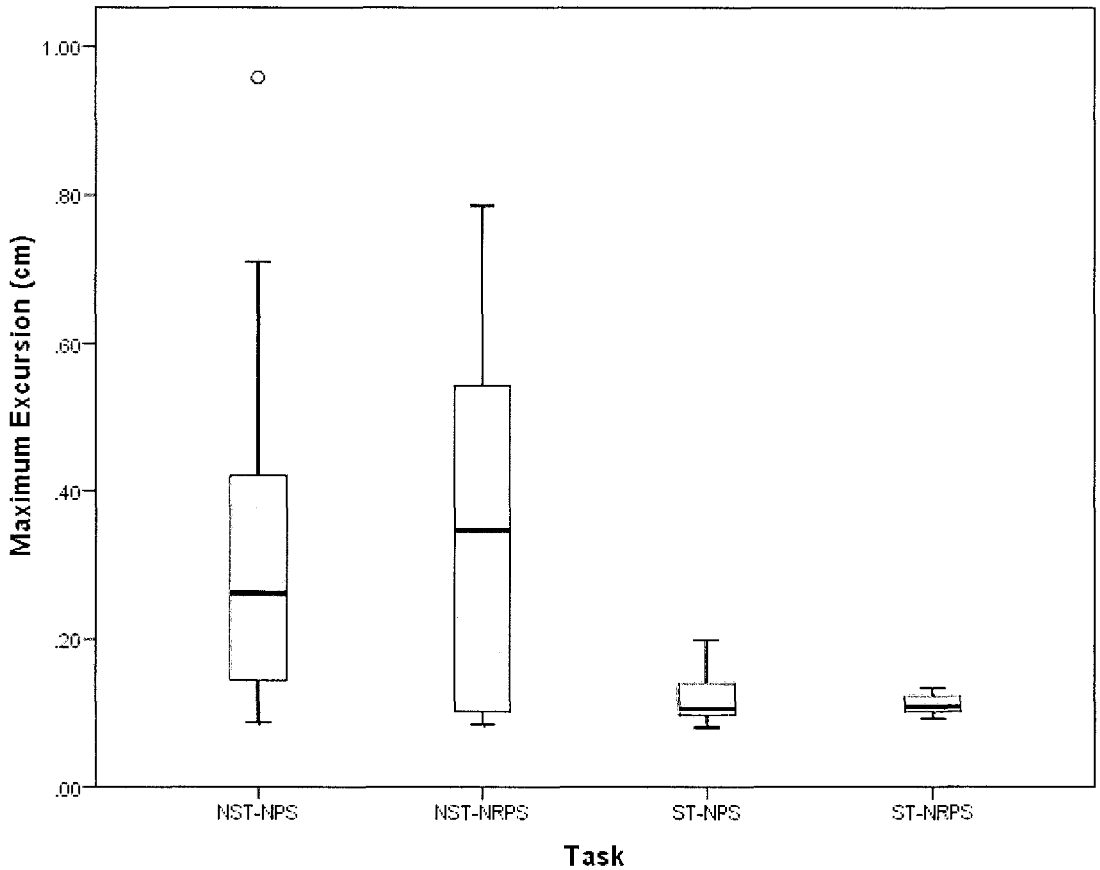
First of all, the upper face showed less movement than the lower face. The smallest excursions occurred at the eyebrows and cheeks on both sides of the face. Furthermore, movements at these markers were similar across tasks. The largest and most variable movement occurred at the lip corners on the NRPS, at the lower lip on the NPS, and at the central lip marker. As such, the lower lips (i.e., lip corners, lower lips and central lip marker) appeared to move more than the upper lips.

Differences in movement are apparent when comparing each side of the face. With the exception of the cheeks and lower lip, the NRPS produced larger and more variable maximum excursions when compared to the NPS. For a summary of the movement asymmetries seen at each individual marker, refer to Appendix H. Although the NPS produced larger movements than the NRPS during all of the speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, *Jack and Jill*) at the lower lip, the NRPS produced larger movements during these same tasks at the lip corners.

Additionally, movement disparities are visible across tasks. The activities that produced the largest and smallest maximum excursions are summarized in Appendix H. Of note, */bi/* and *chewing the winegum* produced some of the largest maximum excursions on the NRPS, whereas *pucker* and */wi/* produced some of the largest movements on the NPS. */fi/* and *Jack and Jill* were observed to make some of the smallest movements on either side of the face.

When comparing the speech (i.e., */bi/*, */pi/, /fi/, /wi/*, and *Jack and Jill*) and non-speech tasks (i.e., *smiling* and *puckering*), the non-speech tasks produced larger and more variable movements regardless of face marker location (see Figure 3.3). Movements were larger and more variable during running speech (i.e., *Jack and Jill*) than during the isolated speech tokens (i.e., */bi/, /pi/, /fi/, /wi/*) (see Figure 3.4).

Figure 3.3: Maximum excursions collapsed across non-speech and speech tasks



Legend

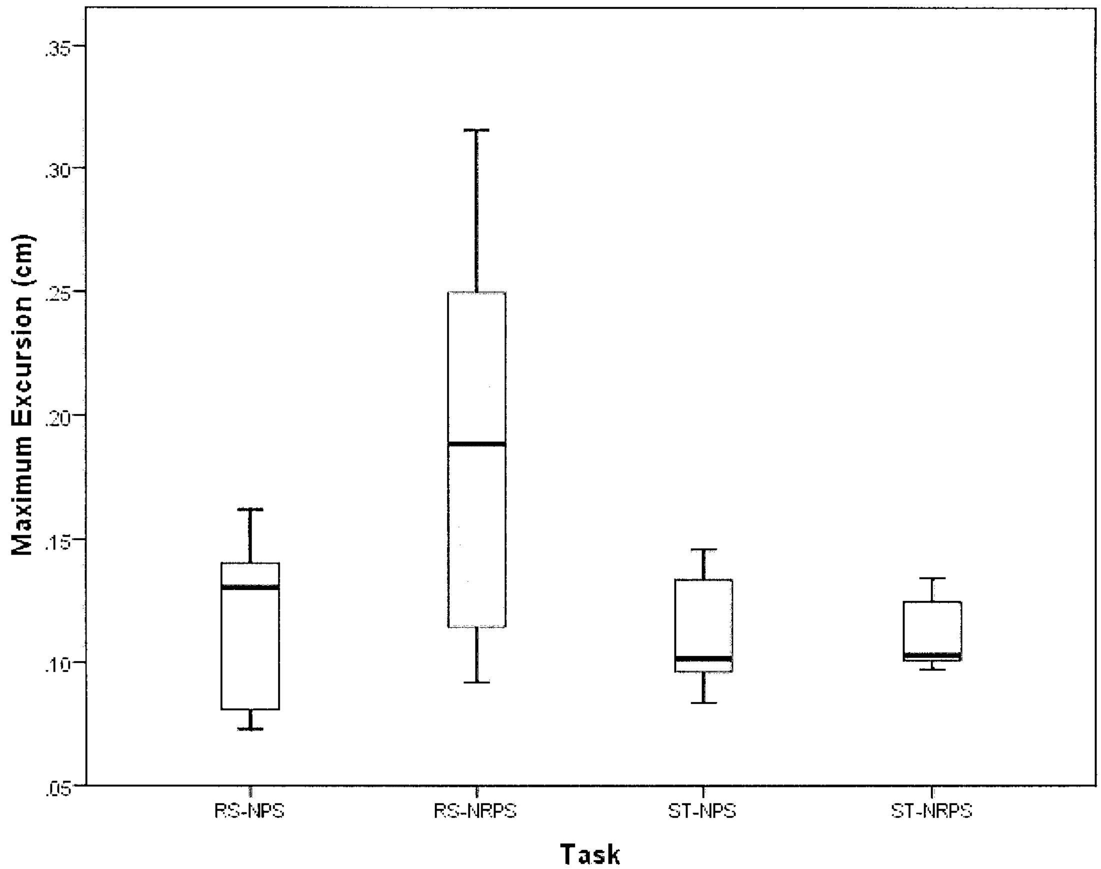
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-NRPS -- Non-Speech Tasks--Non-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-NRPS – Speech Tasks—Non-Repaired Paralyzed Side

Figure 3.4: Maximum excursions collapsed across running speech and the speech tokens



Legend

RS-NPS – Running Speech - Non-Paralyzed Side

RS-NRPS – Running Speech - Non-Repaired Paralyzed Side

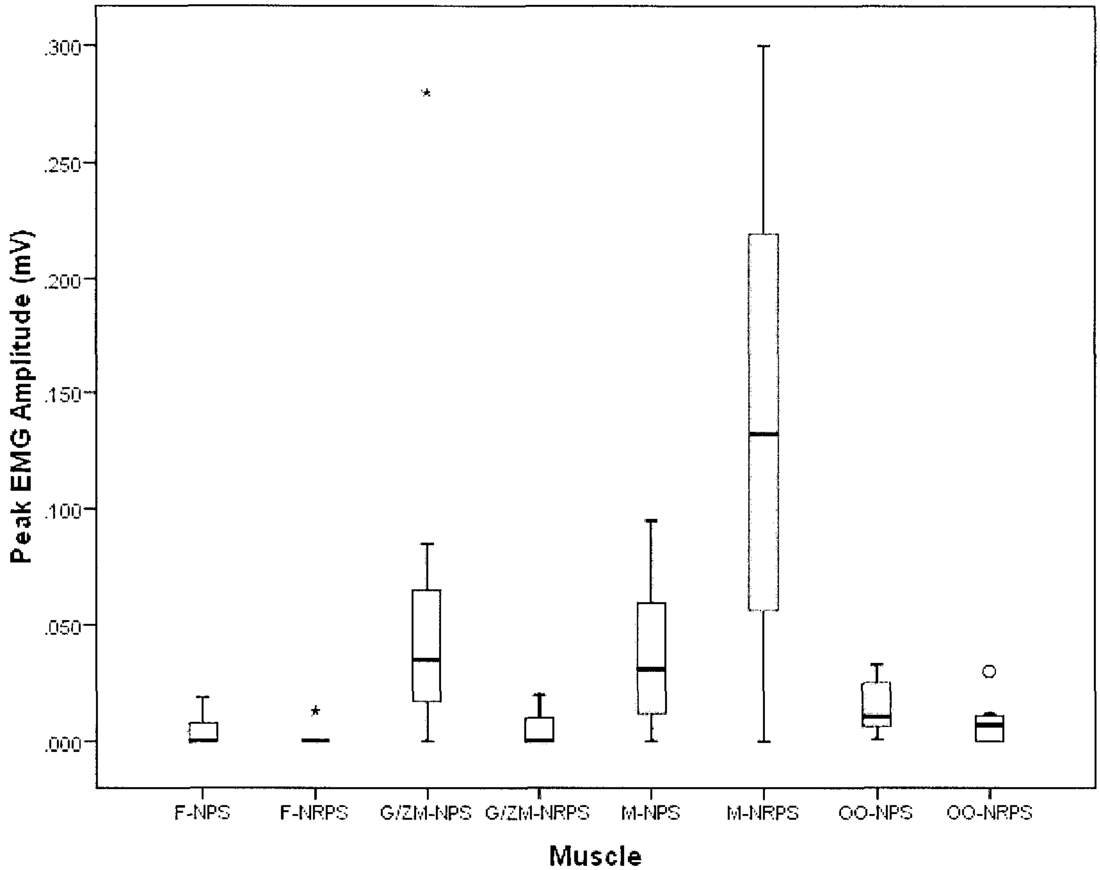
ST-NPS – Speech Tokens - Non-Paralyzed Side

ST-NRPS – Speech Tokens - Non-Repaired Paralyzed Side

EMG

In addition to the standard tasks completed by all of the subjects, EMG data also were recorded during spontaneous conversation for this subject. While a general overview of EMG data is reported next, summary data for each individual muscle can be found in Appendix H. When visually analyzing Figures 3.5, 3.6, and 3.7 for general trends in motor recruitment, several patterns are evident.

Figure 3.5: Peak EMG amplitudes for each muscle collapsed across tasks

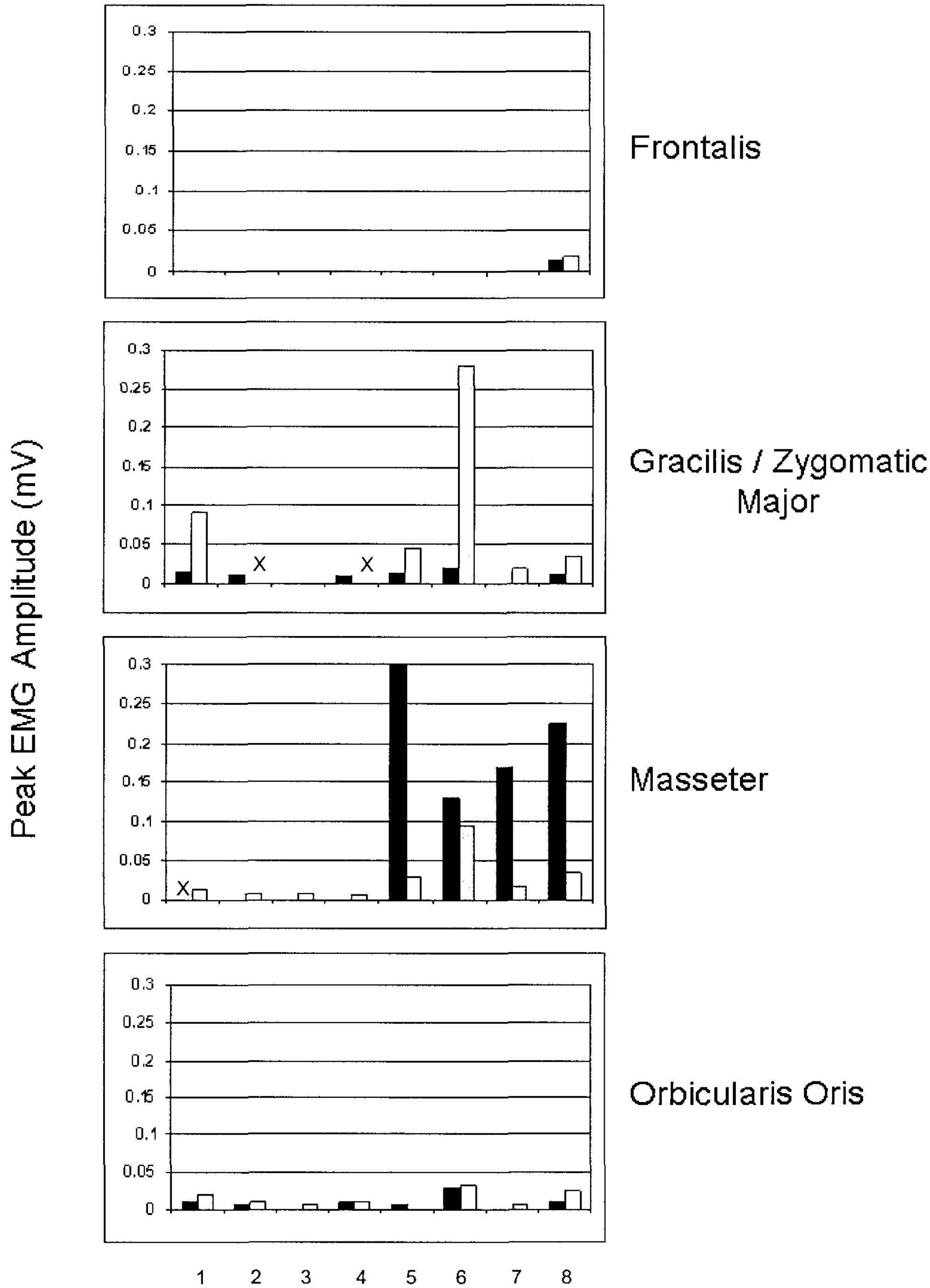


Note: Data point at 1.25 mV at the masseter on the NRPS is not included in this analysis

Legend

F-NPS – Frontalis Non-Paralyzed Side
F-NRPS – Frontalis Non-Repaired Paralyzed Side
G/ZM-NPS – Gracilis/Zygomatic Major Non-Paralyzed Side
G/Z-NRPS – Gracilis/Zygomatic Major Non-Repaired Paralyzed Side
M-NPS – Masseter Non-Paralyzed Side
M-NRPS – Masseter Non-Repaired Paralyzed Side
OO-NPS – Orbicularis Oris Non-Paralyzed Side
OO-NRPS – Orbicularis Oris Non-Repaired Paralyzed Side

Figure 3.6: Peak EMG amplitudes by facial marker and task



Legend

1 – bi 2 – pi 3 – fi 4 – wi

5 – Jack & Jill 6 – Winegum 7 – Smile 8 - Pucker

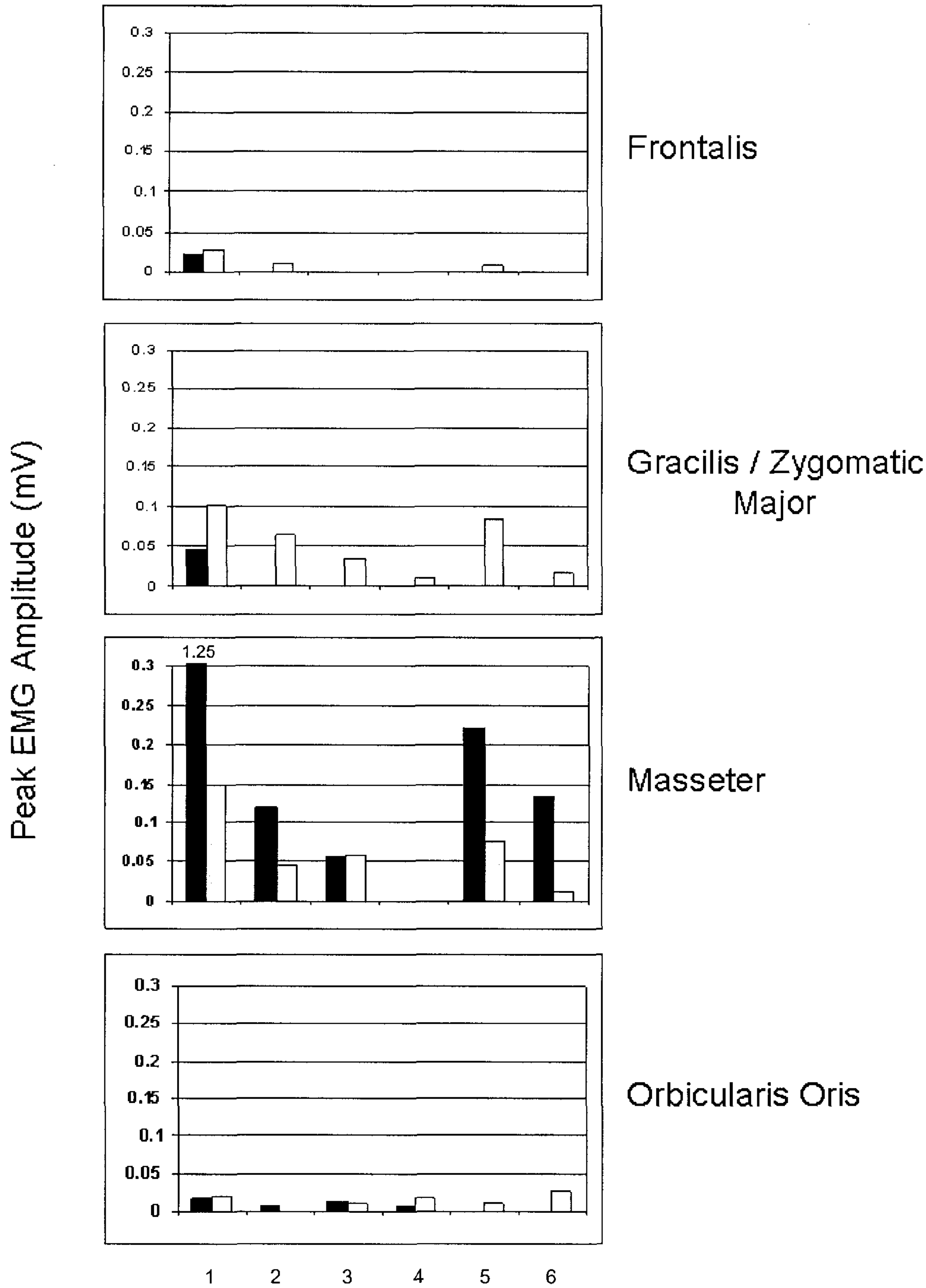
Legend

● Non- Repaired Paralyzed Side

○ Non-Paralyzed Side

X Unable to Analyze

Figure 3.7: Peak EMG amplitudes by facial marker and task



Legend

1 – Convo. 2 – Pudding 3—Drinking

4 – Press 5 – Frown 6 – Clench

Legend

● Non-Repaired Paralyzed Side

○ Non-Paralyzed Side

X Unable to Analyze

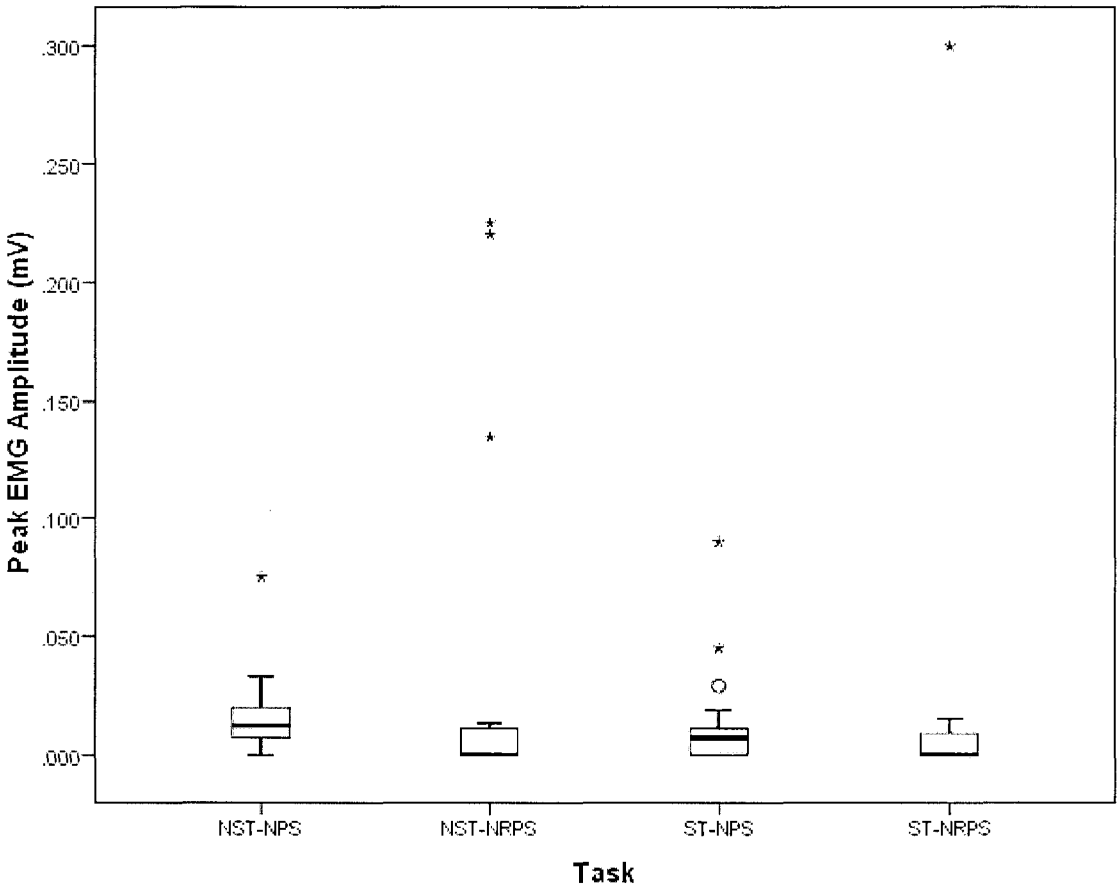
Overall, the smallest peak EMG amplitudes were recorded from both sides of the frontalis. During most tasks, these muscles produced barely detectable signals (<0.0002 mV). Although the orbicularis oris generated peak amplitudes greater than those at the frontalis, they also were consistently small across most tasks. While the masseter produced the largest and most variable peak amplitudes on the NRPS, both the masseter and the gracilis/zygomatic major produced the largest and most variable amplitudes on the NPS.

Comparing each side of the face revealed slightly higher and more variable EMG peak amplitudes on the NPS than on the NRPS (see Tables 4.13 – 4.20 in Appendix H for a summary of asymmetries in peak amplitudes produced at each side of the face). The masseter was an exception to this trend where the opposite pattern was detected. Noticeably, the masseter of the NRPS produced barely detectable peak amplitudes (< 0.0002 mV) during individual speech tokens (i.e., */bi/, /pi/, /fi/, /wi/*), but produced relatively large amplitudes (> 0.05 mV) on most other tasks.

Tasks that were associated with the largest or smallest peak amplitudes varied across muscles. The activities that produced the largest and smallest peak EMG amplitudes are summarized in Appendix H. *Spontaneous conversation* and *puckering* produced some of the largest peak amplitudes on the NRPS whereas *conversation*, *chewing the winegum* and *frowning* produced some of the largest amplitudes on the NPS. Although movement occurred during all of the tasks, very low amplitude signals (< 0.0002 mV) were recorded from all of the muscles throughout several of the tasks. Barely detectable EMG signals for each individual muscle are summarized in Tables 4.13 – 4.20 in Appendix H.

When comparing speech tasks (i.e., */bi/*, */pi/, /fi/, /wi/*, and *Jack and Jill*) to non-speech tasks, non-speech tasks tended to produce slightly higher peak EMG amplitudes from muscles on both sides of the face when compared to non-speech tasks (i.e., *smiling* and *puckering*) (see Figure 3.8). EMG peak amplitudes recorded during spontaneous speech (i.e., *conversation*) were visually compared to those produced during running speech (i.e., *Jack and Jill*) and the speech tokens (i.e., */bi/, /pi/, /fi/, /wi/*) (see Figure 3.9). Across all of the tasks, higher peak amplitudes tended to occur on the NPS while more variable amplitudes occurred on the NRPS. Overall, the largest EMG activity occurred during spontaneous speech, followed by running speech and then the individual speech tokens.

Figure 3.8: Peak EMG amplitudes collapsed across non-speech and speech tasks



Legend

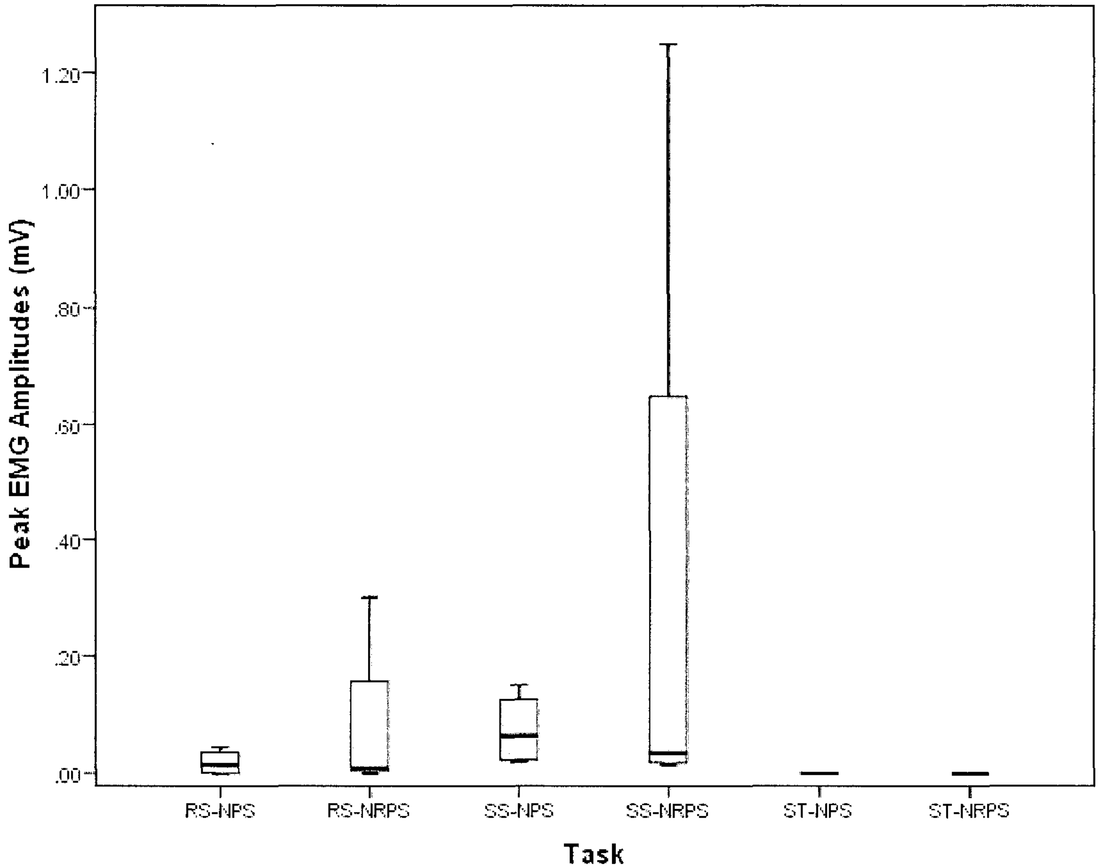
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-NRPS -- Non-Speech Tasks--Non-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-NRPS – Speech Tasks--Non-Repaired Paralyzed Side

Figure 3.9: Peak EMG amplitudes collapsed across spontaneous speech, running speech, and speech tokens.



Legend

RS-NPS – Running Speech--Non-Paralyzed Side

RS-NRPS – Running Speech--Non-Repaired Paralyzed Side

SS-NPS – Spontaneous Speech-Non-Paralyzed Side

SS-NRPS – Spontaneous Speech-Non-Repaired Paralyzed Side

ST-NPS – Speech Tokens--Non-Paralyzed Side

ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

A number of EMG signals produced in gracilis/zygomatic major on the NPS showed atypical waveform patterns. Four out of 56 EMG signals recorded from the NPS were abnormal. Tremor was apparent during three of the maximum contraction tasks in the gracilis/zygomatic major while */bi/* produced atypical waveforms in the masseter. None of the 56 signals recorded from the NRPS were atypical (see Appendix H for a summary).

Relationship Between Kinematic Measures and EMG Peak Amplitudes

Because a one-to-one relationship between movement and EMG did not exist, relationships between these two variables were difficult to discern. Relationships varied across muscles/makers, side of the face and task. Some general trends were evident.

Overall, the lower face showed more muscle activation and larger movements than the upper face. Specifically, the eyebrows and frontalis both showed the smallest and most consistent movements and peak amplitudes when compared to the rest of the face. Relationships on the lower face were more variable. The gracilis and lip corners both produced the largest peak amplitudes and movements on the NPS while the masseter and the central lip both showed the largest peak amplitudes and movements over all. Although the lower lips showed some of the largest maximum excursions on the NPS, the orbicularis oris produced some of the smallest peak amplitudes on both sides of the face.

Relationships again varied across each side of the face. Overall, when completing this comparison, a negative relationship existed between excursion and peak amplitudes. The NPS of the face tended to generated largest peak amplitudes at the frontalis and the gracilis, while the NRPS generated some of the largest maximum excursions at the eyebrows and lip corners. A positive relationship was observed at the orbicularis oris and lower lip. The NPS produced larger peak amplitudes/excursions at both of these muscles/markers. Although asymmetries could not be compared between the masseter and the central lip, it is interesting to note that the NPS produced larger peak amplitudes in the masseter.

Again, asymmetries in movement and peak amplitudes were variable and as such, comparisons across tasks were difficult to make. The frontalis and eyebrows both consistently produced small excursions/peak amplitudes on both sides of the face. While the gracilis produced fairly low and consistent peak amplitudes across tasks, maximum excursions at the lip corners were more variable. Positive and negative relationships were seen between the masseter and central lip. *Chewing the winegum* produced some of the highest amplitudes and maximum excursions in these markers/muscles. While the speech tokens (i.e., */bi/*, */pi/*, */fi/*, */wi/*) produced some of the largest excursions at the central lip, peak amplitudes recorded in the masseter during these tasks was small. Furthermore, *Jack and Jill*, *smiling* and *puckering* all produced small excursions at the central lip, but some of the highest peak amplitudes in the masseter. Like the gracilis and the lip corner, comparison of tasks at the orbicularis and lower lip were difficult to make. The orbicularis oris tended to produce fairly consistent peak amplitudes across tasks, while movement at the lower lip was more variable. *Chewing the winegum*, however, did produce some of the highest movements/amplitudes at these markers/muscles.

S2 Summary

The removal of a pleomorphic adenoma left this subject's face unilaterally paralyzed. Although lip strength and ROM were within normal limits on the NPS, they were moderately impaired on the NRPS. Difficulties with oral competence and mastication were noted during the mastication and swallowing exam. The subject's speech was easy to understand and few articulation errors were noted. Although the gracilis had not yet been transferred to the face, residual function still remained as evidenced by movement and EMG data being recorded on both sides of the face at each face marker and muscle. With a few exceptions, the lower face (i.e., the gracilis/zygomatic major/lip corners and masseter/central lip) showed more muscle activation and larger movements than the upper face (i.e., frontalis and eyebrows).

Although the second phase of surgery had not yet occurred, asymmetries between each side of the face were apparent and in some instances the NRPS produced larger excursions/peak amplitudes than the NPS. With the exception of the cheeks and lower lip, the NRPS produced larger and more variable maximum excursions when compared to the NPS. For example, the NRPS produced larger excursions at the lip corners. During *smiling*, the NRPS moved more than the NPS by 25%. Although this same trend was apparent while *chewing the winegum* and during running speech (i.e., *Jack and Jill*), the opposite pattern was seen during *puckering* where the NPS moved more than the NRPS by 18%. This pattern may be evident for several reasons. For example, objective analysis may not have detected minute movements, the movements were not as refined on the

NRPS or the direction of movement may have been incorrect (please see the discussion section for a complete analysis).

Although asymmetries between each side of the face also were observed in the EMG data, slightly higher and more variable peak amplitudes occurred on the NPS. An exception to this occurred at the masseter where the NRPS generated larger peak amplitudes. The NPS produced larger peak amplitudes during each of the tasks in the area of the zygomatic major. While, the NRPS produced barely detectable peak amplitudes during *smiling*, the NPS produced a peak amplitude of 0.02 mV. Although the amplitude generated on the NPS is larger than that generated on the NRPS during this task, it is comparable to peak amplitudes generated by the other activities in this muscle. For *puckering*, the lip corners on the NPS produced peak amplitudes 71% larger than those on the NRPS. The NPS also generated peak amplitudes that were higher than the NRPS while *chewing the winegum* and during *Jack and Jill*.

Both negative and positive relationships were established between kinematic and EMG data. For example, a positive relationship between movement and EMG data was found during the non-speech tasks (i.e., smiling and puckering) as well as the speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, *Jack and Jill*). A negative relationship between EMG and movement data was found at the masseter and central lip during *Jack and Jill*.

Case Report S3

Case Information and History

This 5 year-old girl was diagnosed with mild Mobius syndrome at birth and as such her face was bilaterally paralyzed. She was reported to have reached her developmental milestones (e.g., sitting and walking) at an appropriate age. Reanimation of both sides of the face was achieved using the ipsilateral motor nerve to the masseter. The first masseter nerve surgery (FMNS) occurred when the subject was 4 years-old and the second masseter nerve surgery (SMNS) occurred 8 months later. Evaluation for the present study took place just prior to the SMNS and then again 4 months following the SMNS. Due to the subject's age, kinematic and EMG data were not obtained; however, clinical data are reviewed below.

Oral Mechanism Exam

At the first testing session, the oral mechanism exam revealed little movement on either side of the face. During spontaneous conversation, the subject's upper face did not move and only small lip movements were noted. Movements during natural speech were larger at the lip corner of the surgically-repaired paralyzed side (SRPS) than on the non-repaired paralyzed side (NRPS). Lip strength was moderately impaired on both sides when the subject smacked her lips together. During this task, the lip corner on the SRPS was noted to move in a more lateral direction when compared to the NRPS. The subject had difficulty puckering her lips and excursion on both sides of the face was moderately impaired during this task. She was able to “make a fish face” by sucking in the center of her lips. Lip excursion during smiling was adequate on the SRPS and small movements were noted on the NRPS during this task. A spontaneous smile was not noted during the exam. Jaw ROM was adequate for opening and closing and side-to-side movement; of note, lateral excursion of the lip corner occurred on the SRPS when the subject opened her mouth. The oral cavity appeared healthy and respiration was adequate for phonation. The subject was judged to have a slightly elevated degree of nasality in her speech. Drooling did not occur at any time during the testing session.

At the second testing session, the subject’s face remained quite expressionless. Some bulkiness was noted in the area of the second transferred muscle. Again, during spontaneous conversation, movement was not observed at the upper face and lip movement was minimal. The lip corners on the side that had been repaired first still appeared to move more than the lip corners on the other side. Lip strength remained impaired on both sides of the face during lip smacking and the subject was unable to fill her cheeks with air; however, she was able to get a lip seal around the opening of a balloon. Lip excursion during puckering remained small on both sides of the face. Although excursion during smiling was not as large on the side that had been repaired most recently, both sides produced comparable movements. Jaw range of motion continued to be within normal limits. Functioning of the facial musculature on the side that had been repaired first was stable at the second testing session.

Mastication and Swallowing Exam

The subject was reluctant to have people watch her eat as she sometimes had difficultly chewing and containing food in the oral cavity. As such, minimal data were collected during this exam. At the first testing session, it was noted that the subject was able to get a good lip seal around the spoon while consuming the pudding; however, she did have to remove some semi-solid residue away from her lips with a napkin and her tongue. While chewing a solid candy, the subject often smiled on the SRPS.

At the second testing session, some difficulties with oral competence were still present. When consuming the winegum, the subject often pushed her lips together with her fingers, especially on the side that had been repaired most recently. While chewing the winegum, the subject's lip corners moved in a lateral direction on both sides of the face. The subject was able to create a tight lip seal around the spoon; the pudding remained difficult for her to eat and residue remained on both sides of her lips. No problems were noted when the subject drank the juice, and mouth opening during mastication was within normal limits. The subject's mother did note that her daughter had a slow rate of eating and drinking.

Speech Measures - Articulation and Speech Intelligibility

Prior to any surgery, the subject had difficulty pronouncing the /p/ and /b/ sounds and she was involved in speech therapy before and after her operations. At the first testing session in this study, moderate difficulties with speech were noted. The average PCC across listeners was 63%. Substitutions for commonly compensated phonemes in both vowel contexts were noted. Errors included substitutions for /b/, /p/, /m/, /n/, /f/, and /v/. At the second testing session, the number and variability of articulation errors decreased. The average PCC across listeners was 77%. Substitutions were only noted for /b/, /p/, /m/, and /v/ in both vowel contexts.

This subject's speech was slightly more difficult to understand when compared to the other subjects. At the first testing session, the average intelligibility rating from listeners was 89%; however, the investigator estimated that she was only able to understand 80% of the subject's speech in face-to-face conversation. Interestingly, intelligibility decreased slightly following the SMNS to 87%. This may be due to the fact that the subject spoke more at the second testing sessions and her sentences were longer and more complex. Again, the investigator estimated that she was still only able to understand 80% of the subject's speech. By 4 years, a child's speech is normally 100% intelligible.

S3 Summary

As a result of Mobius syndrome, limited movement occurred on both sides of this subject's face. When the subject puckered her lips, lip strength and excursion remained impaired on both sides of the face following surgery; however, lip corner excursion during smiling improved on both sides. Mild oral incontinence problems were still apparent following both surgeries and the subject's lip corners were pulled laterally when she chewed. Speech articulation improved following the SMNS, but this may have been the result of normal development or speech therapy. The subject still had difficulty pronouncing bilabials such as /p/ and /b/. Although this subject's intelligibility scores were lower than those of the other subjects, she was still quite easy to understand.

Case Report S4

Case Information and History

This 19 year-old boy was born with Mobius syndrome. In addition, this subject was affected by fetal alcohol syndrome. Because the facial paralysis was bilateral, reanimation was executed using the gracilis muscle transferred to the face with the nerve to the masseter as the donor nerve. Testing for the current study occurred approximately 1 year following the first surgery which reinnervated the right side of the face. At that time, reinnervation of the left side of the face had not yet occurred.

Oral Mechanism Exam

The oral mechanism exam revealed little movement on either side of the face and moderate oral incompetence. During spontaneous conversation, the upper face did not move and very little movement occurred at the lips. Saliva was noted on the lips with some pooling occurring behind the lower lip and in the oral cavity. The strength of the lips was limited. The subject had difficulty grasping the tongue depressor with his lips and was unable to smack his lips or fill his cheeks with air. Lip excursion was extremely limited. The subject was unable to pucker his lips. Furthermore, he had difficulty sealing his lips around a balloon, but could blow it up when he made a seal using his fingers. The subject whistled by blowing air through his teeth. A moderate amount of lip excursion occurred on the surgically-repaired paralyzed side (SRPS) when the subject smiled. This movement occurred in a lateral plane with little upward excursion of the lip corner. A small amount of movement also occurred on the non-repaired paralyzed side (NRPS) during this task. Jaw ROM was adequate for opening and closing and side-to-side movement; however, a small deviation towards the SRPS was noted upon depression of the mandible. Based on clinical judgment, jaw strength in opposition to resistance from the clinician's hand appeared sufficient. The subject was judged to have a slightly elevated degree of nasality in his speech. Respiration appeared adequate for phonation and the tissues of the oral cavity appeared healthy.

Mastication and Swallowing Examination

During this examination, moderate oral incontinence and difficulties with mastication were noted. Although leakage of saliva and semi-solids did not occur, both pooled behind the lips and in the cheeks. Moreover, residue of solid and semi-solid foods was noted in the oral cavity. The subject was observed to use inhalation to suck substances towards the back of his mouth. While chewing, both sides of the subject's mouth remained opened. Interestingly, the corner of the lips would move laterally on the SRPS while masticating. Mastication was characterized by a forward tongue thrust and a non-rotary chewing motion. Furthermore, the jaw appeared to deviate somewhat towards to SRPS when the subject chewed the winegum. Choking and coughing were not noted during exam.

The subject compensated for these difficulties in the following ways. While rate of drinking was within normal limits, mastication of both solids and semi-solids was slow. Food was masticated on the NRPS and adapted cup and spoon positions were used. When drinking and consuming the semi-solid, the subject would grasp the cup/spoon with his teeth and suck the liquid/pudding to the back of the mouth or would lick the pudding off the spoon. Occasionally, he would hold his lower lip closed with his fingers to prevent spillage of solid and semi-solid foods. The subject frequently used a napkin to remove residue of all consistencies of food and drink from his lips.

Speech Measures – Articulation and Speech Intelligibility

Overall, this subject's speech was difficult to understand and difficulty with articulation of bilabials such as "p" and "b" was observed. The average PCC across listeners was 77%. Substitutions for /b/ (/fi/, /vi/, and /thi/ for /bi/ and /lu/ for /bu/), /p/ (/wu/ for /pu/), and /m/ (/ni/ for /mi/) were noted. Although the average intelligibility rating from listeners was 94%, the investigator estimated that she was only able to understand 80% of the subject's speech in face-to-face conversation.

2D Kinematic Measures

Maximum excursions produced at each marker are shown in Figure 4.1 and 4.2. As can be seen, movement was fairly consistent across facial markers and between each side of the side of face. Some variability is apparent across tasks. An overall impression of kinematic measures is summarized below.

Detailed supporting tables for each individual marker are presented in Appendix I.

Figure 4.1: Maximum excursions produced at each marker

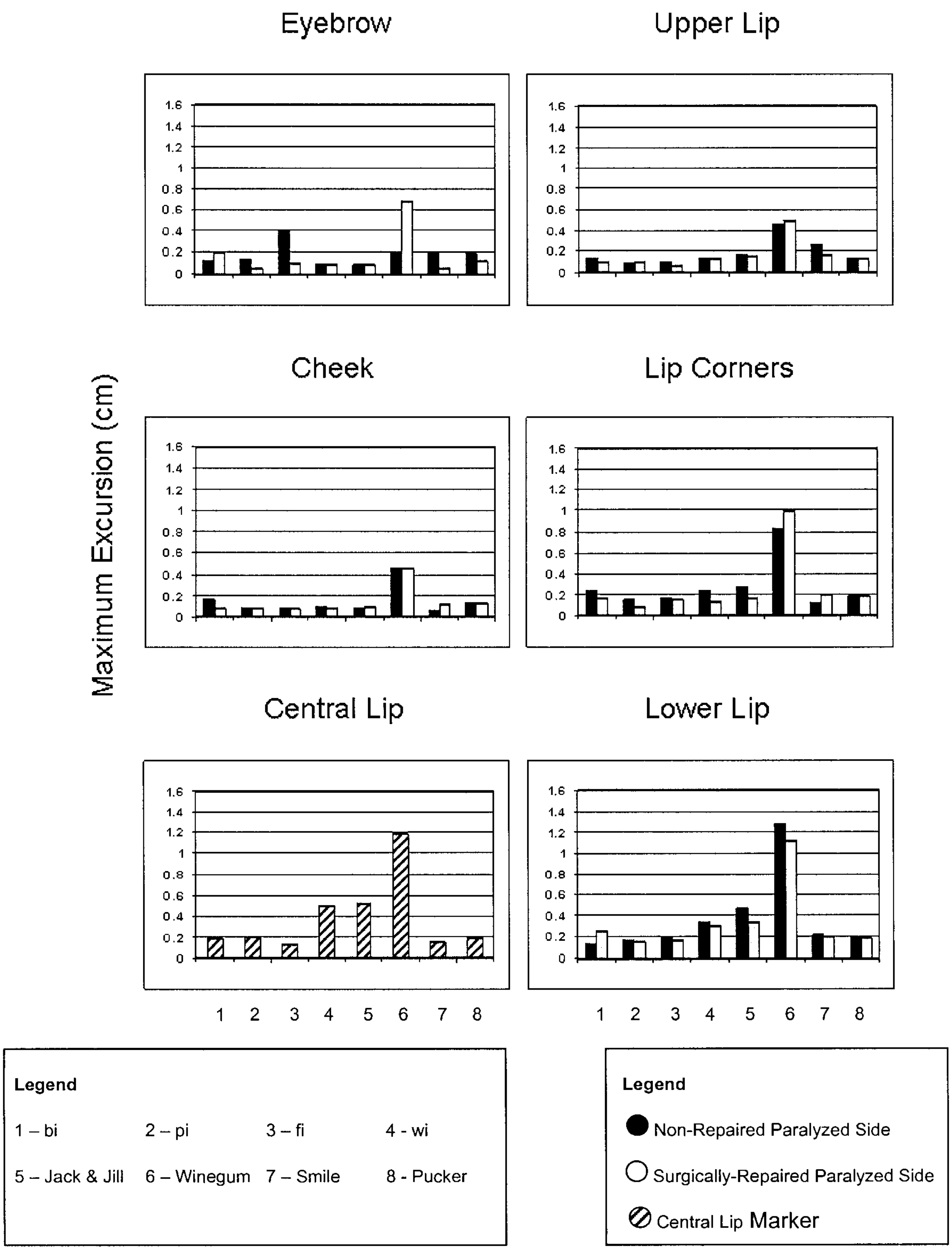
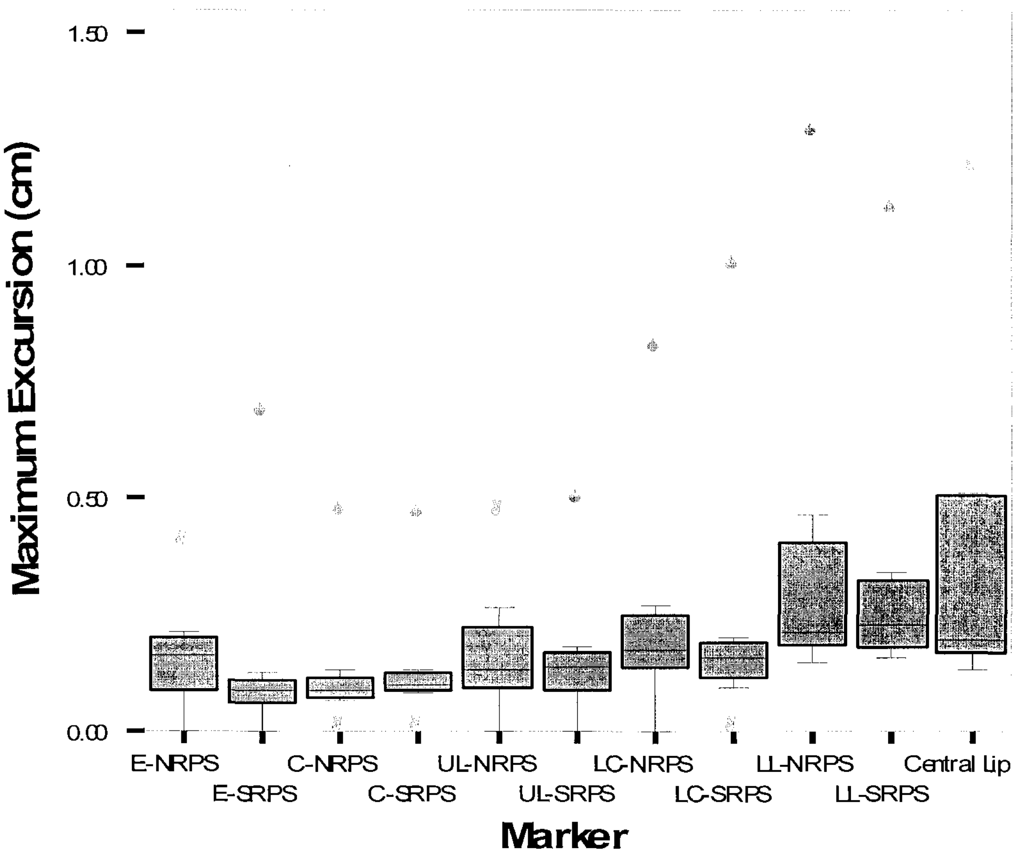


Figure 4.2: Maximum excursions at each marker with tasks collapsed.



Legend

E-NRPS – Eyebrow - Non-Paralyzed Side	E-SRPS – Eyebrow - Surgically-Repaired Paralyzed Side
C-NRPS – Cheek - Non-Paralyzed Side	C-SRPS – Cheek - Surgically-Repaired Paralyzed Side
UL-NRPS – Upper Lip - Non-Paralyzed Side	UL-SRPS – Upper Lip - Surgically-Repaired Paralyzed Side
LC-NRPS – Lip Corner - Non-Paralyzed Side	LP-SRPS – Lip Corner - Surgically-Repaired Paralyzed Side
LL-NRPS – Lower Lip - Non-Paralyzed Side	LL-SRPS – Lower Lip - Surgically-Repaired Paralyzed Side
CL – Central Lip	

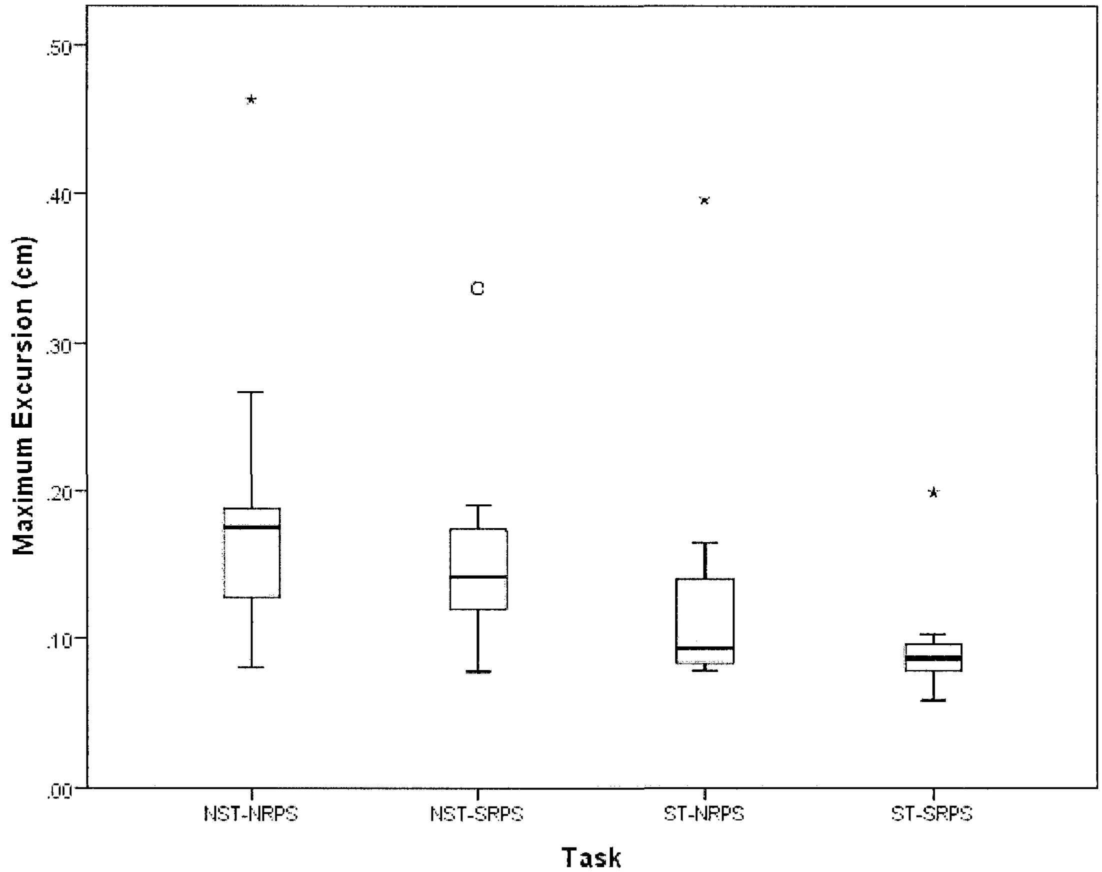
Overall, maximum excursions were small and fairly consistent across all markers. The lower and central lip markers created the largest and most variable movements when compared to the other face markers and the cheeks produced some of the smallest. Although the NRPS lip corner generated excursions that were comparable to most of the markers, it did produce the second largest excursions.

Maximum excursions produced at each side of the face were quite similar. Nonetheless, asymmetries in movement can be observed. With a few exceptions, notably *chewing the winegum* at the eyebrows, upper lip, and lip corners and *smiling* at the cheeks and lip corners, the NRPS tended to generate maximum excursions that were slightly larger than those recorded on the SRPS.

A summary of the activities that produced the largest maximum excursions is listed in Appendix I. Most of the tasks produced similar movements; however, *chewing the winegum* produced large maximum excursions at all of the face markers. */wi/* and *Jack and Jill* also created relatively large movements at the central and lower lips.

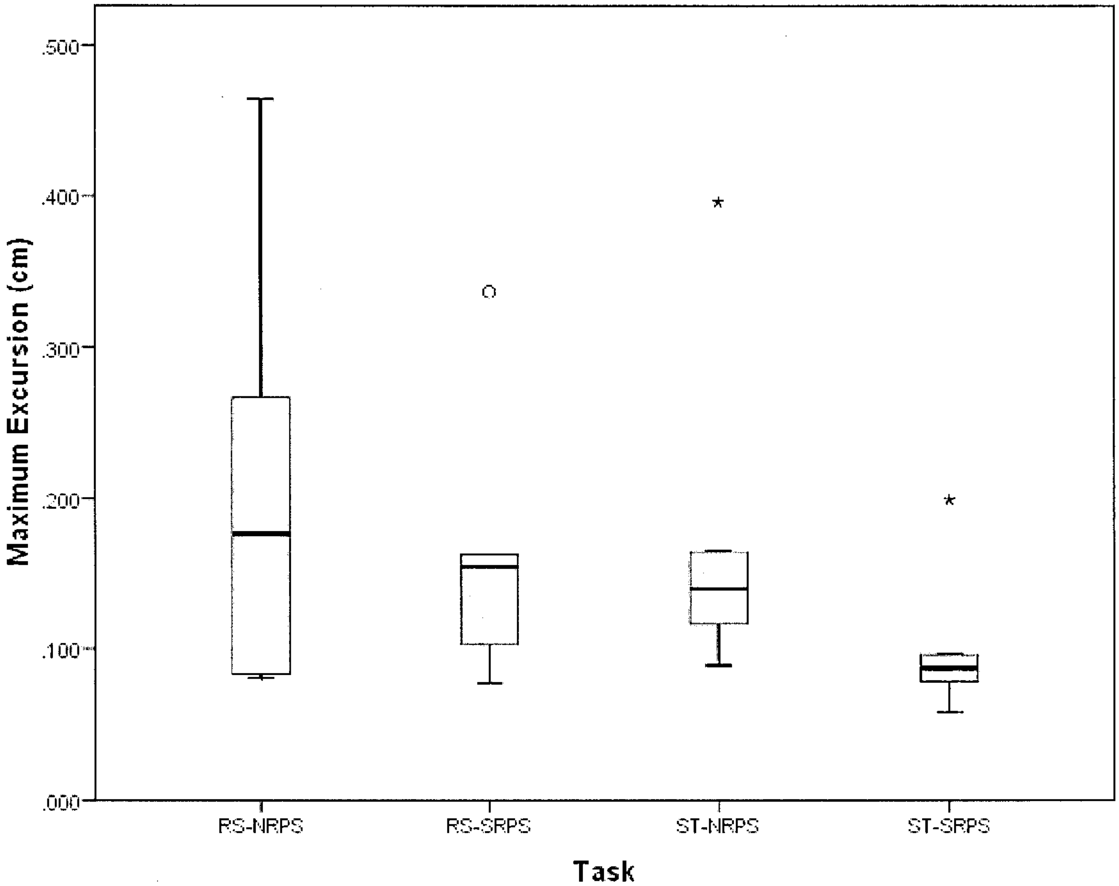
Maximum excursions produced during non-speech tasks (i.e., *smiling* and *puckering*) and speech tasks (i.e., */bi/*, */pi/*, /fi/, /wi/, and *Jack and Jill*) also were compared (see Figure 4.3). When comparing non-speech tasks (i.e., *smiling* and *puckering*) and speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, and *Jack and Jill*), non-speech tasks produced slightly larger and more variable maximum excursions than did the speech tasks. When comparing connected speech (i.e., *Jack and Jill*) to the isolated speech tokens (i.e., */bi/*, */pi/*, /fi/, /wi/), running speech generated larger and more variable maximum excursions (see Figure 4.4). Movements produced on the NRPS during running speech were particularly variable.

Figure 4.3: Maximum excursions collapsed across non-speech and speech tasks



Legend
NST-NRPS -- Non-Speech Tasks--Non-Repaired Paralyzed Side
NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side
ST-NRPS – Speech Tasks--Non-Repaired Paralyzed Side
ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 4.4: Maximum excursions collapsed across running speech and the speech tokens



Legend

RS-NRPS – Running Speech--Non-Repaired Paralyzed Side

RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side

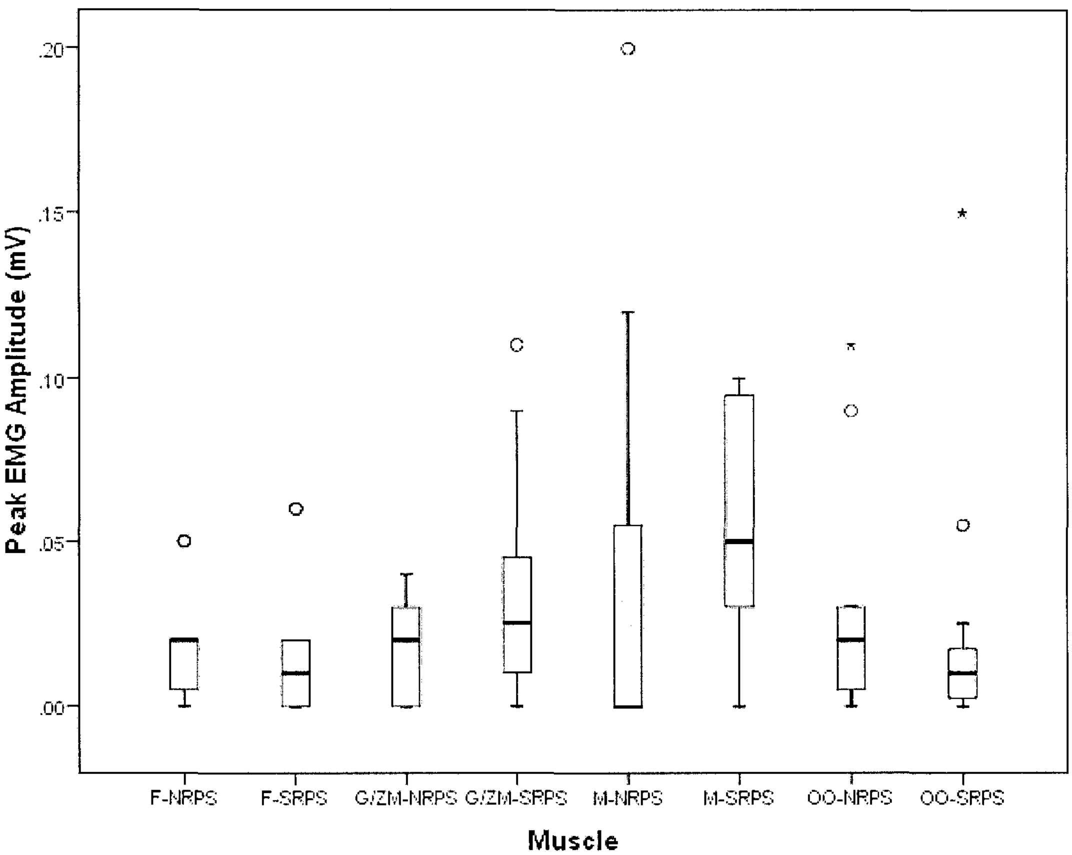
ST-NRPS – Speech Tokens--Non-Repaired Paralyzed Side

ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

EMG

Peak EMG amplitudes produced at each muscle are shown in Figure 4.5, 4.6 and 4.7. Although the peak amplitudes recorded were quite similar, some variability existed across muscles, side of the face and tasks. While a synopsis of the EMG data is presented and reviewed below, tables reviewing the data for each individual muscle are listed in Appendix I.

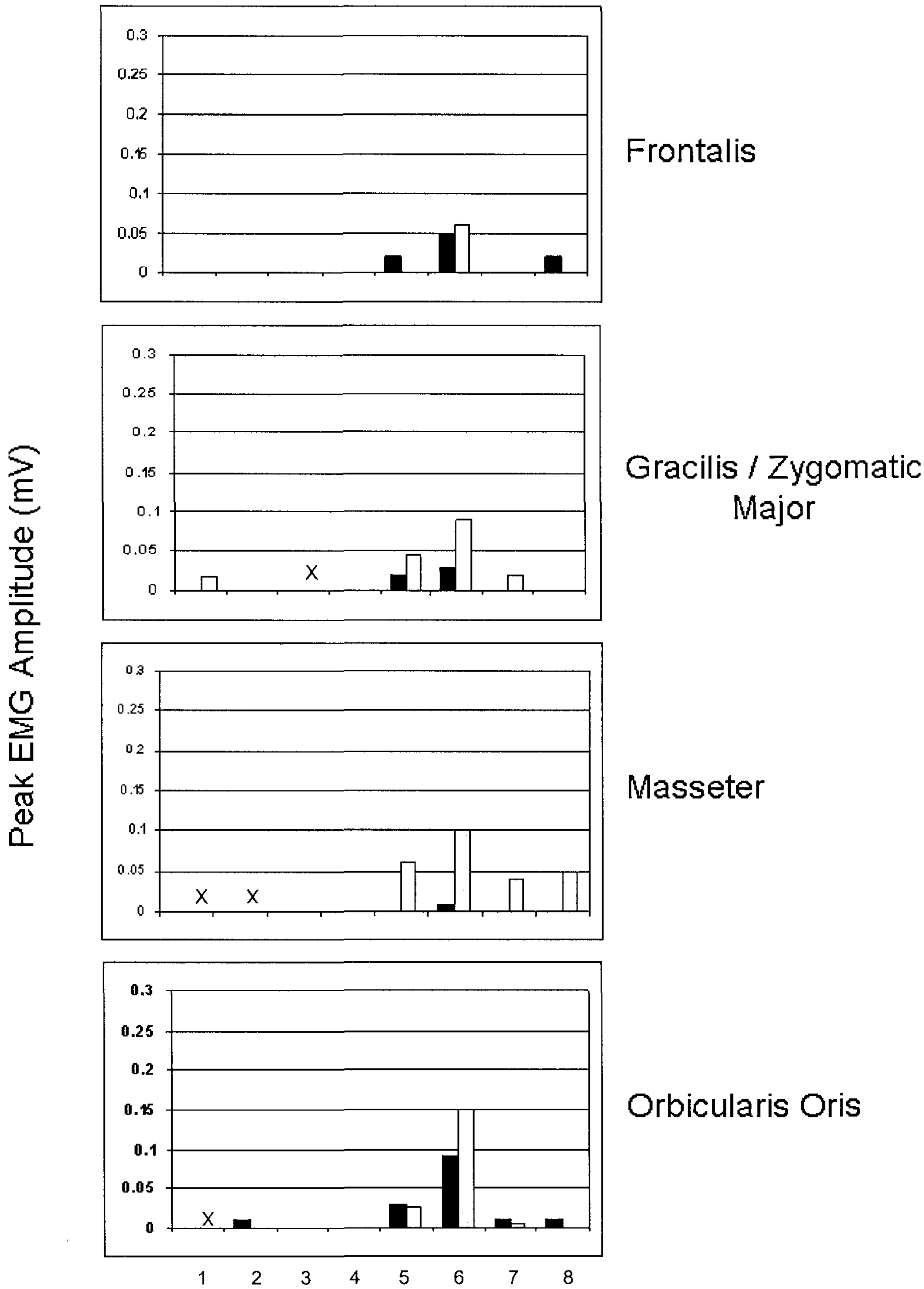
Figure 4.5: Peak EMG amplitudes for each muscle collapsed across tasks



Legend

F-NRPS – Frontalis Non-Repaired Paralyzed Side
F-SRPS – Frontalis Surgically-Repaired Paralyzed Side
G/ZM-NRPS – Gracilis/Zygomatic Major Non-Repaired Paralyzed Side
G/Z-SRPS – Gracilis/Zygomatic Major Surgically-Repaired Paralyzed Side
M-NRPS – Masseter Non-Repaired Paralyzed Side
M-SRPS – Masseter Surgically-Repaired Paralyzed Side
OO-NRPS – Orbicularis Oris Non-Repaired Paralyzed Side
OO-SRPS – Orbicularis Oris Surgically-Repaired Paralyzed Side

Figure 4.6: Peak EMG amplitudes by facial marker and task



Legend

1 – bi　2 – pi　3 – fi　4 – wi

5 – Jack & Jill　6 – Winegum　7 – Smile　8 - Pucker

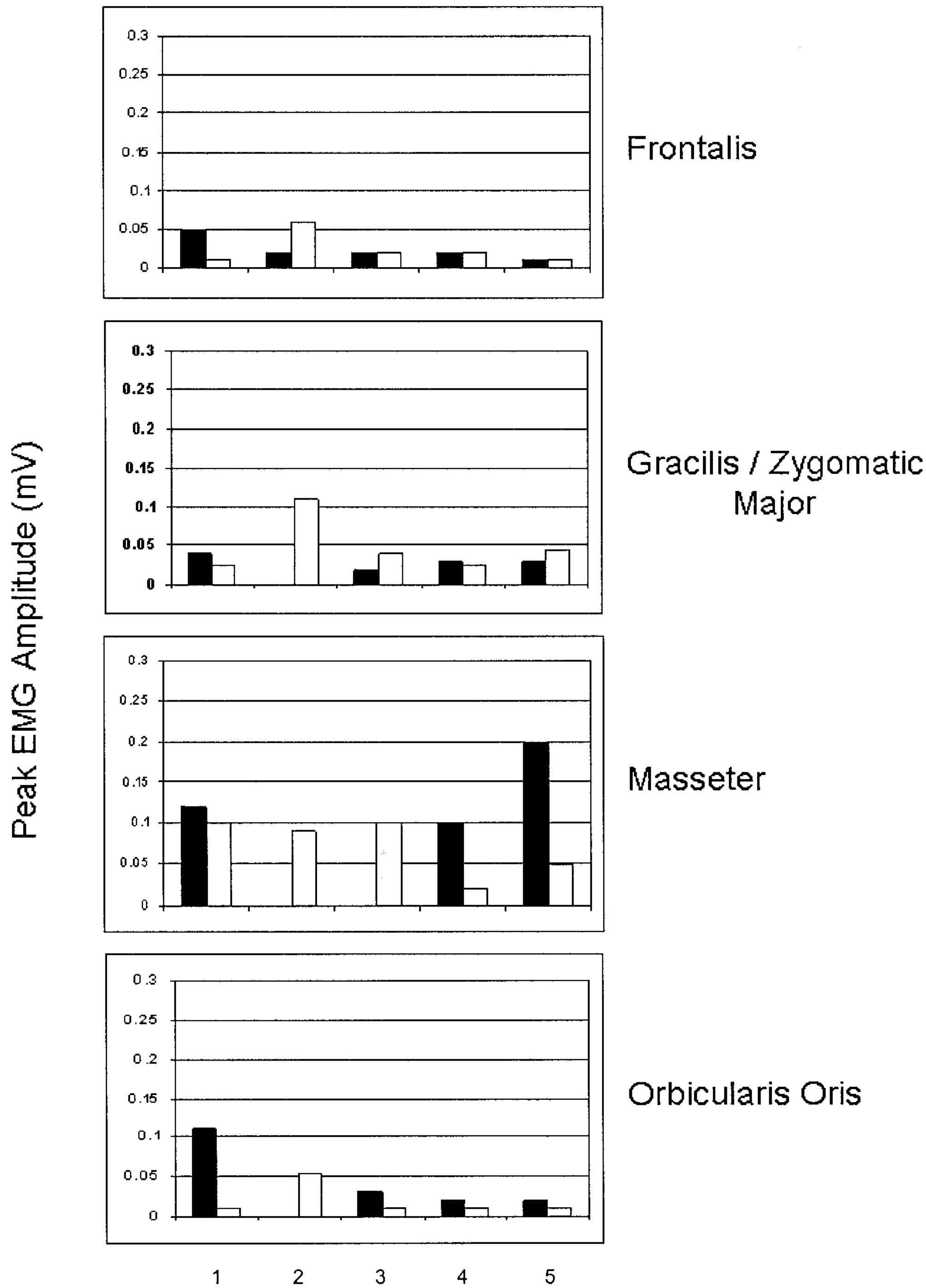
Legend

● Non-Repaired Paralyzed Side

○ Surgically-Repaired Paralyzed Side

X Unable to Analyze

Figure 4.7: Peak EMG amplitudes by facial marker and task



Legend

1 – Pudding 2 – Drinking

3 – Press 4 – Frown 7 – Clench

Legend

● Non-Repaired Paralyzed Side

○ Surgically-Repaired Paralyzed Side

X Unable to Analyze

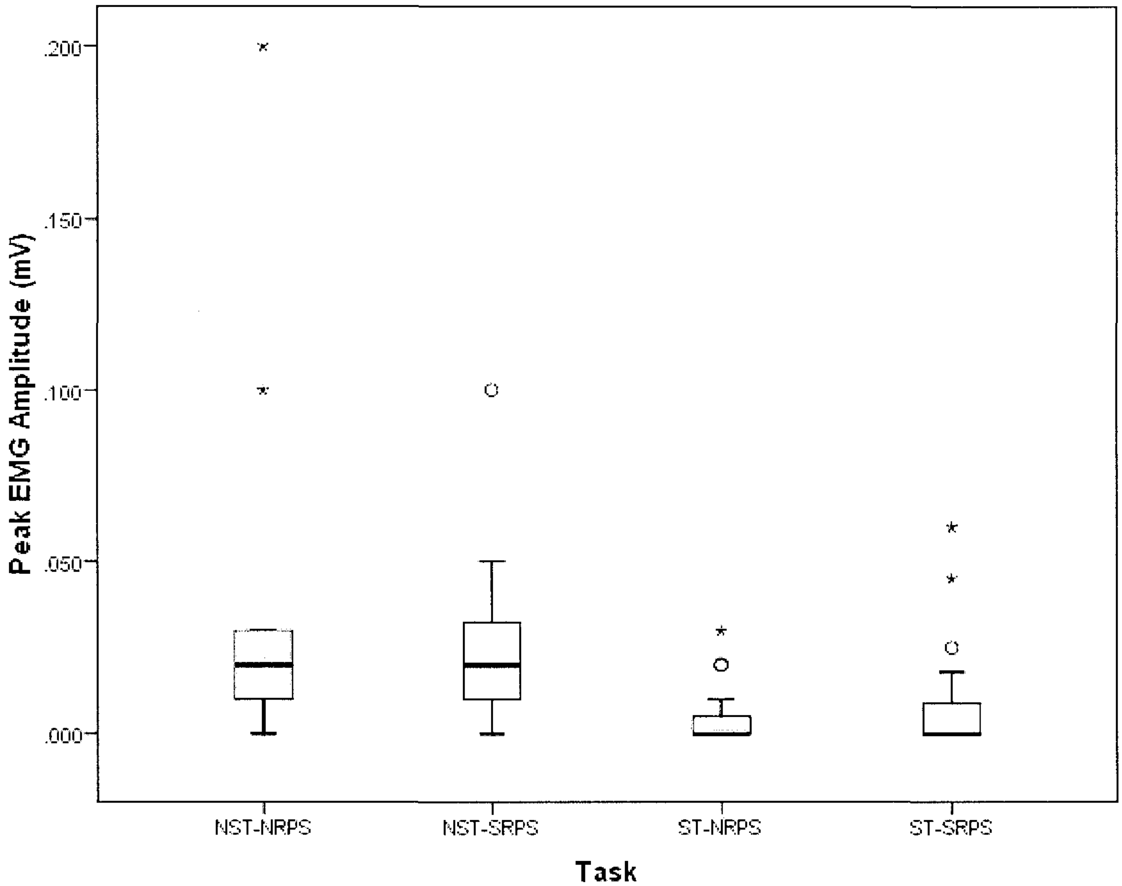
Overall, peak amplitudes were comparable across each of the muscles. However, the largest amplitudes were produced at the masseter on the SRPS. Although the masseter produced some of the largest amplitudes on the NRPS during some of the activities, the orbicularis oris produced some of the most consistent amplitudes on this side.

Asymmetries in the peak amplitudes produced at each side of the face were variable across muscles. With the exception of *chewing the winegum* and *drinking*, peak amplitudes recorded on the NRPS were larger than those recorded on the SRPS at the frontalis and the orbicularis oris. With the exception of *consuming the pudding* and *frowning*, peak amplitudes produced on the SRPS were larger than those produced on the NRPS at the gracilis and the masseter.

With the exception of the individual speech tokens (i.e., */bi/*, */pi/*, */fi/*, and */wi/*), many of the tasks produced relatively large peak amplitudes (see Table 5.21 in Appendix I for a summary of the activities that produced the largest peak amplitudes). In particular, the masticatory tasks (*chewing the pudding* and *consuming the pudding* on the NRPS and *chewing the winegum* and *drinking* on the SRPS) produced some of the largest peak amplitudes. Some tasks produced barely detectable signals (i.e., < 0.005 mV) (see Tables 5.13 – 5.20 for a summary).

Non-speech tasks (i.e., *smiling* and *puckering*) tended to produce slightly higher peak amplitudes than the speech tasks (i.e., */bi/*, */pi/, /fi/, /wi/*, and *Jack and Jill*) (see Figure 4.8). Moreover, running speech (i.e., *Jack and Jill*) produced larger and more variable maximum excursions when compared to the speech tokens (i.e., */bi/*, */pi/, /fi/, /wi/*) (see Figure 4.9).

Figure 4.8: Peak EMG amplitudes collapsed across non-speech and speech tasks



Legend

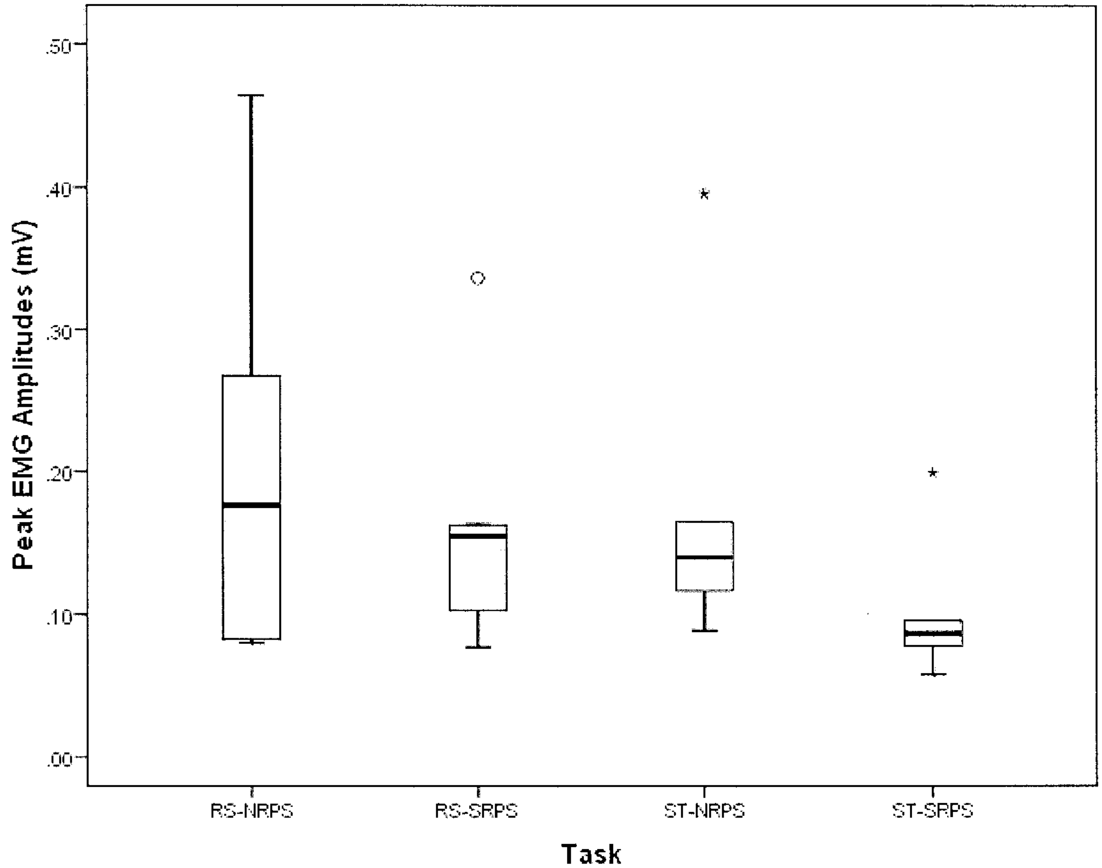
NST-NRPS -- Non-Speech Tasks--Non- Repaired Paralyzed Side

NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side

ST-NRPS – Speech Tasks--Non-Repaired Paralyzed Side

ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 4.9: Peak EMG amplitudes collapsed across running speech and the speech tokens



Legend

RS-NRPS – Running Speech--Non-Repaired Paralyzed Side

RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side

ST-NRPS – Speech Tokens--Non-Repaired Paralyzed Side

ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

Atypical waveforms were recorded from several of the muscles (see Table 5.22 in Appendix I for a summary). Three out of the out of 52 EMG signals recorded from the NRPS and 2/52 signals recorded from the NPS were abnormal. These abnormal waveforms tended to occur during the masticatory tasks.

Relationship Between Kinematic Measures and EMG Peak Amplitudes

The relationship between kinematic and EMG measures again was ambiguous and variable in this subject. When analyzing overall facial activation, it is apparent that the lower half of the face (i.e., the masseter/central lip and the orbicularis oris/lower lip) produced larger maximum excursions and peak amplitudes when compared to the upper face (i.e., the frontalis/eyebrows).

Asymmetries in EMG between each side of the face were not necessarily the same as the asymmetries in movement between each side of the face. One side of the face usually produced larger maximum excursions or peak amplitudes when compared to the other. The side that produced the largest excursions did not necessarily produce the largest peak amplitudes. For instance, the SRPS produced larger peak amplitudes in the gracilis while the NRPS produced larger maximum excursions at the lip corners. However, the NRPS did produced excursions *and* amplitudes that were larger than those produced at the SRPS in gracilis/lip corners and the orbicularis oris/lower lip.

The relationship between kinematic and EMG measures varied across tasks and markers/muscles and both positive and negative relationships were evident. For example, a positive relationship existed between kinematic and

EMG data during chewing at all of the muscle/marker pairs. This activity produced relatively high peak amplitudes and correspondingly large movement excursions. A positive relationship also was noted during *Jack and Jill* at the masseter and central lip and the orbicularis oris and lower lip. This activity produced moderate maximum excursions of movement and peak EMG amplitudes on both these muscle/marker pairs. Several negative relationships also were evident. For example, a negative relationship was apparent at both the masseter/central lip and the orbicularis oris and lower lip; this activity produced some of the largest movements at these markers, but small peak EMG amplitudes in the corresponding muscles. A negative relationship also existed at the orbicularis oris and the lower lip during smiling. Relatively small peak EMG amplitudes were recorded at the orbicularis oris during this task, but movements at the lower lip were quite large.

S4 Summary

As a result of Mobius syndrome, this subject's face has been bilaterally paralyzed since birth. During spontaneous speech, he had very little facial expression and when not smiling, his faced moved only a small amount. His speech was difficult to understand and listeners reported several sound substitutions for the bilabials /p/, /b/ and /m/. Moderate difficulties with mastication and oral continence were noted. Saliva and semi-solids often pooled behind his lower lip and in the oral cavity. Following the first masseter nerve surgery, movement and EMG recordings were detected during most tasks. In terms of overall facial activity, the lower half of the face (i.e., the masseter/central lip and the orbicularis oris/lower lip) produced larger maximum excursions and peak amplitudes when compared to the upper face (i.e., the frontalis/eyebrows).

Asymmetries in movement between each side of the face were apparent and in some cases, the NRPS produced larger excursions/peak EMG amplitudes than did the SRPS. For instance, during most tasks the NRPS lip corner produced maximum excursions that were equal to or larger than those produced at the SRPS lip corner. For instance, while excursions on both sides of the face were similar during *puckering*, the NRPS generated excursions that were 57% larger those on the SRPS during running speech (i.e., *Jack and Jill*). Two exceptions to this trend were observed during *smiling* and while *chewing the winegum*. During *smiling*, the SRPS produced excursions that were 39% larger than those produced on the SRPS while the excursions recorded on the SRPS were 18% larger during *chewing*.

Asymmetries in peak amplitudes also were observed when comparing each side of the face. Peak EMG amplitudes generated on the SRPS were usually larger than those generated on the NRPS in the gracilis and the masseter. For example, while a barely detectable signal (< 0.005 mV) was recorded during *smiling* at the gracilis/zygomatic major on the NRPS, a peak amplitude of 0.02 mV was recorded during this same task at the gracilis/zygomatic major on the SRPS. While barely detectable signals were recorded on both sides of the face during *puckering*, the SRPS also produced larger peak amplitudes than the NRPS during running speech (i.e., *Jack and Jill*) and *while chewing the winegum*.

During most tasks, including *smiling*, *puckering*, *Jack and Jill*, *chewing the winegum* and *drinking*, larger peak EMG amplitudes were recorded in the masseter on the SRPS. For instance, the SRPS produced peak amplitudes that were 90% larger than those produced at the NRPS while *chewing the winegum*. Interestingly, the opposite pattern was seen while the subject *consumed the pudding* and *clenched* his teeth. While clenching, NRPS produced peak amplitudes that were 75% larger than those produced on the SRPS.

The relationship between EMG and kinematic data was variable and both positive and negative relationships were evident. For example, a positive relationship existed between peak EMG amplitudes and maximum movement excursions during non-speech (i.e., *smiling* and puckering) and speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, and *Jack and Jill*). A negative relationship existed at the orbicularis oris and lower lips during *smiling* (i.e., movement was relatively high, while peak EMG amplitudes were quite low).

Case Report S5

Case Information and History

When this 11 year-old boy was 2 years old, he suffered a right occipital skull fracture which resulted in unilateral facial palsy. In addition, he was diagnosed with right-sided sensorineural hearing loss. Hearing in the left ear was within normal limits. Nerve transposition of the facial nerve occurred 7 months prior to the transfer of the gracilis muscle to the face. Evaluation for the present investigation took place 1 year and 5 months following the transfer of the gracilis to the face.

Oral Mechanism Exam

The oral mechanism exam revealed mild flaccidity of the facial musculature and a mildly drooped lip on the surgically repaired paralyzed side (SRPS). Ptosis and drooling were not noted. During spontaneous conversation, the non-paralyzed side (NPS) of the upper face (i.e., eyebrow) moved more than SRPS of the upper face. Moreover, lip movement on the SRPS during running speech was minimal. Lip strength was mildly impaired on the SRPS when the subject smacked his lips and when he was asked to hold a tongue depressor between his lips on that side in opposition to the clinician pulling on the depressor. Furthermore, the subject held slightly less air in the SRPS cheek than the NPS when puffing out his cheeks. Although the subject had adequate lip corner excursion on the NPS, his smile was asymmetrical with less lateral excursion on the SRPS. Excursion on the SRPS was even smaller when the smile was spontaneous. Larger excursions also were observed on the NPS of the lips when the subject puckered. Instead of moving medially and anteriorly, the SRPS tended to move laterally during this task. Although the subject was unable to blow up a balloon, he did appear to have an adequate lip seal around the opening. Based on clinical judgment, jaw strength and range of motion appeared adequate. Respiration and voice were within normal limits and tissues of the palate and oral cavity appeared healthy.

Mastication and Swallowing Exam

Although some mild difficulties with oral competence and mastication were noted during this exam, this subject's mastication and swallowing were completely functional. Coughing, choking or dribbling of the food bolus outside of the oral cavity did not occur while eating or drinking. Additionally, the amount of food per bite and rate of mastication were typical. Although the subject was able to create a tight lip seal around the cup and spoon, a small amount of liquid and semi-solid residue was noted on his lips. Mild mouth opening occasionally occurred on the SRPS when the subject consumed the winegum. The subject was noted to make the following adaptations. Food was masticated on the NPS and an adapted spoon position was used (i.e., the spoon was turned towards the NPS of the mouth). The subject did remove liquid and solid residue from his lips using a napkin and his tongue.

Speech Measures - Articulation and Speech Intelligibility

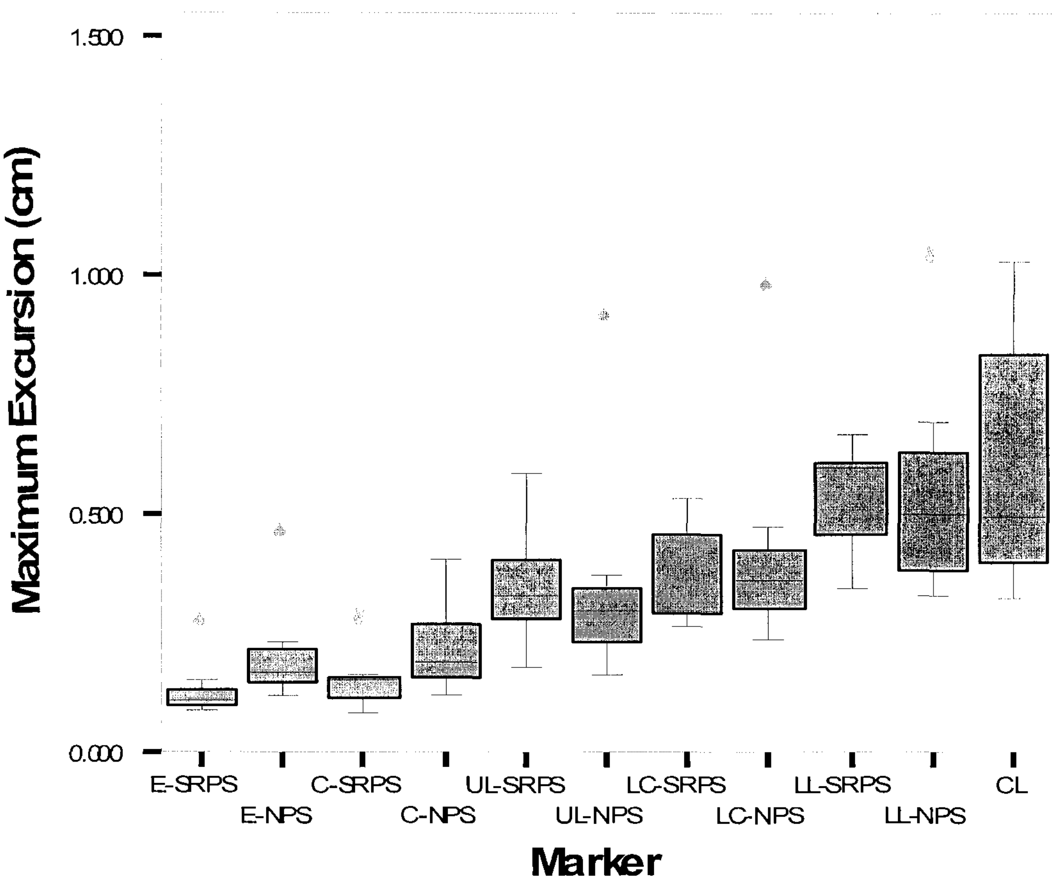
On the whole, scores on articulation and intelligibility measures were high and difficulties in speech were not observed during testing. The average PCC across listeners was 97%. Two errors were reported each involving substitutions of /m/ for /n/ (i.e., /mi/ for /ni/ and /mu/ for /nu/). The average intelligibility rating from listeners was 94%. Furthermore, the investigator was able to understand everything the subject said in face-to-face conversation.

2D Kinematic Measures

An overall summary of kinematic data is presented next while summary tables for each individual marker are reported in Appendix J. Please note that kinematic and EMG data were not recorded during smiling for this subject. Maximum excursions produced at each marker are shown in Figure 5.1 and

Figure 5.2. It is apparent that movement was variable across markers, side of the face and task.

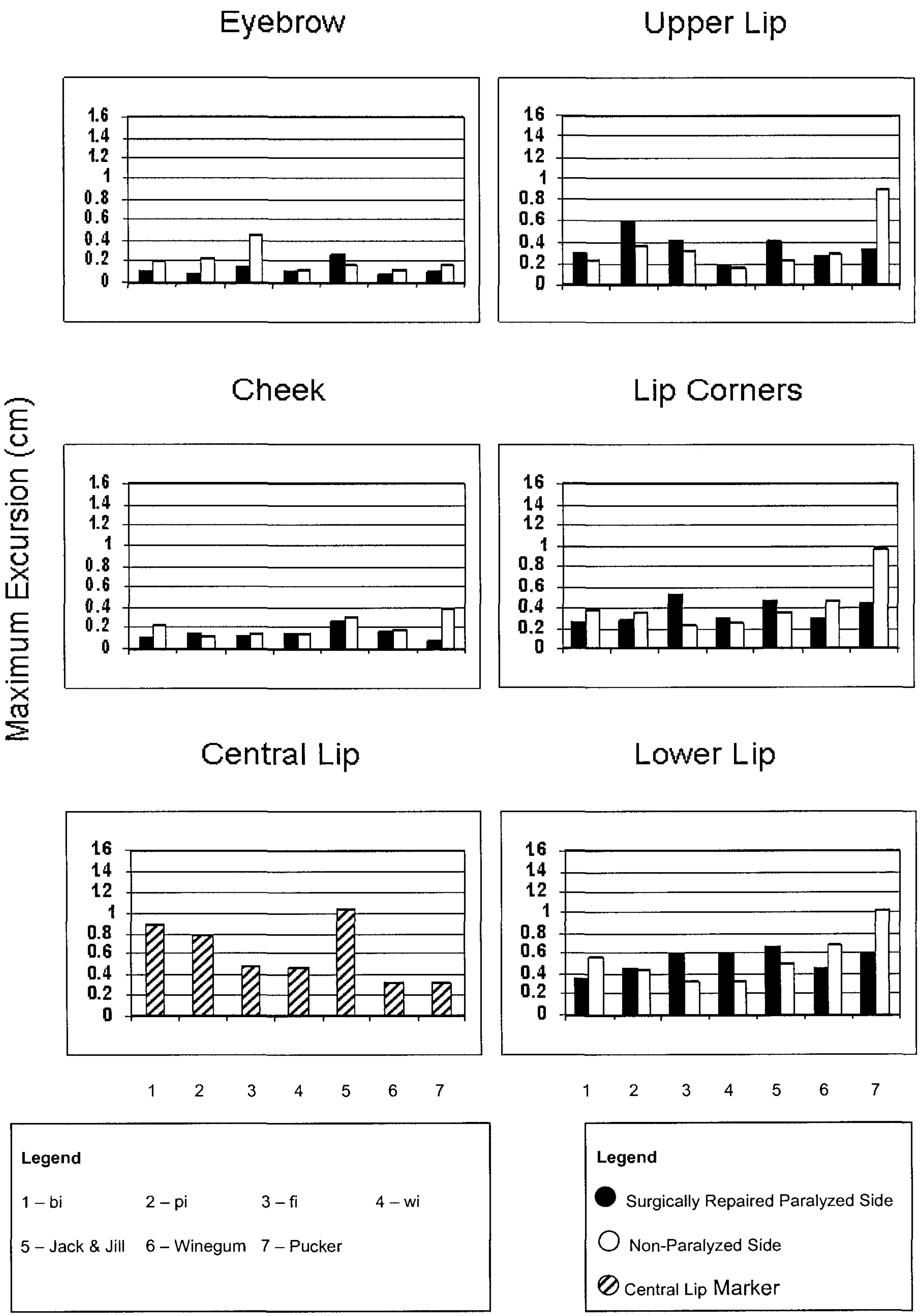
Figure 5.1: Maximum excursions at each marker with tasks collapsed



Legend

E-NPS – Eyebrow - Non-Paralyzed Side	E-SRPS – Eyebrow - Surgically-Repaired Paralyzed Side
C-NPS – Cheek - Non-Paralyzed Side	C-SRPS – Cheek - Surgically-Repaired Paralyzed Side
UL-NPS – Upper Lip - Non-Paralyzed Side	UL-SRPS – Upper Lip - Surgically-Repaired Paralyzed Side
LC-NPS – Lip Corner - Non-Paralyzed Side	LP-SRPS – Lip Corner - Surgically-Repaired Paralyzed Side
LL-NPS – Lower Lip - Non-Paralyzed Side	LL-SRPS – Lower Lip - Surgically-Repaired Paralyzed Side
CL – Central Lip	

Figure 5.2: Maximum excursions produced at each marker



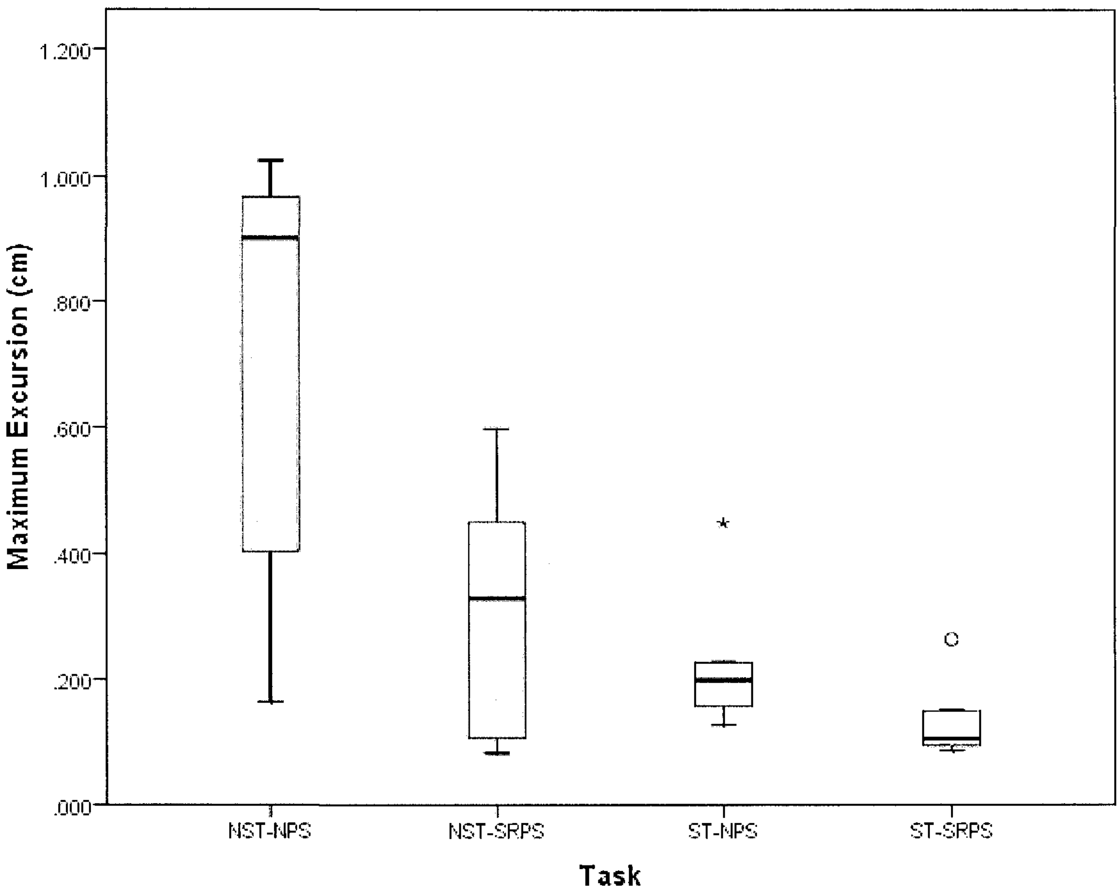
When visually analyzing the figures 5.1 and 5.2 for trends related to overall movement, it is apparent that the lower face produced larger maximum excursions when compared to the upper face. The largest excursions were recorded on both sides of the lower lips and at the central lip marker. The smallest excursions were found on both sides of the eyebrows.

When comparing maximum excursions across the face, the side that produced the largest movements varied across tasks and markers (see Tables 6.1 – 6.11 in Appendix J for a summary). Overall, the NPS generated larger and more variable maximum excursions than did the SRPS. The exception to this trend was observed at the upper lip where the SRPS produced larger movements. Across markers, excursions tended to be larger on the SRPS during *Jack and Jill*, */fi/*, and */wi/.*

A summary of the activities that produced the largest maximum excursions is listed in Appendix J. Whereas *chewing the winegum* and *puckering* produced some of the largest excursions on the NPS, *Jack and Jill* produced some of the largest excursions on the SRPS. Interestingly, some the individual speech tokens (i.e., */bi/*, */pi/*, */fi/*, */wi/*) also produced relatively large excursions when compared to the other tasks (i.e., */fi/* on the SRPS and */bi/* and */pi/* on the NPS).

Maximum excursions produced during non-speech tasks (i.e., *puckering*) and speech tasks (i.e., */bi/*, */pi/*, /fi/, /wi/, and *Jack and Jill*) also were compared (see Figure 5.3). Maximum excursions recorded during the non-speech tasks were larger and more variable than those recorded during speech tasks. Additionally, maximum excursions tended to be larger and more variable during connected speech (i.e., *Jack and Jill*) than during the production of isolated speech tokens (see Figure 5.4).

Figure 5.3: Maximum excursions collapsed across non-speech and speech tasks



Legend

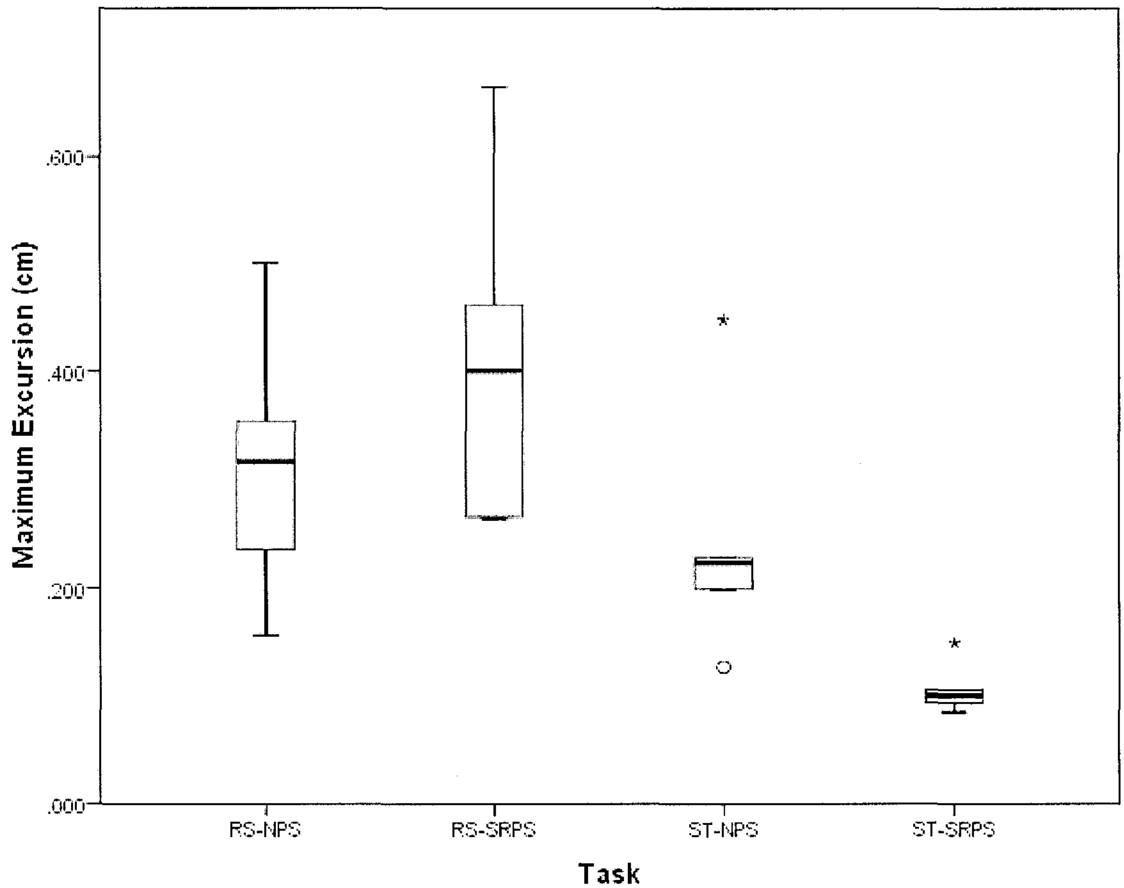
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 5.4: Maximum excursions collapsed across running speech and the speech tokens



Legend

RS-NPS – Running Speech--Non-Paralyzed Side

RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tokens--Non-Paralyzed Side

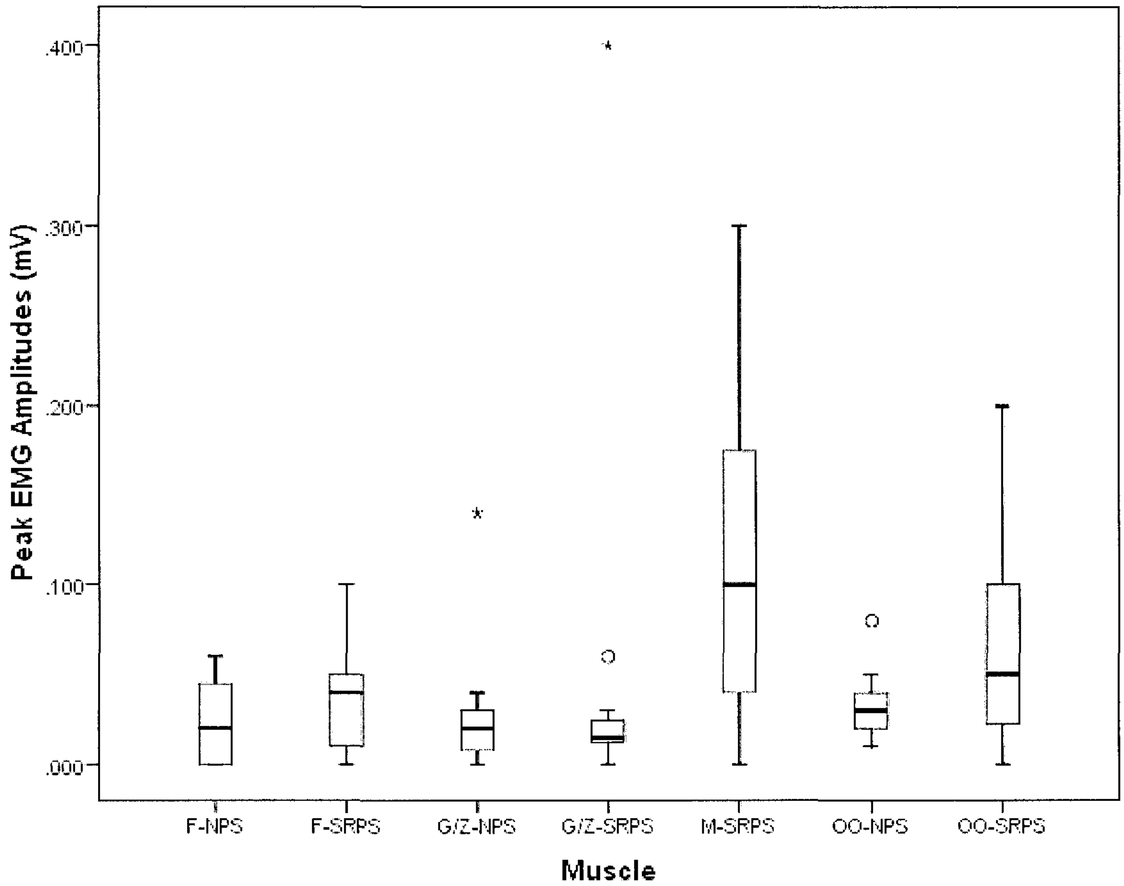
ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

EMG

Peak EMG amplitudes by facial marker are shown in Figure 5.5, 5.6, and 5.7. Like the kinematic data, peak amplitudes varied across muscles, side of the face, and task. Note that EMG data were not collected during *smiling*.

Additionally, data obtained from the masseter on the NPS were unusable. An overall impression of EMG measures is reviewed below while summary tables for each individual muscle are presented in Appendix J.

Figure 5.5: Peak EMG amplitudes for each muscle collapsed across tasks



Legend

F-NPS – Frontalis Non-Paralyzed Side
F-SRPS – Frontalis Surgically-Repaired Paralyzed Side
G/ZM-NPS – *Gracilis/Zygomatic Major* Non-Paralyzed Side
G/Z-SRPS – Gracilis/Zygomatic Major Surgically-Repaired Paralyzed Side
M-NPS – Masseter Non-Paralyzed Side
M-SRPS – Masseter Surgically-Repaired Paralyzed Side
OO-NPS – Orbicularis Oris Non-Paralyzed Side
OO-SRPS – Orbicularis Oris Surgically-Repaired Paralyzed Side

Figure 5.6: Peak EMG amplitudes by facial marker and task

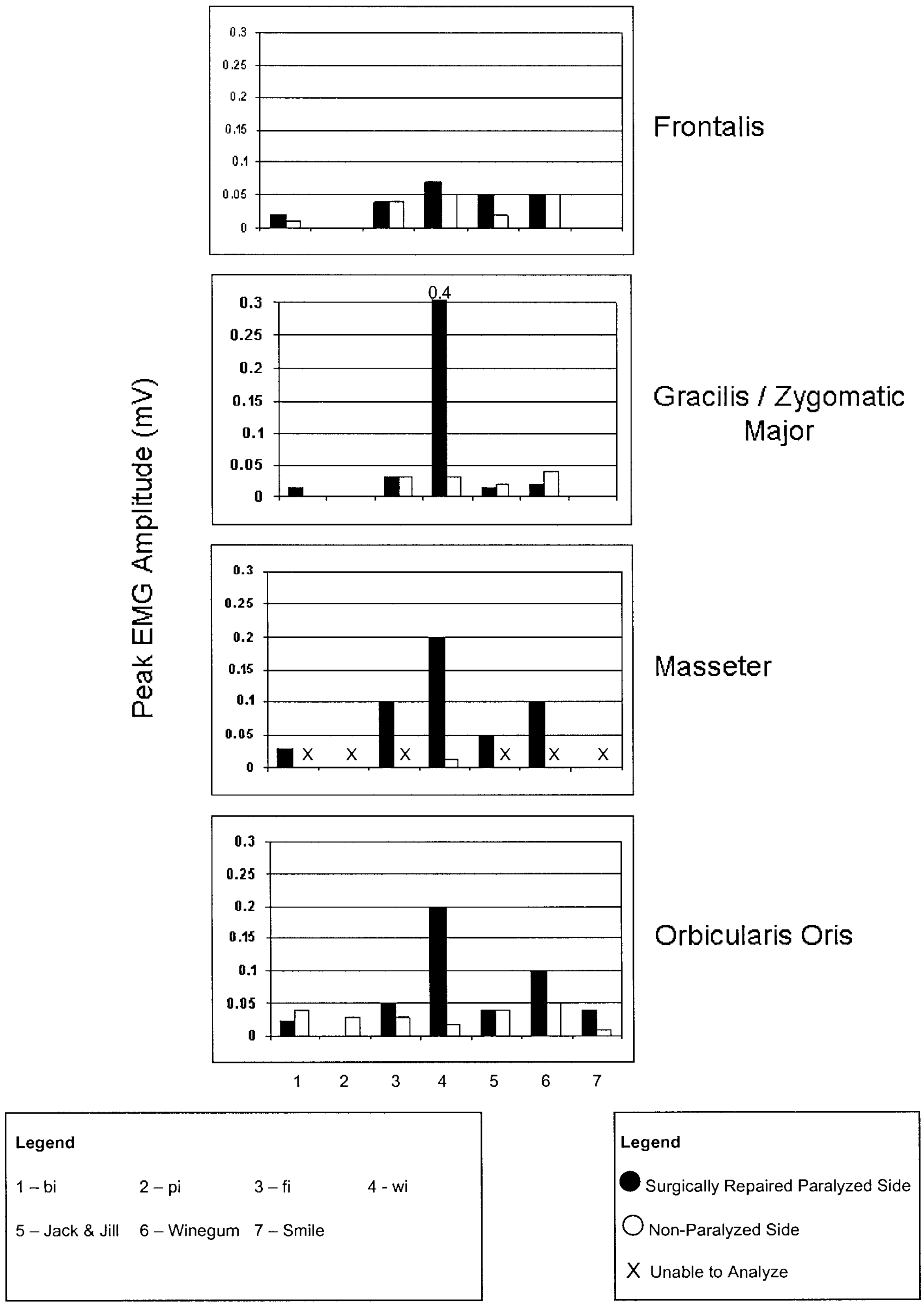
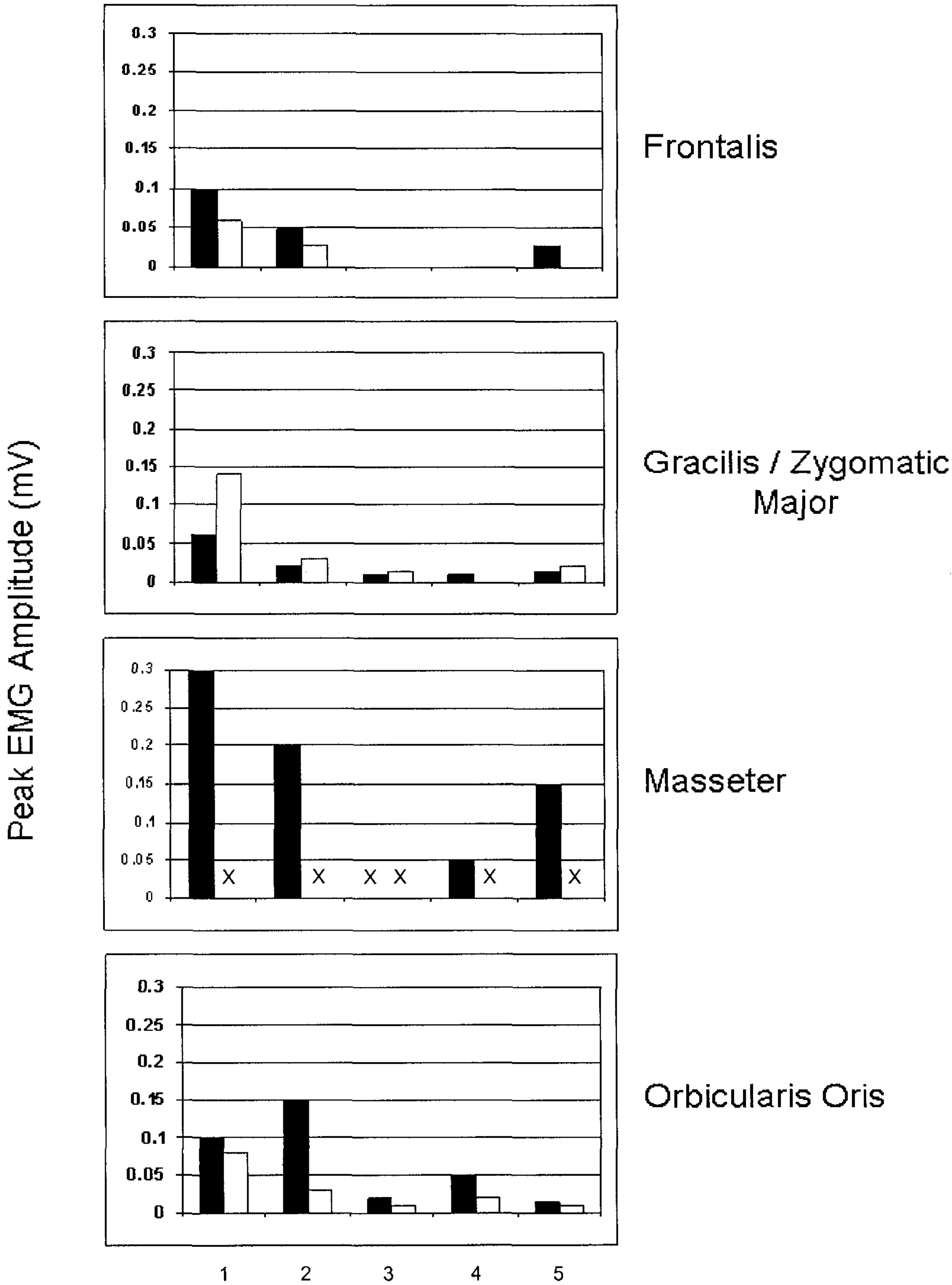


Figure 5.7: Peak EMG amplitudes by facial marker and task



Legend

1 – Pudding 2 – Drinking

3 – Press 4 – Frown 7 – Clench

Legend

● Surgically Repaired Paralyzed Side

○ Non-Paralyzed Side

X Unable to Analyze

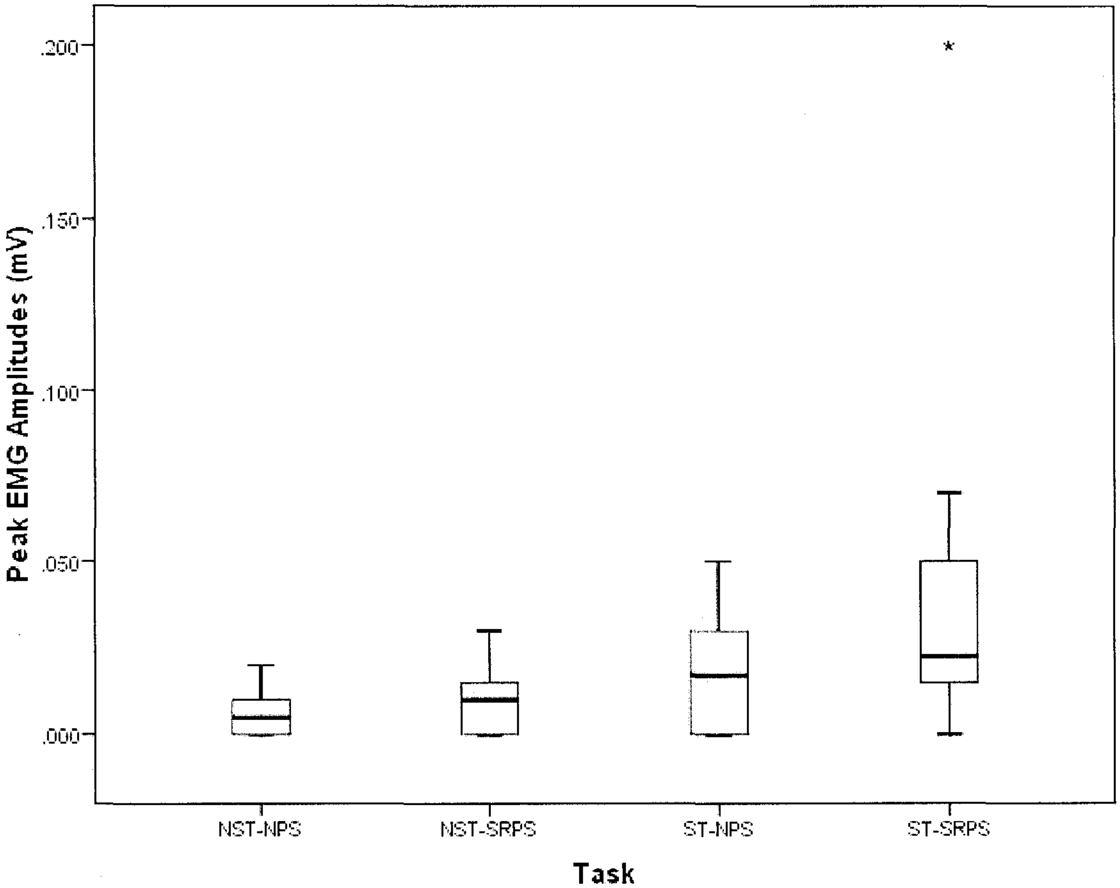
With a few exceptions (see Tables 6.13 – 6.20 in Appendix J for a summary of barely detectable signals), peak EMG amplitudes were generated across tasks in each of the muscles. The masseter produced the largest and most variable peak amplitudes on the SRPS. Although the highest and most consistent peak amplitudes were produced at the orbicularis oris on the NPS, the frontalis also generated some relatively high peak amplitudes on this side of the face.

It is apparent from Figures 5.5, 5.6, and 5.7 above that asymmetries in peak EMG amplitudes existed between each side of the face. This varied across muscles and tasks. While the SRPS tended to generate larger peak amplitudes in the frontalis and the orbicularis oris, the NPS generated larger peak amplitudes in the gracilis/zygomatic major. Again, the masseter was excluded from this analysis as data obtained on the NPS of this muscle were unusable.

Several activities generated relatively large peak EMG amplitudes (see summary in Appendix J). In particular, */wi/*, *consuming the pudding*, and *drinking* produced some of the largest EMG signals on SRPS whereas *consuming the pudding* and *chewing the winegum* produced some of the largest signals on the NPS. The highest peak amplitudes across all muscles and tasks were produced in the gracilis/zygomatic major on the SRPS during the production of */wi/* and in the masseter on the SRPS while *consuming the pudding* .

When comparing the non-speech tasks (i.e., *puckering*) to the speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, and *Jack and Jill*), the speech tasks tended to produce higher and more variable amplitudes (see Figure 5.8). When comparing running speech (i.e., *Jack and Jill*) to the individual speech tokens (i.e., */bi/*, */pi/*, */fi/*, */wi/*), running speech tended to produce higher and more variable maximum amplitudes (see Figure 5.9).

Figure 5.8: Peak EMG amplitudes collapsed across non-speech and speech tasks



Legend

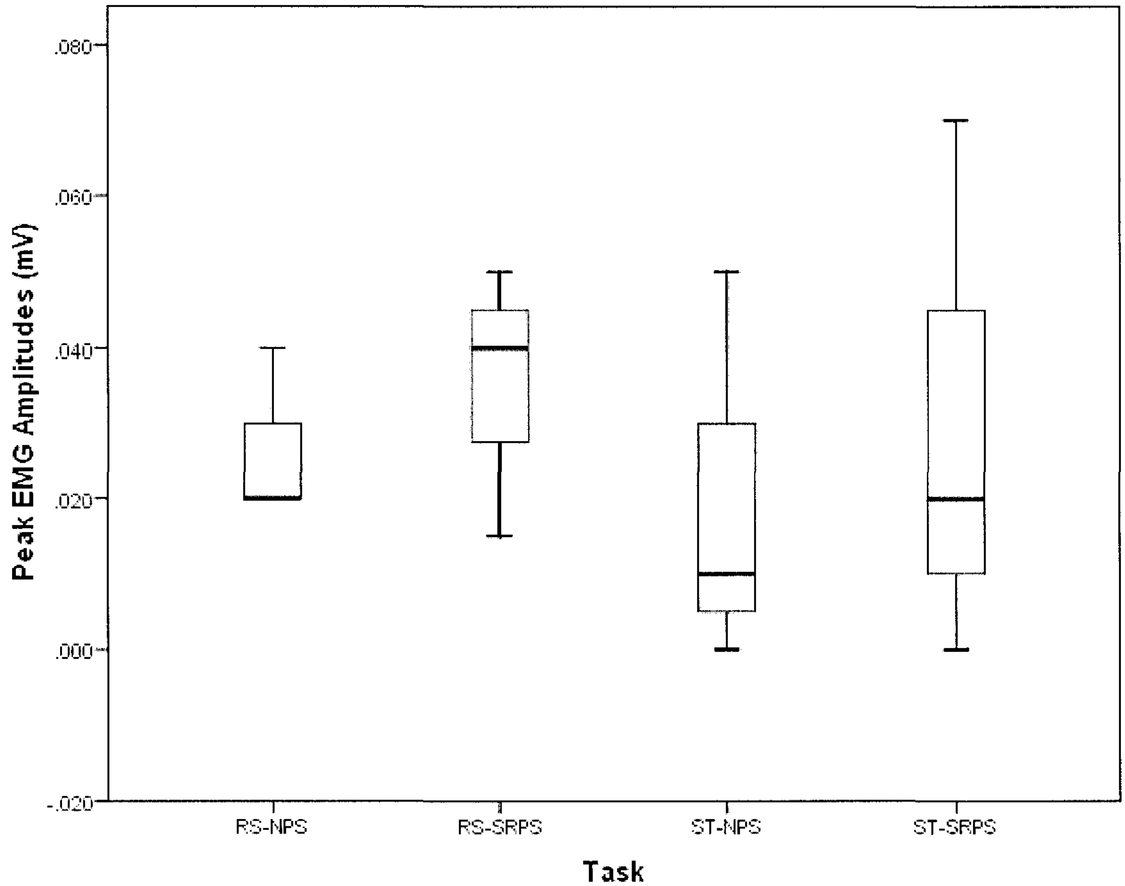
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 5.9: Peak EMG amplitudes collapsed across running speech and speech tokens



Legend

RS-NPS – Running Speech--Non-Paralyzed Side

RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tokens--Non-Paralyzed Side

ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

Although all 48 of the waveforms recorded on the NPS were typical, abnormal waveforms were recorded at each of the muscles on the SRPS (see Table 6.22 in Appendix J for a summary). 20/48 EMG signals recorded on the SRPS were atypical. These waveforms tended to occur during individual speech tokens (specifically, */bi/* and */fi/*) and the mastication tasks (particularity while *consuming the pudding* and *drinking*).

Relationship Between Kinematic Measures and EMG Peak Amplitudes

Relationships between kinematic and EMG measures again were variable. The orbicularis oris/lower lip and masseter/central lip muscle/markers pairs both produced some of the largest peak amplitudes/excursions. Although the frontalis also generated relatively large peak amplitudes, the eyebrows generated some of the smallest excursions when compared to the other face markers.

Asymmetries in EMG between each side of the face were not necessarily the same as the asymmetries in movement between each side of the face. Maximum excursions/peak amplitudes recorded at the gracilis and the lip corner were both larger on the NPS when compared to the SRPS. However, peak amplitudes were higher on the SRPS in the frontalis while maximum excursions were larger on the NPS of the eyebrows. While larger peak amplitudes were produced on the SRPS of the orbicularis oris, larger maximum excursions were recorded from the NPS of the lower lip.

Although the relationship between kinematic and EMG measures varied across tasks, the majority of these associations were negative in nature. For instance, a negative relationship existed between kinematic and EMG data during */wi/* at all of the muscle/marker pairs. This activity produced relatively high peak amplitudes, but small movement excursions. A negative relationship also was noted while *chewing the winegum* at the frontalis/eyebrows and at the masseter/central lip. This task also tended to produce large peak amplitudes, but small excursions at these muscle/marker pairs.

S5 Summary

After suffering an occipital skull fracture, this boy's face became unilaterally paralyzed characterized by mild weakness and flaccidity of the facial musculature and decreased lip ROM on the affected side. This subject was completely intelligible during spontaneous speech and listeners reported few articulation errors. Although very mild difficulties with oral continence were noted, this subject's mastication and swallowing were completely functional. Movement and EMG activity were recorded on both sides of the face during most tasks. Some of the largest peak amplitudes and excursions were recorded on the lower face (i.e., the masseter/central lip and the orbicularis oris/lower lip). Although large peak amplitudes also were produced at the frontalis, the eyebrows generated some of the smallest movements.

Although residual/recovered function was present following surgery, differences in movement and peak amplitudes between each side of the face still remained. In most cases, excursions recorded on the NPS were larger than those recorded on the SRPS. For example, movement at NPS lip corner was 54% larger than the movement recorded on the SRPS during *puckering*. Similarly, movement at the lip corner on the NPS was 38% larger than on the

SRPS during *puckering*. The opposite pattern occurred during running speech (i.e., *Jack and Jill*); the SRPS produced excursions that were 23% larger than those on the NPS during this task.

Although the SRPS generated larger peak amplitudes when compared to the NPS at the frontalis and orbicularis oris, the NPS produced larger peak amplitudes at the gracilis/zygomatic major. Even though both sides produced barely detectable signals (< 0.01 mV) during *puckering*, the NPS generated peak amplitudes that were 25% larger than those at the SRPS during running speech and 50% larger than those at the SRPS while *chewing the winegum*. This pattern also was evident during the other mastication tasks (i.e., *consuming the pudding* and *drinking*).

Positive and negative relationships between kinematic and EMG data were evident. For instance, a positive relationship existed between peak EMG amplitudes and maximum movement excursions during running speech (i.e., *Jack and Jill*) and the speech tokens (i.e., */bi/*, */pi/*, */fi/*, */wi/*). A negative relationship existed during non-speech (i.e., *smiling* and puckering) and speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, and *Jack and Jill*).

Case Report S6

Case Information and History

This 17-year-old female was born with left unilateral facial palsy. Reconstruction was achieved using the contralateral facial nerve grafted to a microvascular transfer of the gracilis muscle. The muscle was transferred 10 months after the initial nerve transposition procedure was complete. In addition, a revision of the free flap was completed to remove some of the bulkiness 1 year 8 months following the original muscle transfer. Testing for the current study occurred 2 years 11 months after the muscle transfer.

Oral Mechanism Exam

The oral mechanism exam revealed mild ptosis of the left eyelid, flaccidity of the left facial muscles. Some bulkiness was noted in the left cheek in the area of the transferred muscle. Whereas the eyebrow and upper face of the NPS showed animation during spontaneous speech, puckering and smiling, the eyebrow and upper face of the SRPS did not move during those tasks. Although the subject had adequate lip corner excursion on the NPS, her smile was slightly asymmetrical with less lateral excursion on the SRPS. Upper lip movement during smiling and puckering was limited on the SRPS. When puckering her lips, the subject's NPS tended to pull her SRPS towards center. No drooling was noted. Jaw ROM was adequate for opening and closing and side-to-side movement; however, a small deviation to the left was noted upon depression of the mandible. Based on clinical judgment, jaw strength in opposition to resistance from the clinician's hand appeared sufficient. Respiration and voice were within normal limits and tissues of the palate and oral cavity appeared healthy.

Mastication and Swallowing Examination

Based on the clinical examination, swallowing was deemed to be within normal limits and completely functional. Coughing, choking or dribbling of the food bolus outside of the oral cavity did not occur while eating or drinking. The amount of food per bite, mouth opening, and rate of mastication were all typical. However, the following adaptations were noted. Chewing solid food was predominantly done on the NPS and this subject used a slightly elevated spoon angle when consuming the pudding. A small amount of residue was noted on the paralyzed side of the lip while eating the pudding. The subject also used an adapted cup position turned toward the NPS when drinking.

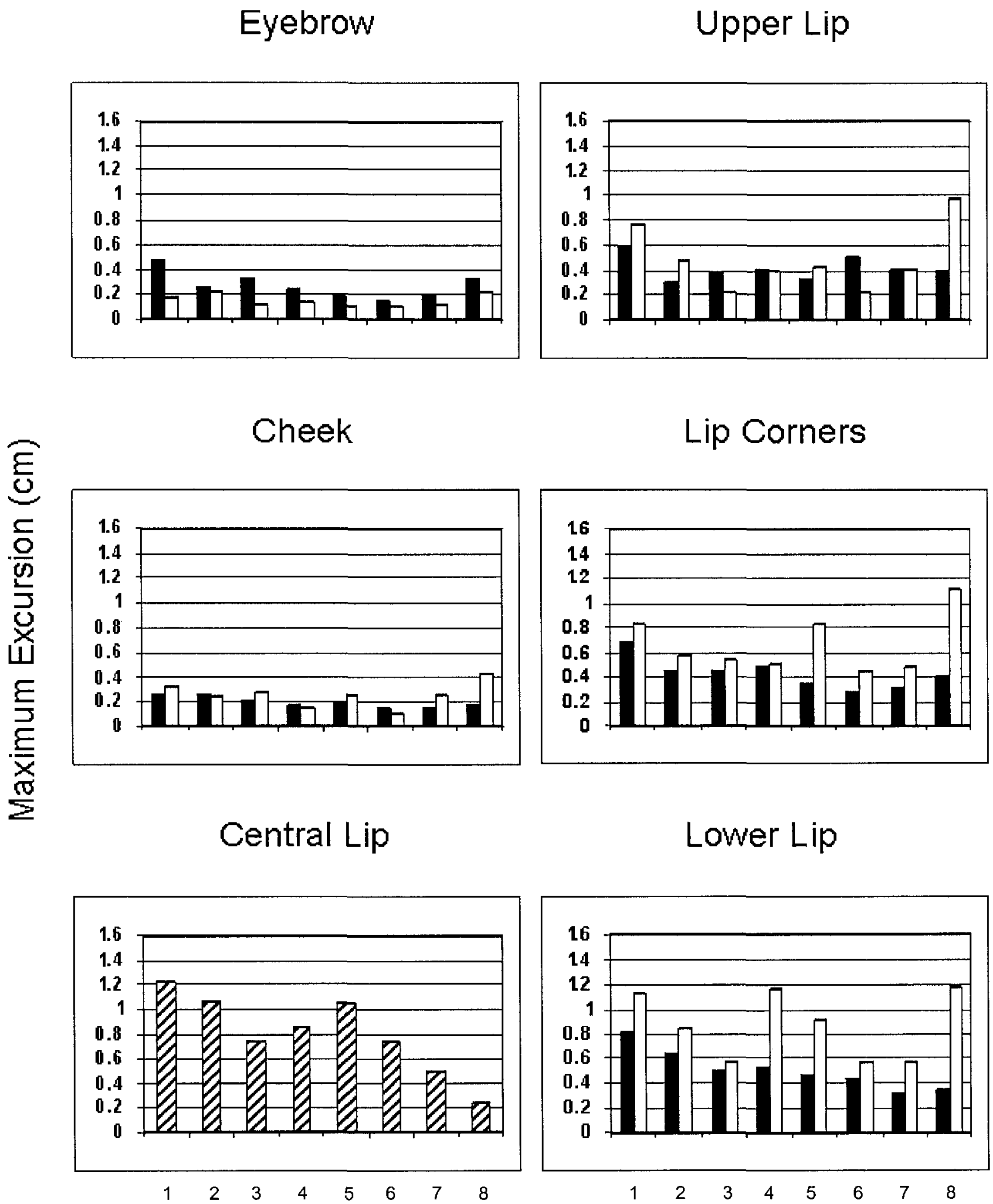
Speech Measures – Articulation and Speech Intelligibility

Overall, scores on articulation and intelligibility measures were high. The average PCC across listeners was 97%. Only one listener reported errors which consisted of substitutions of /n/ for /m/ in both vowel contexts (i.e., /nu/ for /mu/ and /ni/ for /mi/). The average intelligibility rating from listeners was 97%. Moreover, the investigator was able to understand everything the subject said in face-to-face conversation.

2D Kinematic Measures

All of the movement displacements by facial marker and task are shown in Figure 6.1. As can be seen, the amount of movement varied as a function of facial marker, side of face, and task. An overall impression of kinematic measures is summarized next. Detailed supporting tables for each individual marker are presented in Appendix K.

Figure 6.1: Maximum excursions produced at each marker



Legend

1 – bi 2 – pi 3 – fi 4 - wi

5 – Jack & Jill 6 – Winegum 7 – Smile 8 - Pucker

Legend

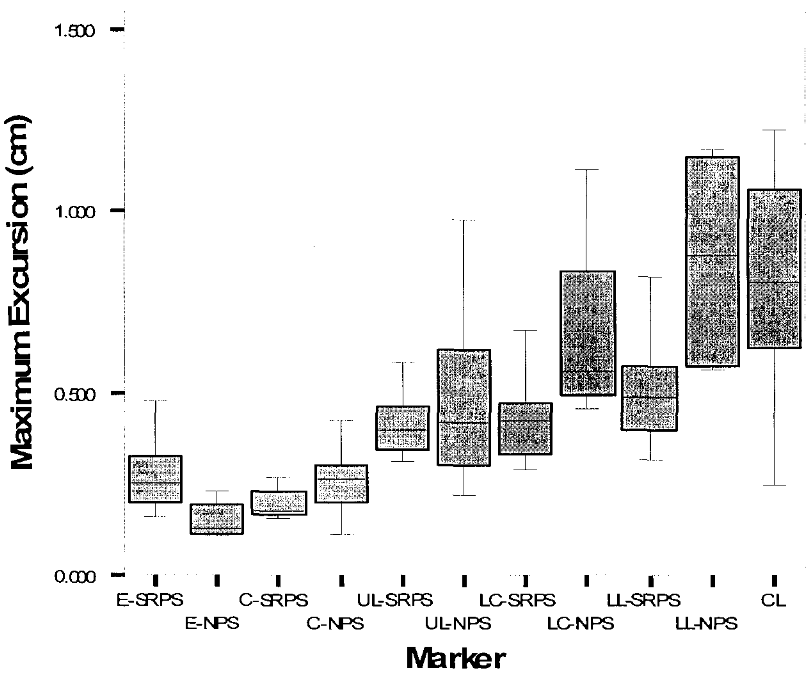
Surgically Repaired Paralyzed Side

Non-Paralyzed Side

Central Lip Marker

To visualize overall facial movements, box plots shown in Figure 6.2 provide summarized data for each marker collapsed across tasks. Several overall trends can be seen. First, markers on the lower face showed more movement than those on the upper face. Second, the largest and most variable maximum excursions occurred at the lower and central lip markers, whereas movement remained small and less variable at the eyebrows on the NPS and at cheeks on the SRPS. Finally, lower lips appeared to move more than upper lips.

Figure 6.2: Maximum excursions at each marker with tasks collapsed.



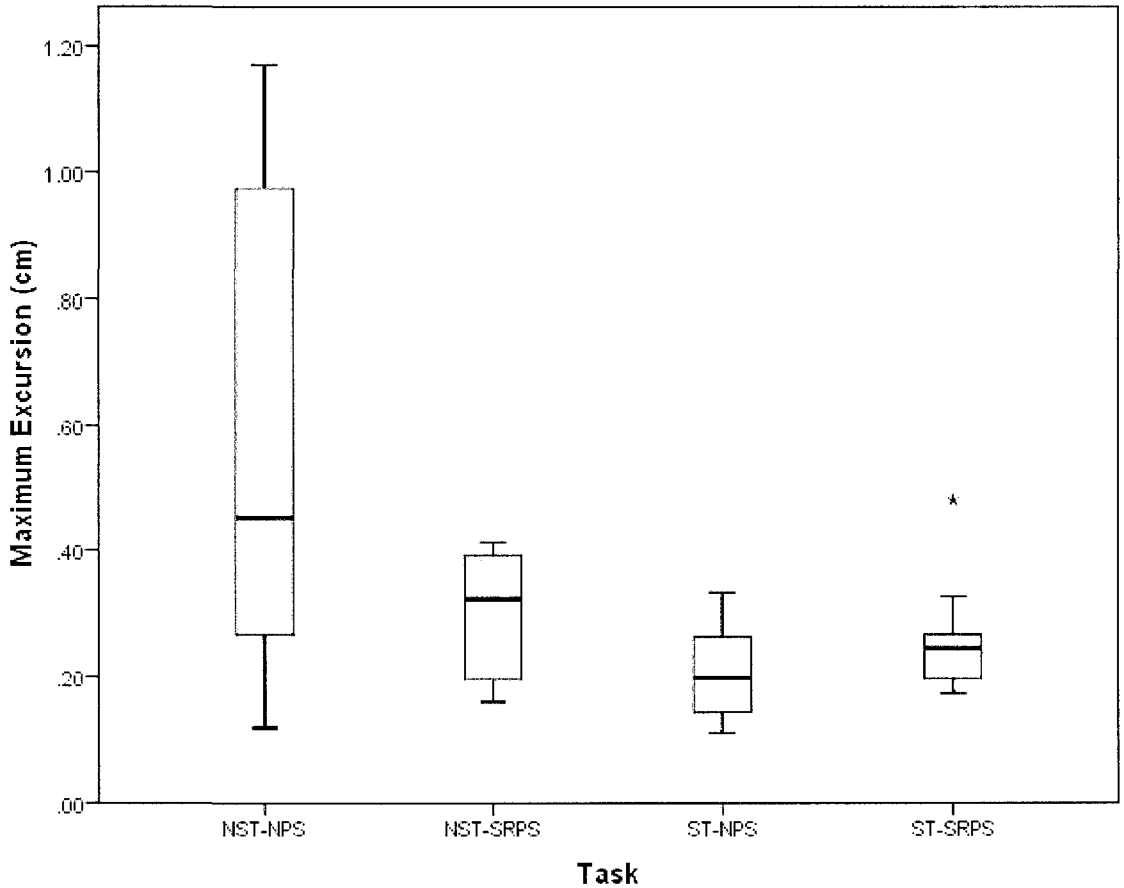
Legend

E-NPS – Eyebrow - Non-Paralyzed Side	E-SRPS – Eyebrow - Surgically-Repaired Paralyzed Side
C-NPS – Cheek - Non-Paralyzed Side	C-SRPS – Cheek - Surgically-Repaired Paralyzed Side
UL-NPS – Upper Lip - Non-Paralyzed Side	UL-SRPS – Upper Lip - Surgically-Repaired Paralyzed Side
LC-NPS – Lip Corner - Non-Paralyzed Side	LP-SRPS – Lip Corner - Surgically-Repaired Paralyzed Side
LL-NPS – Lower Lip - Non-Paralyzed Side	LL-SRPS – Lower Lip - Surgically-Repaired Paralyzed Side
CL – Central Lip	

Movement asymmetries also can be observed (see Tables 7.1 – 7.10 in Appendix K for a summary). The NPS produced larger and variable maximum excursions compared to the SRPS with the exception of the eyebrows where the opposite pattern was observed. Tasks that were associated with the largest or smallest movements were variable within and between facial markers. The activities that produced the largest and smallest maximum excursions are summarized in Appendix K.

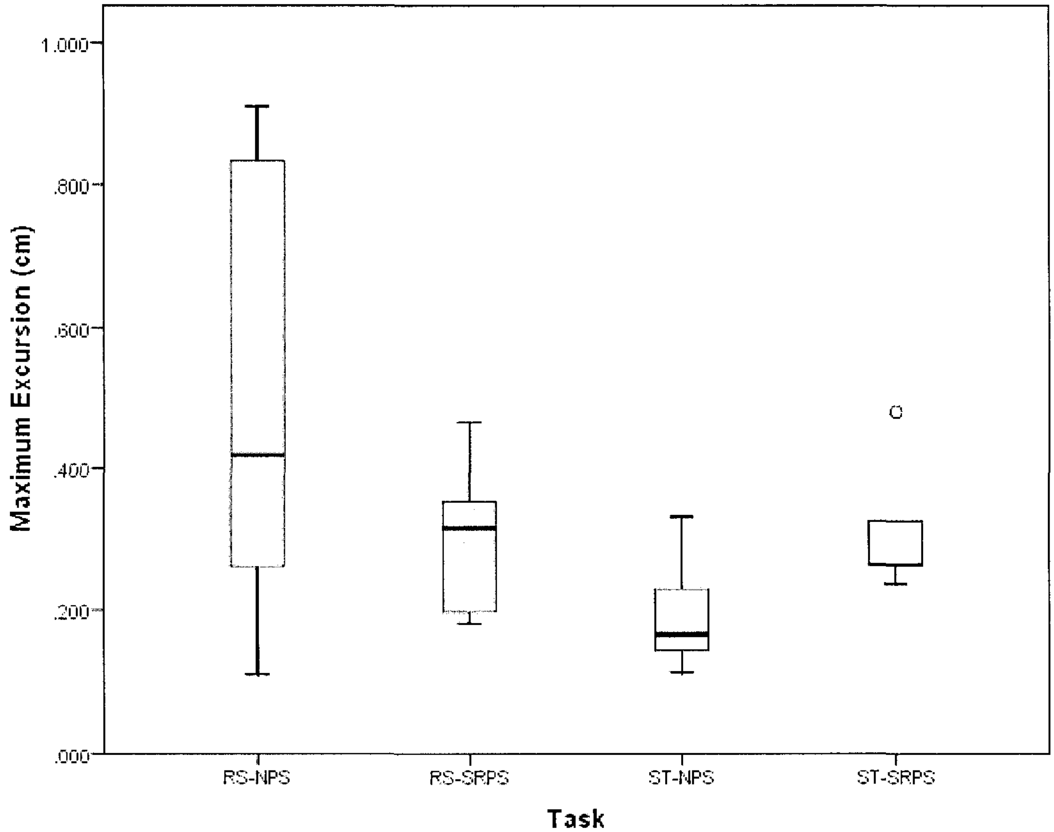
Several additional trends become apparent when comparing non-speech tasks (i.e., *smiling* and *puckering*) to speech tasks (i.e., */bi/*, */pi/, /fi/, /wi/*, and *Jack and Jill*) (see Figure 6.3). Overall, the non-speech tasks produce more movement and were more variable relative to the speech tasks. Maximum excursions, regardless of face marker location, tended to be larger and more variable during running speech (i.e., *Jack and Jill*) than during the production of isolated speech tokens (i.e., */bi/*, */pi/, /fi/, /wi/*) (see Figure 6.4).

Figure 6.3: Maximum excursions collapsed across non-speech and speech tasks



Legend
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side
NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side
ST-NPS – Speech Tasks--Non-Paralyzed Side
ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 6.4: Maximum excursions collapsed across running speech and the speech tokens



Legend
RS-NPS – Running Speech--Non-Paralyzed Side
RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side
ST-NPS – Speech Tokens--Non-Paralyzed Side
ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

EMG

Peak EMG amplitudes by facial marker and task are shown in Figures 6.5 and 6.6. Amplitudes varied across muscles, side of the face, and task. A general summary of EMG activity is presented below. Information regarding specific muscles can be found in Appendix K.

Figure 6.5: Peak EMG amplitudes by facial marker and task

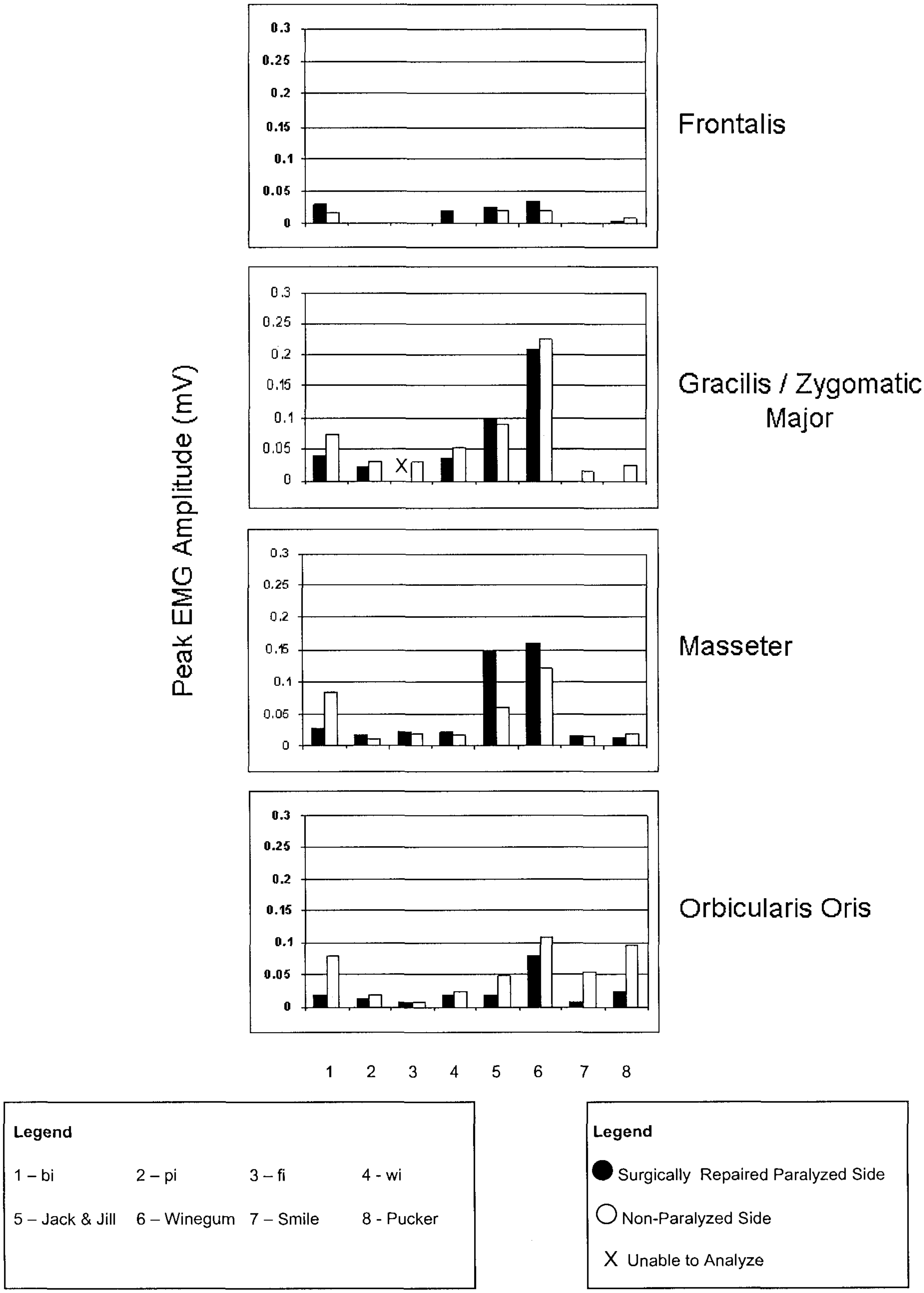
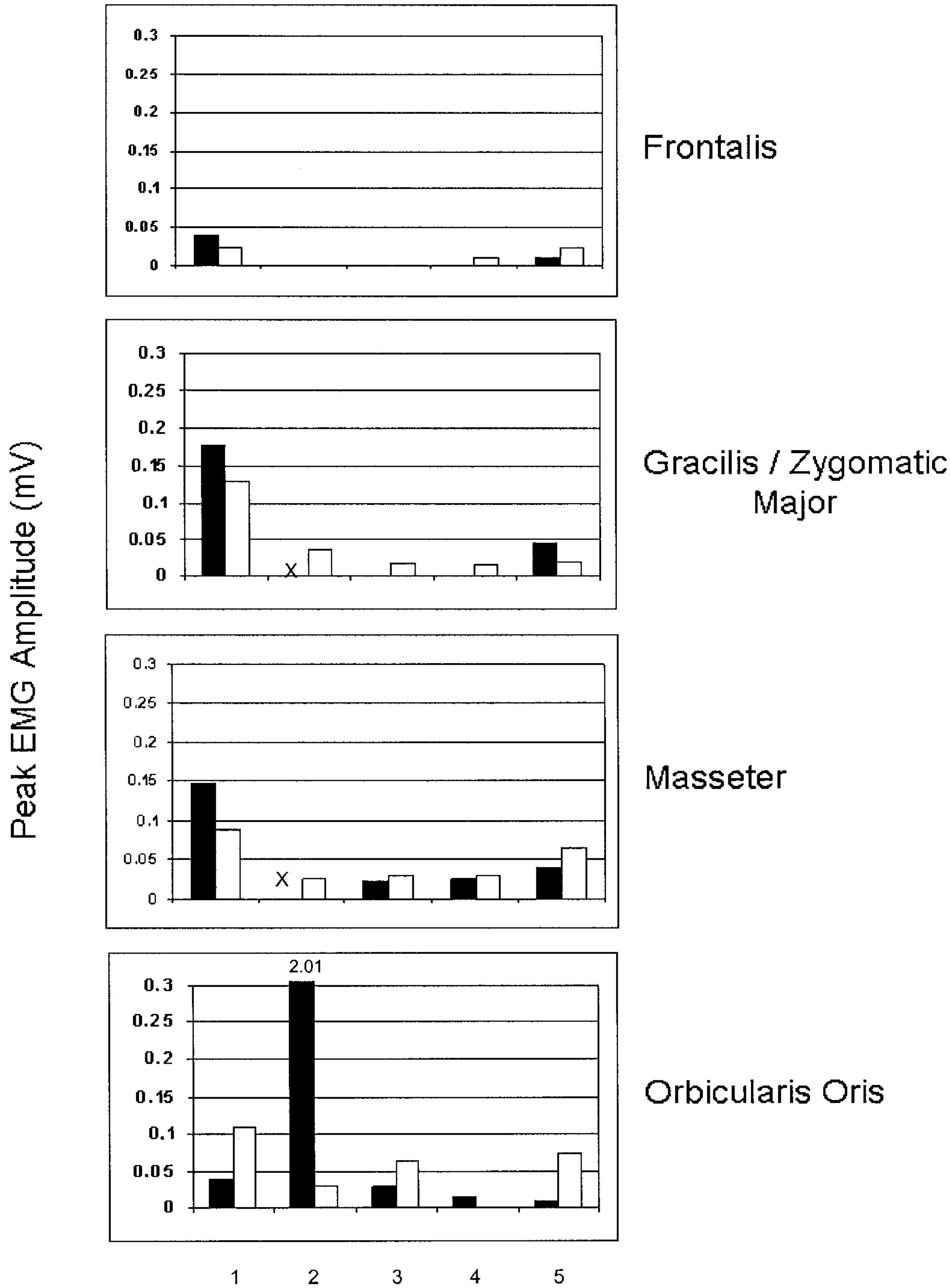


Figure 6.6: Peak EMG amplitudes by facial marker and task



Legend

1 – Pudding 2 – Drinking

3 – Press 4 – Frown 7 – Clench

Legend

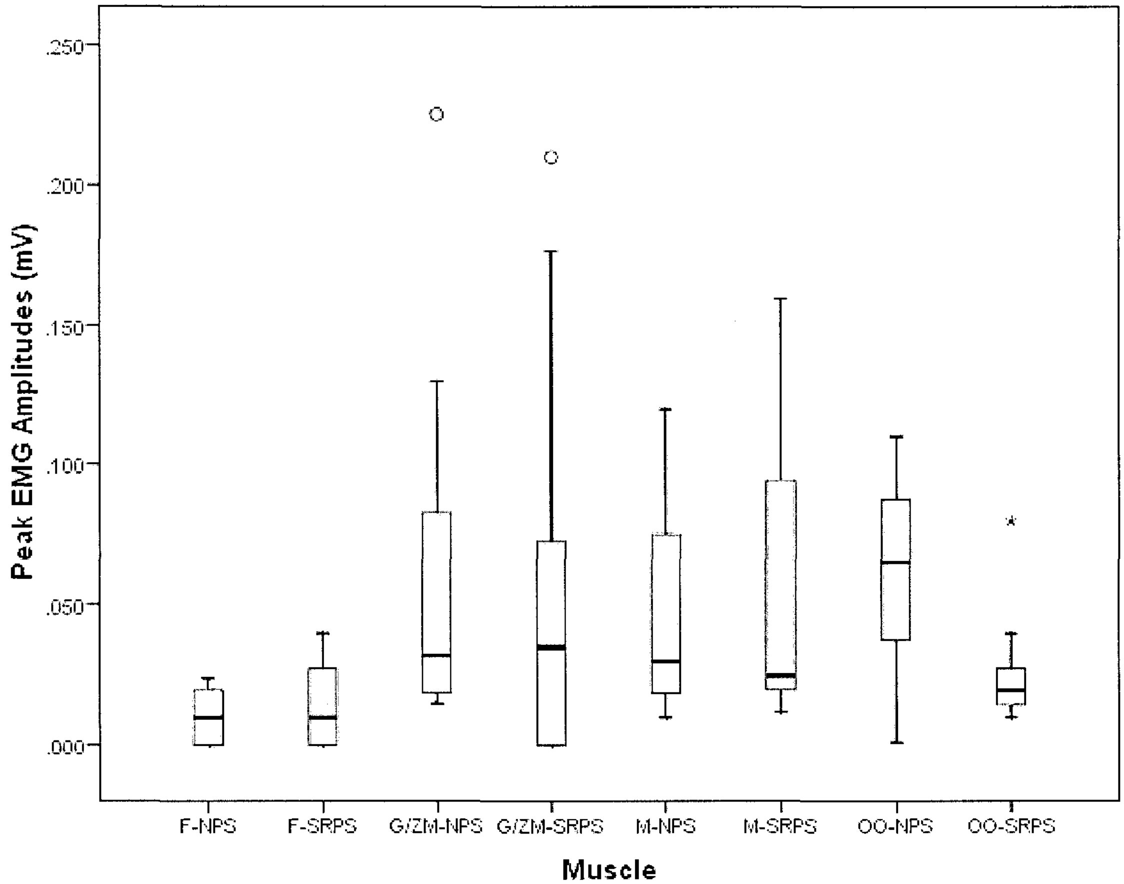
● Surgically Repaired Paralyzed Side

○ Non-Paralyzed Side

X Unable to Analyze

To visualize muscle activity, box plots shown in Figure 6.7 provide summarized data for each muscle collapsed across tasks. Several overall trends are apparent. In general, the frontalis demonstrated the least activity on both sides of the face, showing small or barely detectable (< 0.001 mV) peak amplitudes across tasks. Although the masseter, gracilis/zygomatic major, and orbicularis oris all had similar activity levels, the orbicularis oris appeared to have slightly larger peak amplitudes on the NPS whereas the gracilis/zygomatic major had slightly larger amplitudes on the SRPS.

Figure 6.7: Peak EMG amplitudes for each muscle collapsed across tasks



Note: Data point at 2.1 mV at the orbicularis oris on the SRPS not included in this analysis

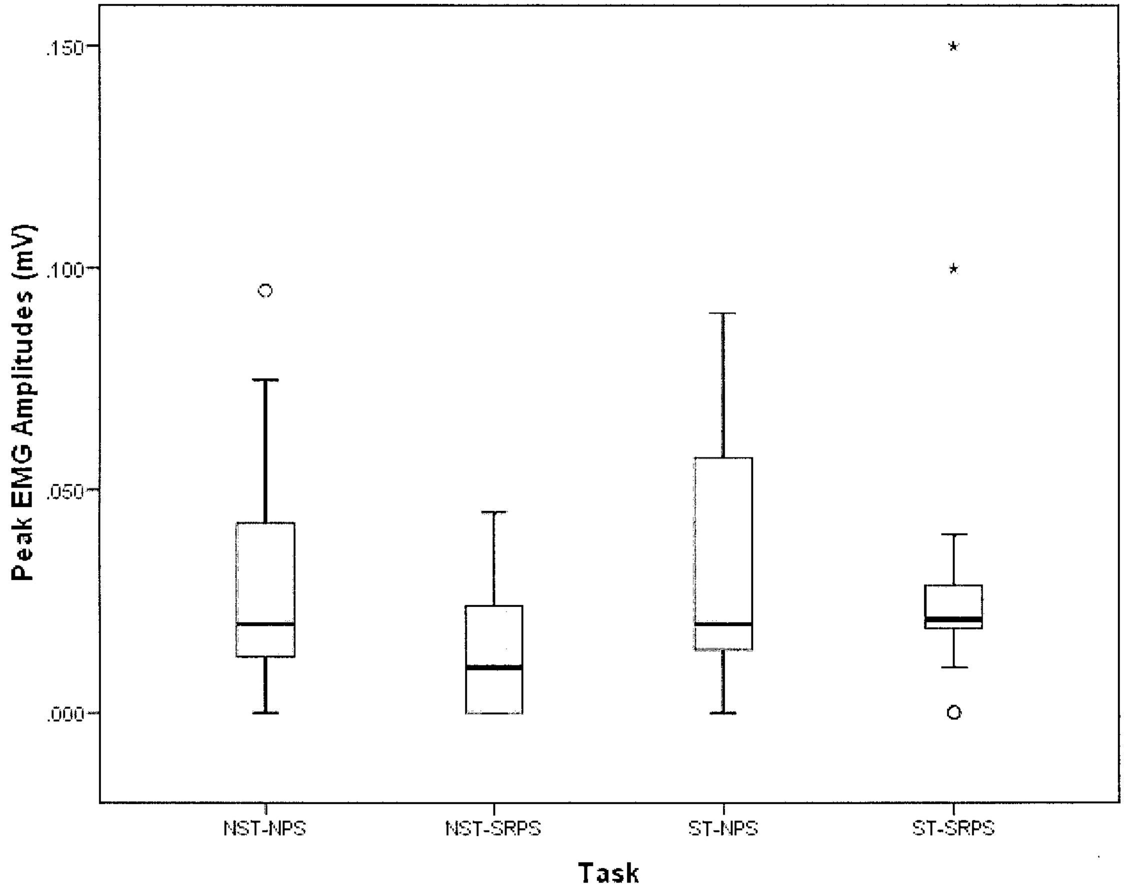
Legend

E-NPS – Eyebrow - Non-Paralyzed Side	E-SRPS – Eyebrow - Surgically-Repaired Paralyzed Side
C-NPS – Cheek - Non-Paralyzed Side	C-SRPS – Cheek - Surgically-Repaired Paralyzed Side
UL-NPS – Upper Lip - Non-Paralyzed Side	UL-SRPS – Upper Lip - Surgically-Repaired Paralyzed Side
LC-NPS – Lip Corner - Non-Paralyzed Side	LP-SRPS – Lip Corner - Surgically-Repaired Paralyzed Side
LL-NPS – Lower Lip - Non-Paralyzed Side	LL-SRPS – Lower Lip - Surgically-Repaired Paralyzed Side
CL – Central Lip	

Comparing each side of the face revealed higher and more variable EMG peak amplitudes on the NPS than on the SRPS; however, several exceptions were evident (see Tables 7.14 – 7.21 in Appendix K for a summary). In particular, larger peak EMG amplitudes were observed for the frontalis on the SRPS than on the NPS. Although most activities produced small/comparable EMG peak amplitudes across all of the muscles, a few generated relatively large activity levels in addition to activity observed in the frontalis muscles (see Table 7.22 in Appendix K for a summary). Although movement occurred during all of the tasks, very low amplitude signals (< 0.001 mV) were recorded from both the frontalis and the gracilis/zygomatic major during several of the activities. EMG signals below 0.001 mV are shown by muscle and task in Table 7.23 in Appendix K.

Speech tasks (i.e., */bi/*, */pi/*, */fi/*, */wi/*, and *Jack and Jill*) tended to produce slightly higher peak EMG amplitudes from muscles on both sides of the face when compared to non-speech tasks (i.e., *smiling* and *puckering*) (see Figure 6.8). Moreover, running speech (i.e., *Jack and Jill*) produced larger and more variable maximum excursions when compared to the speech tokens (i.e., */bi/*, */pi/*, */fi/*, */wi/*) (see Figure 6.9).

6.8: Peak EMG amplitudes during non-speech and speech tasks



Legend

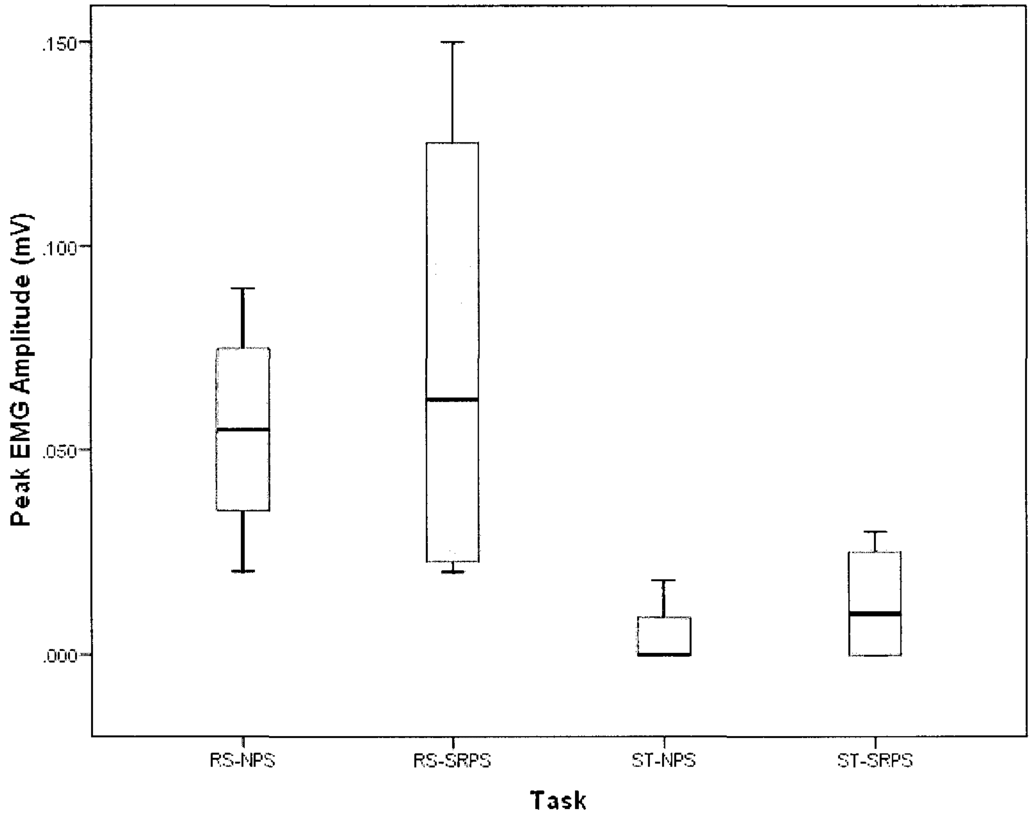
NST-NPS -- Non-Speech Tasks--Non-Paralyzed Side

NST-SRPS -- Non-Speech Tasks--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tasks--Non-Paralyzed Side

ST-SRPS – Speech Tasks--Surgically-Repaired Paralyzed Side

Figure 6.9: Peak EMG amplitudes during running speech and speech tokens.



Legend

RS-NPS – Running Speech--Non-Paralyzed Side

RS-SRPS – Running Speech--Surgically-Repaired Paralyzed Side

ST-NPS – Speech Tokens--Non-Paralyzed Side

ST-SRPS – Speech Tokens--Surgically-Repaired Paralyzed Side

A number of EMG signals produced at each of the muscles showed atypical waveform patterns. Nine out of 52 EMG signals recorded from the SRPS and 10 out of 52 signals recorded from the NPS were abnormal. The specifics of these EMG signals are summarized in Table 7.24 in Appendix K. These waveforms tended to occur during the speech tokens or maximum contraction tasks. In particular, abnormal activity was produced in all muscles on the SRPS when saying /wi/.

Relationship between Kinematic Measures and EMG Peak Amplitudes

Visual inspection of the data presented in Figures 6.5, 6.6, and 6.7 for relationships between movement and EMG motor recruitment revealed several patterns worth noting. As a whole, the lower face showed more movement and EMG activity than the upper face. The frontalis and eyebrows showed the least amount of movement and EMG activity, relative to the other muscles/markers. The largest movements and EMG activities were seen in the orbicularis oris and lower lip which showed large peak EMG amplitudes and greater maximum excursions when compared to the other muscles/markers.

In most cases, movement asymmetries from one side of the face to the other corresponded to asymmetries in EMG amplitudes from one side of the face to the other. Overall, the SRPS showed more activity (i.e., larger maximum excursions and peak amplitudes) than the NPS in the frontalis/eyebrows, and the NPS showed more activity in the gracilis/cheeks/lip corners and the orbicularis oris/lower lip.

The relationship between movement and EMG activity also was compared across tasks. Strong positive relationships between movement and peak EMG amplitudes were seen during */bi/* and *Jack and Jill* which produced some of the highest maximum excursions and peak amplitudes. Strong negative relationships between movement and EMG data were seen in several muscles during two different tasks: *chewing the winegum* and *puckering.*

S6 Summary

This subject was born with left facial palsy which resulted in mild left-sided weakness and flaccidity with decreased lip ROM on the affected side. Decreased animation of the upper face on the SRPS of the face was particularly noticeable during spontaneous conversation and activities. This subject was completely intelligible and few articulation errors were noted. Mastication was completely functional; only mild deficits when chewing and drinking were observed (e.g., mild pudding residue on the lips). Indication of residual/recovered function on the paralyzed side was evident; movement and EMG activity was recorded on both sides of the face during many of the tasks. Overall, this subject's lower face (i.e., orbicularis oris and the lips) tended to have larger maximum excursions and EMG amplitudes than did the upper face (i.e., frontalis and the eyebrows).

Although recovered function was apparent, asymmetries in movement and peak amplitudes across each side of the face were still evident. With the exception of the frontalis EMG and eyebrow movement, it was observed that larger maximum excursions and EMG amplitudes occurred on the NPS than on the SRPS for most tasks. For instance, movement at NPS lip corner was 37% larger than the movement recorded on the SRPS during *smiling*. Similarly, the NPS lip corner was 69% larger than the SRPS during *puckering*. The same pattern occurred during running speech (i.e., *Jack and Jill*) and while *chewing the winegum*.

Asymmetries across each side of the face also were present in the EMG data. With a few exceptions, higher and more variable EMG peak amplitudes occurred on the NPS than on the SRPS. The peak amplitudes recorded at the gracilis/zygomatic major tended to follow this trend. Whereas the gracilis on the SRPS produced barely detectable signals (< 0.001 mV) during *smiling*, the zygomatic major on the NPS generated a peak amplitude of 0.015 mV. Likewise, the gracilis produced barely detectable signals (< 0.001 mV) during *puckering*, while the zygomatic major generated a 0.025 mV peak amplitude. Although the same pattern was observed at the gracilis/zygomatic major while *chewing the winegum* and *drinking*, the SRPS produced larger peak amplitudes while *consuming the pudding* and during running speech (i.e., *Jack and Jill*).

The relationship between movement and EMG data varied across markers/muscles, side of the face and tasks. Both positive and negative relationships were evident. For example, a positive relationship existed during Jack and Jill. Both maximum excursions and peak amplitudes were high during the task. A negative relationship existed while chewing the winegum. While peak amplitudes tended to be high during this task, maximum excursions tended to be low.

Coherence

EMG coherence between the gracilis/zygomatic major and the other muscles of interest (i.e., the frontalis, masseter, and orbicularis oris) was compared during running speech (i.e. *Jack and Jill*) and the individual speech tokens (i.e., */bi/*, */pi/*, */fi/*, and */wi/*). There was little coherence above the 95% line in any frequency band for any of the muscle pairs during the speech tokens. An exemplar taken from S6 is shown in Figures 7.1 and 7.2. As can be seen, statistically significant coherence (above the 95% confidence interval) was found in the β band (i.e., 24 – 40 Hz) for both comparisons of the gracilis/zygomatic major to the masseter and the gracilis/zygomatic major to orbicularis during running speech. In contrast, significant coherence was not observed between the gracilis/zygomatic major and the frontalis during running speech. This suggests that a *distributed* system is controlling these facial muscles during the individual speech tokens whereas a *central* processor may control these muscles during running speech.

Figure 7.1: EMG coherence for the gracilis/zygomatic major and masseter from S6 during running speech (i.e., *Jack and Jill*)

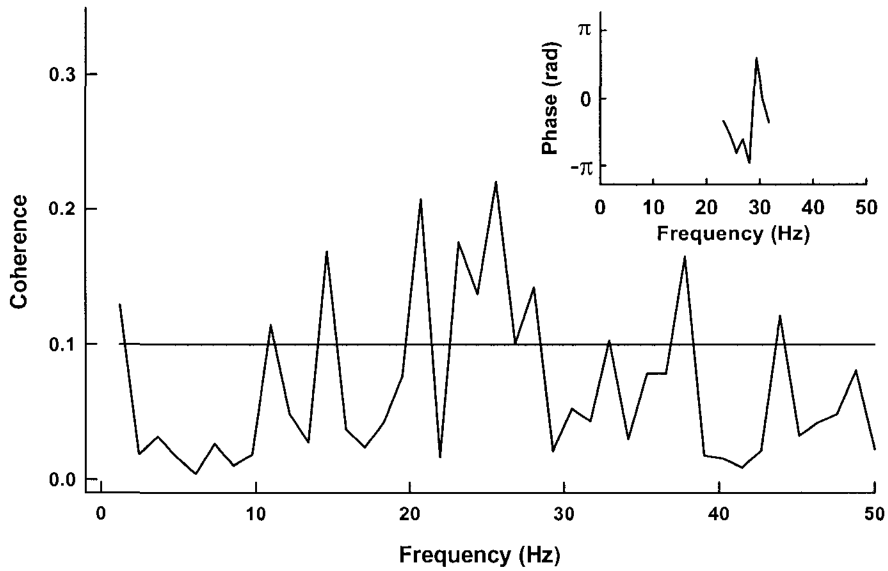
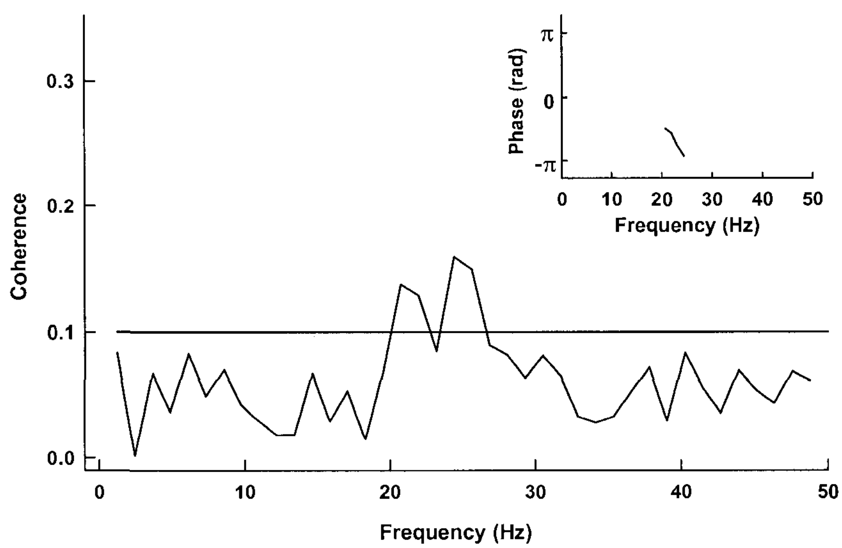


Figure 7.2: EMG coherence for the gracilis/zygomatic major and orbicularis oris from S6 during running speech (i.e., *Jack and Jill*)



Coherence data were collapsed across all subjects and the relative area above the 95% confidence cutoff was calculated for all muscle comparisons and tasks. Paired t-tests were then completed to determine if this area was significantly different than 0. With the exception of the frontalis and the masseter and the frontalis and the gracilis/zygomatic major, the area of coherence above the 95% interval was significantly different from 0 in all of the muscles during running speech (see Table 2.1 below). In contrast, the area of coherence above the 95% interval was not significantly different than 0 in any of the muscles during the speech tokens (see Table 2.2). This finding suggests that there is a different type of control mechanism for running speech than for isolated speech token productions that characterizes all individuals in this study.

Table 2.1: Total area of coherence above the 95% confidence line during running speech collapsed across subjects

Muscle Pair Compared	Total Area of Coherence Above 95% confidence Line	Significance
frontalis & masseter	0.0002	No significance
frontalis & gracilis/ zygomatic major	0	No significance
frontalis & orbicularis oris	0.02395	Significant p<0.05
frontalis & frontalis	0.015	Significant p<0.05
masseter & masseter	0.02115	Significant p<0.05
gracilis/zygomatic major & gracilis/zygomatic major	0.00257	Significant p<0.05
orbicularis oris & orbicularis oris	0.0328	Significant p<0.05
masseter & gracilis	0.02556	Significant p<0.05
masseter & orbicularis oris	0.01756	Significant p<0.05
gracilis/zygomatic major & orbicularis oris	0.0351	Significant p<0.05

Table 2.2: Total area of coherence above the 95% confidence line during the individual speech tokens collapsed across subjects

Muscle Pair Compared	Total Area of Coherence Above 95% confidence Line	Significance
frontalis & masseter	0	No significance
frontalis & gracilis/ zygomatic major	0.002	No significance
frontalis & orbicularis oris	0	No significance
frontalis & frontalis	0	No significance
masseter & masseter	0	No significance
gracilis/zygomatic major & gracilis/zygomatic major	0.0001	No significance
orbicularis oris & orbicularis oris	0	No significance
masseter & gracilis	0	No significance
masseter & orbicularis oris	0	No significance
gracilis/zygomatic major & orbicularis oris	0.0002	No significance

DISCUSSION

The purpose of the current study was to compile a comprehensive evaluation of functional outcomes, muscle activation and movement following facial reanimation surgery. Specifically, the following questions were addressed. 1. What is the overall function of the face during speech and non-speech activities? 2. Do the two sides of the face function differently? 3. Are differences in muscle activation and movement apparent when different tasks (specifically differences between speech and non-speech tasks) are completed? 4. What is the relationship between movement and EMG motor recruitment? 5. Is there a common synaptic drive to the motorneurons of the facial muscles during different tasks?

Six subjects with varying degrees of facial paralysis were tested following facial reanimation surgery that utilized either the contralateral facial nerve or the nerve to the masseter depending on clinical situation. Several procedures were used to compile an objective evaluation of outcomes. These included an oral mechanism exam, non-standardized articulation and intelligibility tests, a clinical mastication and swallowing exam, two-dimensional kinematic analysis, and EMG recordings.

Oral Mechanism Exam

In general, and across participants, the oral mechanism revealed mild flaccidity of facial muscles on the affected side of the face. Whereas movement of the affected side was observed during the oral mechanism exam, the strength and excursion of the lips on that side was different from the unaffected side irrespective of post-surgical status. For example, lip excursion on the surgically-repaired paralyzed side was often observed when subjects were asked to smile; however, this excursion was almost always judged to be smaller than that produced at the lip corners on the non-paralyzed side.

Mastication and Swallowing Exam

Results from other studies that have evaluated outcomes following facial reanimation indicate that patients often report an increase in oral competence and an improved ability to eat and drink following surgery (Goldberg, DeLorie, Zuker, & Manktelow, 2003; O'Brien, Pederson, Khazanchi, Morrison, MacLeod, Kumar, 1990). All of the subjects in the current study also reported improvements in mastication and swallowing and upon clinical examination most had functional mastication abilities. However, problems such as oral containment of food (especially liquid) and residual food and liquid on the lips and in the oral cavity still existed following facial reanimation in the patients that were studied. Furthermore, compensatory strategies, such as head posturing, adaptive spoon and cup placement were still being used in an effort to deal with these deficits. Subjects with bilateral paralysis tended to have more difficulty with labial competence (i.e., pooling of liquid and food in the lips) and tended to use more compensatory strategies (i.e., using the fingers to hold the bolus in the mouth) than those with unilateral paralysis. The mastication difficulties and compensatory strategies noted in this study are comparable to those found by Secil, Aydogdu, and Ertekin (2002) who used a similar checklist to assess mastication in people with unilateral paralysis who had not undergone facial reanimation surgery. Subjects in that study also reported increased incidence of coughing and choking when eating, a problem the subjects in the current study did not report, and that was not observed during the clinical examination.

The use of the trigeminal nerve for facial reanimation surgery has been criticized because patients may not be able to smile independent of jaw movement and its use may downgrade other oral functions (Terzis & Noah, 2003). The subjects who had undergone facial reanimation surgery utilizing the nerve to the masseter were able to smile independently of jaw movement.

However, when the subjects chewed solids, smiling sometimes occurred. Although oral competence was still an issue in these patients, mastication did not appear to be affected by the surgery

Speech Measures - Articulation and Intelligibility

In terms of articulation, those with unilateral facial paralysis tended to produce few articulation errors (average PCC ranged from 97% - 100%) including the subject who had not yet undergone the second stage of her facial reanimation surgery. However, subjects with bilateral paralysis tended to have errors consisting of substitutions for the bilabial sounds (i.e., /p/, /b/, /m/) in both vowel contexts (i.e., /i/ and /u/) (average PCC ranged from 70% - 94%). To date, no studies have assessed the speech or intelligibility of those with unilateral paralysis; however, previous studies have reported that articulation improves in those with bilateral paralysis following surgery. For example, Goldberg, DeLorie, Zuker, and Manktelow (2003) screened for commonly compensated phonemes in patients with Mobius syndrome who had undergone facial reanimation surgery. Although the authors reported that there was a decrease in the frequency of the compensatory errors screened for postoperatively, the specifics of these results were not reported. They did note that 83% of patients still reported that they had occasional or frequent speech problems following surgery. The results of the current study and previous research are an indication that although articulation may improve in some patients following facial reanimation surgery, it remains a problem in others.

In terms of intelligibility, all of the subjects in the present study were easy to understand and were judged to be over 87% intelligible in connected speech. In a study conducted by Goldberg, DeLorie, Zuker, and Manktelow, the intelligibility of those with bilateral facial paralysis also was tested. A single unblinded observer rated intelligibility on a subjective scale from 1 to 5 with 5 being the best. Improved intelligibility was observed in 83% of patients following surgery (average intelligibility improved from 2.9 prior to surgery to 3.7 following, although this was not significant) and patients and their families reported that intelligibility was improved in 92% of cases. Although it is apparent from previous findings that those with facial paralysis still may have difficulty with articulation and pronouncing sounds following surgery, the research on intelligibility demonstrates that they still manage to be heard and understood by unfamiliar listeners.

2D Kinematic Measures

The two-dimensional kinematic analysis revealed that movement was variable across subjects, markers, and tasks, and between the two sides of the face. In light of this variability, movement was detected on both sides of the face across all tasks in each of the subjects. This indicates that there is evidence of residual and/or recovered function following facial reanimation surgery. Whereas movement was detected at each of the lip corners during each of the tasks, excursions were usually larger on the non-paralyzed side (NPS). For example, excursions on the surgically-repaired paralyzed side (SRPS) were approximately 60 – 76% of those that were recorded on the non-paralyzed side (NPS) during *smiling*. This pattern also has been observed in other studies (Erni, Lieger, & Banic, 1999; Johnson, Bajaj-Luthra, Llull, & Johnson, 1997; Yong-Chan, Zuker, Manktelow, & Wade, 2006; Zuker, Goldberg, & Manktelow, 2000). For instance, Johnson, Bajaj-Luthra, Llull, and Johnson (1997) used the Maximal Static Response Assay to calculate the x and y displacement of selected facial markers using digitized photographs. The Pythagorean Theorem then was used to calculate the direction and magnitude of the vector. Movement at the lip corners on the SRPS, on average, improved from an excursion of 2.8 mm preoperatively to 4.9 mm postoperatively during smiling. Because the muscles on the SRPS could withstand the forces of the muscles on the NPS, excursions recorded on the NPS decreased from 9.4 mm preoperatively to 5.7 mm postoperatively. Hence, the SRPS moved approximately 86% of that on the NPS. Although the movement on the SRPS was more similar to that of the NPS in that study than it was in the present study, both sets of data indicate that excursions produced at the SRPS are less than those on the NPS. Schliephake, Schmelziesen, and Troger (2000) used a measurement system similar to that of Johnson et al. and reported results that were more comparable to the results found in the current study. On average, the SRPS moved approximately 65% of that produced at the non-paralyzed side.

Curiously, in some cases, maximum excursions recorded on the paralyzed side of the face were larger than those on the non-paralyzed side. This pattern is particularly apparent in the data collected for S2 (who had not yet had the second stage of the cross-facial nerve surgery). Several factors may contribute to this observation. Although it subjectively appeared that the NPS moved more than the SRPS, the objective analysis of facial movement may have revealed small movements that were undetectable by the naked eye. Movement at each of the markers was very small. For example, excursion at the lip corners ranged from 1.8 mm to 5.4 mm. Although the SRPS moved more than the NPS in some cases, the difference was minute. Secondly, some of the movements on the paralyzed side of the face were not as refined as those on the non-paralyzed side. For example, it was noted that the paralyzed side of S2's face moved more than the NPS during mastication and running speech as it appeared that this side of the face was unable to produce the precise movements required for these tasks. Lastly, our system for analyzing kinematic measures did not take into account the trajectories of the movement. Although the paralyzed side of the face may have produced larger movements than those on the NPS, they may have been in a paradoxical direction. Johnson, Bajaj-Luthra, Llull, and Johnson (1997) did note that prior to surgery, the muscles on the NPS pulled on the muscles of the paretic side. As a result, the paretic side of the face was in a non-anatomical, asymmetrical position. This may be an indication that S2's NPS may move more than her SRPS following her second cross-facial nerve surgery.

When analyzing the movements produced during the non-speech (i.e., *smiling* and *puckering*) and the speech tasks (i.e., */bi/*, */pi/, /fi/, /wi/*, and *Jack and Jill*), several trends were evident. In all cases, the non-speech tasks produced more movement when compared to the speech tasks, and running speech (i.e., *Jack and Jill*) produced more movement when compared to the isolated speech tokens (i.e., */bi/, /pi/, /fi/, /wi/*). These results support the idea that these tasks are fundamentally different and generate distinctive movement patterns.

EMG

Peak EMG Amplitudes

Like the kinematic data, peak EMG amplitudes were variable across subjects, markers, task and between the sides of the face. In some cases the NPS produced larger amplitudes, in some cases the SRPS produced larger amplitudes; however, the gracilis/zygomatic major produced amplitudes that were always larger on the NPS. In some cases, the new gracilis muscle produced barely detectable signals when compared to those produced by the functioning zygomatic major on the NPS side. The newly transferred gracilis produced peak amplitudes that were less than those recorded on the non-affected side. However, muscle activity was detected in the gracilis during several of the tasks across all subjects. These results support the evidence collected by other investigations that indicate that nerve regeneration has occurred and the transferred muscle has become reinnervated (Sassoon, Poole, & Rushworth, 1991; Schliephake, Schmelziesen & Troger, 2000; Terzis & Noah, 1997; Ueda, Harii, Yamada, 1995).

As was previously stated, the SRPS generated peak EMG amplitudes that were larger than those generated on the NPS in some cases. This is particularly evident when analyzing S5's data and the peak amplitudes generated by the masseter and the frontalis in several of the other subjects. A number of reasons may account for this observation. These results may be an indication that residual function was present in these muscles prior to facial reanimation surgery. Several studies also have demonstrated that the contralateral facial nerve will often reinnervate muscles on the affected side in those with unilateral facial paralysis (Jacobus Gilhuis, Beurskens, de Vries, Marres, Hartman, & Zwarts, 2003; Tankere, Bernat, Vitte, Lamas, Bouche, & Fournier, et., al (2003). Muscle reinnervation may explain the peak amplitudes seen on the SRPS. Lastly, because surface electrodes were used in the present study, several factors may have disrupted the EMG signal and decreased the reliability of the data. For example, the amount of tissue overlying the facial muscles may have impeded the signal or there may have been cross talk between the electrodes. Aniss and Sachdev (1996) compared surface and needle EMG recordings of the facial muscles during a variety of expressions. Although they found good correspondence between these two types of measures, correspondence decreased when the EMG activity was itself low. As such, the results of the present study should be reviewed with caution.

Several interesting compensatory patterns were noted when analyzing the EMG data. For instance, as was mentioned above, relatively high peak amplitudes were observed in the masseter on the affected side in those with unilateral facial paralysis during all tasks. This finding suggests that the masseter on the affected side of the jaw may be compensating for the paralyzed facial muscles on that side of the face. Because the muscles on the paralyzed side tend to be flaccid, the jaw may be stabilizing this side of the face.

Interestingly, the subject with bilateral facial paralysis who had undergone the first nerve to masseter surgery appeared to have a different pattern of activation than those with unilateral paralysis. With the exception of clenching, the SRPS generated larger peak amplitudes in the masseter than the NRPS. Although the masseter nerve on the SRPS was partially removed, it is likely that some of the innervation to this muscle is redundant and some residual function was present. It is likely that the SRPS may have been compensating for deficits on this side of the face in an unknown way. It also may be possible that this muscle was activated inappropriately. This may indicate abnormal function/physiology in the partially deinnervated muscle (e.g., larger number of nerve fibre recruitment with fewer functioning axons).

In many cases, the frontalis also produced higher peak amplitudes on the SRPS and may have been compensating for the lack of animation on the affected side of the face. Additionally, during many of the masticatory tasks (i.e., *chewing the winegum*, *consuming the pudding* and *drinking*), one side of the face tended to have relatively large peak amplitudes when compared to the other side. For instance, the NPS tended to produce larger amplitudes while the subject's *chewed the winegum*. This may have been due to the fact that many of the participants were observed to chew the winegum on the NPS. In contrast, the SRPS tended to produce larger amplitudes when the subjects *consumed the pudding*. It was observed that pudding would often leak from the SRPS of the mouth and subjects may have increased their effort on this side of the face to contain it.

Like the increased movement observed in the kinematic data, non-speech tasks produced larger EMG amplitudes when compared to the speech tasks, and running speech (i.e., *Jack and Jill*) produced larger peak amplitudes when compared to the isolated speech tokens (i.e., */bi/*, */pi/, /fi/, /wi/*). Again, these results support the idea that these tasks are fundamentally different and generate distinctive muscle activation levels.

Coherence

In order to understand more about how the muscles in those with facial paralysis are controlled, a coherence analysis of the EMG data was completed. This process yields coherence values between 0 and 1 where 0 indicates that the two muscles being compared are independently controlled at a given frequency and a value of 1 indicates that the muscles are controlled by a common drive at a given frequency. Coherence detected in the β band arises from the cortex, while coherence detected in the α band arises subcortically or spinally (Marsden, Ashby, Limousin-Dowsey, Rothwell, & Brown, 2000).

With the exception of the frontalis muscle, statistically significant coherence (above the 95% confidence interval) was found in the β band (i.e., 24 – 40 Hz) for each of the muscle comparisons during running speech (i.e., *Jack and Jill*). In contrast, significant coherence was not observed between any of the muscles during the individual speech tokens (i.e., */bi/*, */pi/*, */fi/*, */wi/*). Consistent with movement and muscle physiology data, these coherence results suggest that the motor programs responsible for producing the individual speech tokens and running speech are fundamentally different. Muscle groups comparisons on coherence measures (i.e., orbicularis oris and gracilis/zygomatic major; masseter and gracilis/zygomatic major) indicated a common cortical control for running speech which was not apparent for the production of individual tokens. Running speech is ostensibly different from the production of single tokens in terms of the skills requiring motor planning, motor sequencing and cognitive formulation (among others). The cognitive load for producing running speech may be sufficient to recruit a common cortical command to the peripheral system for execution of this task. In contrast, productions of isolated speech tokens do not require the same cognitive, linguistic or motor complexity associated with running speech. Therefore, it may be possible that a more “distributed” cortical or subcortical controller be recruited to signal the peripheral system. Like the speech tokens, non-speech tasks like puckering and smiling lack the cognitive/linguistic components that are inherent in the running speech task. As such, it may be that these tasks are also controlled by a more distributed cortical control.

Although significant coherence was detected between the gracilis/zygomatic major, the masseter and the orbicularis oris during running speech, it was not detected between the frontalis and these muscles. This may have been because the tasks completed in the study lacked spontaneous emotion and facial expression at the eyebrows was limited. As such, this muscle was relatively uninvolved during either of the speech tasks and co-contraction of this muscle with the others was unnecessary during these tasks.

Not only do these data relate to outcomes following facial reanimation surgery, but they are applicable to clinical speech therapy. Although research does not provide support for the use oral motor exercises (i.e., non speech activities such as blowing bubbles or tongue pushups that supposedly condition the muscles of the mouth and face) for the treatment of articulation disorders (for a review, see Forrest, 2002), speech language pathologists continue to use these activities in therapy. Many clinicians use oral motor exercises or small segments of speech (i.e., individual speech tokens) to teach more complicated speech motor patterns. This is in part because the principles of motor learning signify that learning a complex behavior may be enhanced by breaking that task into its individual parts. As such, practicing segmented individual tasks (i.e., oral motor exercises or speech tokens) theoretically will lead to an increased ability to perform the whole task (i.e., whole words or sentences). However, this is only true in a limited set of circumstances. When a behavior involves high cognitive loads (as in complex speech), practicing the individual parts of this behavior may actually hinder skill acquisition. Individual segments only increase the motor learning of a complex behavior if they are truly representative of that behavior (Naylor & Briggs, 1963 as cited in Forrest, 2002).

Based on the movement, muscle physiology and coherence data from the current study, it is apparent that the speech tokens, and likely oral motor exercise, are fundamentally different from complex speech (i.e., words and sentences). Because speech tokens and oral motor exercise lack the cognitive, linguistic, and motoric demands that are inherent in longer speech, they are controlled by different cortical mechanisms (i.e., a central processor versus a more “distributed” system). As such, change or improvement in one area, may not lead to change or improvement in the other (Naylor & Briggs, 1963 as cited in Forrest, 2002).

Having considered the central nervous system’s role in the results of this study, it is important to consider what is happening at the periphery and how this relates to central control mechanisms. As was stated previously, axonal regeneration in humans has been reported as 1 mm/day (Fagan, 1989; Gordon, Olawale, & Boyd, 2003); however muscle regeneration and activation following facial reanimation surgery is variable. Those who have undergone facial reanimation surgery have reported that the first muscle contractions begin 6 – 48 weeks post operatively (Terzis and Noah, 1997). This fairly lengthy time frame may be due to the fact that regenerating axons may not take an efficient path across the suture site. For example, axons may grow back into the proximal nerve stump before crossing the suture site. Furthermore, there may be broad misdirection of regenerated axons even when the nerve fascicles are matched between proximal and distal nerve stumps with microsurgical techniques. This may contribute to poor functional recovery when targets are reinnervated (Gordon, Olawale, & Boyd, 2003). This supports the idea that the peripheral nervous system is continually changing in this population. As the peripheral nervous system changes over time (i.e., the new muscle becomes reinnervated), the related central nervous system pathways must continually adjust to the new motor system.

Relationship between Kinematic Measures and Peak EMG Amplitudes

A one-to-one correspondence did not exist between movement and peak EMG amplitudes. The relationship between these two variables was inconsistent; both positive and negative relationships existed. An example related to facial expression can be used to highlight the case where movement was detected but no EMG resulted. Facial expression results from the complex actions of many muscles working in unison, with no one single muscle having sole responsibility (Cacou, Greenfield, Hunt, & McGrouther, 1996). Although movement may be detected, it may be the result of unexpected muscle activation or a muscle that is not being recorded at the time. An example related to mastication can be used to highlight the case where EMG amplitude was recorded, but no movement was detected. In this case, muscular contraction meets resistance, as in isometric exercise, and the length of the muscle remains the same; no movement will be detected. For instance, while chewing, a muscle may be contracting (i.e., a high peak amplitude may be recorded), but the muscle may be meeting resistance from the bolus creating an isometric contraction situation that results in no detection of movement. Lastly, results may be biased if the electrode is placed above an area with a greater (or lesser) concentration of muscle fiber activation that is not representative of the average activation across the entire muscle. For instance, the electrode may have recorded high muscle fiber activation levels in its receptive area when in actuality the overall average muscle activity may be very low. Because there is no muscle fiber activation in the muscle as a whole, it may be likely that no movement is occurring. Thus, a high EMG activity level may be recorded, but movement may be negligible.

Limitations

Although the protocol for the present study was effective for collecting a detailed evaluation of outcomes following facial reanimation, several limitations should be considered. As was mentioned before, although our method of collecting kinematic data revealed maximum excursions, it did not provide direction or trajectory of movement. As such, it was difficult to interpret if movements occurred in the biomechanically-correct direction for the targeted behavior. Furthermore, it would be interesting to note whether movement following surgery was refined (i.e., had a straight path and consistent velocity of motion) or more erratic (i.e., had a variable path and velocity of motion).

Due to a limited time frame, only one subject was tested more than once. As such, it cannot be determined whether the outcome measures for the remaining patients were the result of residual function or surgical intervention. Furthermore, because measures were not taken before and after surgery, the degree to which these functional outcomes have improved also cannot be determined.

The number of subjects in this study was relatively low (n = 6) and as such, separate case studies were presented. In order to better identify trends in outcomes in this population and statistically confirm data, more participants are needed. Due to the relatively low number of patients undergoing facial reanimation surgery at any given centre, it would be beneficial to develop standardized protocols for evaluating outcomes so that multiple centers may compare and combine data such that facial reanimation surgery can be more effectively evaluated.

Future Research

Although several methods of evaluating three dimensional facial kinematics have been proposed (Frey, Giovanoli, Gerber, Slameczka, & Stussi, 1999; Ghoddousi, Edler, Haers, Wertheim, & Greenhill, 2007), none have reported results following facial reanimation. Studies that have measured facial movement following surgery have used two-dimensional techniques. This may be a limitation as facial expression and movement occur in three-dimensional space. Furthermore, other researchers have shown that two-dimensional movements grossly underestimate movement in three-dimensional space (Gross, Trotman, Moffat, 1996). Future research should focus on evaluating facial movement in three dimensions.

It is intuitive that there is cortical adaptation associated with motor skill adjustment and consequent functional gain following facial reanimation. Several studies have assessed cortical plasticity in rats (Franchi, 2000; Franchi, Maggiolini, Muzzioli, & Guandalini, 2006) and humans (Rodel, Tergal, Markus, & Laskawi, 2004) and have found that somatotopy in the primary motor cortex is disrupted following facial nerve damage. In general, this means that cortical representations of injured areas of the body are taken over by neighbouring representations. Although these results look promising, few studies have assessed neuroplasticity at the level of the central nervous system following facial reanimation surgery. As such, it would be interesting to objectively evaluate central and peripheral nervous system changes and their relation to function following surgery.

Many of the tasks included in the present study were contrived and involved little spontaneous emotion. For example, movement and muscle physiology were only evaluated during an unnatural smile and not during a spontaneous smile. Some studies have shown that voluntary posed facial expressions (i.e., "make a happy/sad/mad face") produced greater EMG activity than imagined states (i.e., "show me how you would feel if you won a lot of money") (Aniss & Sachdev, 1996). Furthermore, studies have shown that different cortical pathways may control voluntary and spontaneous facial expression (Root & Stephens, 2003). Future research utilizing more spontaneous facial expressions may reveal different kinematic, muscle physiology, and coherence data.

Conclusion

In order to effectively evaluate physiological and functional outcomes following facial reanimation surgery, a comprehensive assessment is necessary. The data from the current study suggest that nerve regeneration and functional recovery of the transferred muscle has occurred. Although lip excursion on the SRPS during smiling and several other activities may improve following surgery, it usually does not equal that of the NPS. Mild problems with articulation and mastication are present following surgery; however, patients still manage to be heard and understood by unfamiliar listeners and swallowing appears to be completely functional. The data from this study imply that different cortical control mechanisms may be recruited for the production of individual speech tokens versus running speech. This research not only contributes to the literature on outcomes following facial reanimation, but it advances knowledge in the areas of neurophysiology and clinical speech language pathology. The description of physiological and functional outcomes following surgery may lead to improved evaluations pre and post-operatively, enhance surgical procedures and rehabilitative programs.

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APPENDIX A: RECRUITMENT LETTER

Jaret L. Olson*, MD, FRCSC
Divisions of Pediatric and Plastic Surgery
* Denotes Professional Corporation

Department of Surgery
2D3.78 Walter C. MacKenzie Health Sciences Centre
8440-112 ST
EDMONTON AB T6G 2B7

Tel (780)407-8108
Fax (780)407-8131

January 5, 2007

John Smith
123 456 Street
Edmonton, AB T0H 0H0

Dear:

A Master's student at the University of Alberta is conducting a research study for her thesis. We would like your help. You are being told about this study because you have had or will have facial reanimation surgery or "smile surgery". We hope to understand how the muscles in your face change after you have had surgery. We also want to know how your brain learns to make the new face muscle work once it has been transplanted. We will observe how these changes relate to function such as your ability to smile, speak, eat and drink.

We will be tracking the changes in your brain using an MRI (a large magnet that takes pictures of your brain). We will also see how your muscles function and move while you perform tasks such as smiling, speaking, eating and drinking. Your swallowing will be observed and we will examine your face and the inside of your mouth. Lastly, we will be recording some of your speech.

If you decide to participate, you will be given the above tests three or four times over a one year period. Each testing session will be approximately 4 hours. The study will take place at the University of Alberta and at COMPRU in the Misericordia Hospital. If you are from out of town, your transportation and food will be reimbursed. If you live in Edmonton or the surrounding area, you will be reimbursed for parking.

We hope that the results from this study will help us understand the changes that occur after facial surgery. This will begin to help us develop treatments that will lead to better recovery of function in future patients. Although the MRI exam has no known harmful effects, there may be some minor discomfort during the exam. If you feel too uncomfortable, you will be removed from the scanner immediately.

If you choose to participate, you may withdraw at any point in the study. The information that we collect from you will be completely confidential.

If you would like more information regarding this study or would like to participate, please call Dr. Carol Boliek Associate Professor in the Department of Speech Language Pathology and Audiology at 780-492-0841. Alternatively, you may fill out the release form below and return it in the enclosed envelope. The researchers will then call you in approximately one week to see if you are interested in participating in the study. At any time you can say "no" to participating with no consequences to your treatment. Thank you for your time and consideration.

Sincerely,

Jaret L. Olson, MD, FRCSC

I ______________________ would like a phone call to get more information regarding the facial reanimation research study. Please call me between the hours of ________ am/pm and _________am/pm. I can be reached at (____)_______________.

_________________________ Signature

__________________ Date

Jaret L. Olson*, MD, FRCSC
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January 5, 2007

The Parents of
123 456 Street
Edmonton, AB T0H 0H0

To the Parents of :

A Master's student at the University of Alberta is conducting a research study for her thesis. We would like your help. You are being told about this study because your child has had or will have facial reanimation surgery or "smile surgery". We hope to understand how the muscles in your child's face change after he or she has had surgery. We also want to know how his or her brain learns to make the new face muscle work once it has been transplanted. We will observe how these changes relate to function such as your child's ability to smile, speak, eat and drink.

We will be tracking the changes in your child's brain using an MRI (a large magnet that takes pictures of your brain). We will also see how your child's muscles function and move while he or she performs tasks such as smiling, speaking, eating and drinking. Your child's swallowing will be observed and we will examine his or her face and the inside of his or her mouth. Lastly, we will be recording some of your child's speech.

If you decide to participate, your child will be given the above tests three or four times over a one year period. Each testing session will be approximately 4 hours. The study will take place at the University of Alberta and at COMPRU in the Misericordia Hospital. If you are from out of town, your transportation and food will be reimbursed. If you live in Edmonton or the surrounding area, you will be reimbursed for parking.

We hope that the results from this study will help us understand the changes that occur after facial surgery. This will begin to help us develop treatments that will lead to better recovery of function in future patients. Although the MRI exam has no known harmful effects, there may be some minor discomfort during the exam.

If your child feels too uncomfortable, he or she will be removed from the scanner immediately. If you allow your child to participate, he or she may withdraw at any point in the study. The information that we collect from your child will be completely confidential.

If you would like more information regarding this study or would like to participate, please call Dr. Carol Boliek Associate Professor in the Department of Speech Language Pathology and Audiology at 780-492-0841. Alternatively, you may fill out the release form below and return it in the enclosed envelope. The researchers will then call you in approximately one week to see if you and your child are interested in participating in the study. At any time you and your child can say "no" to participating with no consequences to your treatment. Thank you for your time and consideration.

Sincerely,

Jaret L. Olson, MD, FRCSC

I ______________________ would like a phone call to get more information regarding the facial reanimation research study. Please call me between the hours of ________ am/pm and _________am/pm. I can be reached at (____) _____________.

_________________________ Signature

__________________ Date

APPENDIX B: INFORMATION LETTERS

UNIVERSITY OF ALBERTA

Information Letter

Project Title: *Neuroplasticity and functional outcomes in patients with facial paralysis following facial reanimation surgery.*

Investigator (s):

Co-supervisors: Carol Boliek, PhD and Jana Rieger, PhD
Melissa Harasem, BSc

Throughout this information sheet the words "you" and "your" refer to the research subject.

Purpose of Study:
You have been asked to participate in this study because you have had or will have a surgery that transfers a new muscle to your face and allows you to smile. The surgery itself is not a part of the study. We want to look at what happens after you have surgery.

We hope to understand how the muscles on your face that help you smile, talk, and chew change after you have had surgery. We also want to know how your brain learns to make the new face muscle work once it has been transplanted. We will observe how these changes relate to function such as your ability to smile, speak, eat and drink.

Procedure:
At the beginning of the study, we will be taking a 3D picture of your head using a scanner. The scanner will move around your head and send a picture of your face to a computer. We will be using this picture as a reference for measuring facial movements after surgery. It will take about 7 seconds to scan your entire head; it will not hurt. This scan will be done once at the beginning of the study and we will keep the picture on file. This scan will be performed at the Misericordia Hospital.

After we take the 3D picture of your head, we will be giving you several tests. These tests are all listed below. If you *have not* had your surgery, we will be giving you these tests four times. You will be tested once before surgery, and then at 2, 6, and 12 months after surgery. If you *have* had surgery, we will be giving you these tests three times. You will be tested at 12, 18, and 24 months after surgery. The total time span for this study is approximately one year.

The tests listed below may be done in any order. Each testing session will be done in one visit. It will take about 4 hours per visit to complete all the tests.
We will be tracking the changes in your brain using an MRI (a large magnet that takes pictures of your brain).We are asking you to undergo three MRI exams. You will be asked to complete a screening questionnaire to ensure it is safe for you to have a scan. The MRI scans will take about 20-30 minutes. The MRI examination itself is painless. The examination involves lying very still on your back. If you move in the scanner, the MRI pictures may be blurry and unreadable. The MRI scans make a knocking sound that is normal. We will supply earplugs and ear protector muffs to reduce the noise.

We will also see how your muscles are working when you do several different tasks. To do this, we will place 8 electrodes (little metal disks) on your face with a sticky substance called micropore tape. The electrodes will monitor how well your muscles are functioning. You will be required to smile, frown, pucker your lips, chew a small piece of candy, bite, drink juice, eat pudding and talk.

We also will want to take pictures of your face while you are doing these activities. To do this, we will place small lights on your face with special tape. These will be placed next to the EMG monitors. The lights are used by special cameras to help us see how you move your mouth, lips, and cheeks when you are doing the activities listed above. We will assess drooling and your ability to chew food and drink liquids. To do this, we will ask you to drink the juice, eat the pudding, and chew the wine gum a second time without the electrodes covering your face. We will use a checklist to report how you perform these tasks.

After you are all done with these activities, we will examine the inside your mouth to see how your tongue and teeth look. We will also ask you to do some activities to see how well your lips, tongue, jaw and cheeks function.

Finally, we will be testing your speech. You will be asked to read a short paragraph and say a number of different syllables that contain different sounds. You will also be asked a number of open-ended questions so that we can record how you talk in everyday conversation. All of these speech samples will be recorded with a video and audio tape recorder.

If you are from out of town, you will be reimbursed a rate of $0.39 per kilometre, up to 300 km, for travel expenses, $12 for parking at the University of Alberta and $45.00 per person per day for food. If you are from Edmonton and the surrounding area, you will be reimbursed $12.00 for parking. These amounts will be reimbursed after each session you attend.

Possible Benefits:
We hope that the results from this study will help us understand the changes that occur after facial surgery. This information will help us know more about

functional outcomes after surgery. Results from this study will begin to help us develop treatments that will lead to better recovery of function in future patients.

Possible Risks:

The MRI exam has no known harmful effects assuming you have none of the risk factors listed on the MRI screening questionnaire. Great care should be taken in reviewing the MRI screening form since items on that list could be hazardous to your safety in the MRI room. You will be advised to avoid bringing any metallic objects into the scanning room as these could pose as a serious hazard as 'airborne projectiles'.

There may be some minor discomfort during the MRI. There is a possibility that you may feel a tapping or twitching. Should you feel too uncomfortable or claustrophobic while in the MRI scanner, you will be removed from the scanner promptly. You will be given a "panic" button to notify the investigator if you want the scan stopped. The investigator will be in continual contact with you inside the magnet via headphones.

Confidentiality:

Only the people conducting this study will see the information obtained. We will not give your name to anyone outside the study. The information you provide will be kept for at least five years after the study is completed. The researcher will store the information in a locked filing cabinet. Your name will not be attached to the data you provide. Your name will not be used in any presentations or publications. If we would like to use pictures of your face to show your recovery, we will ask your permission to do so before hand.

For this study, the researchers may need to access your personal health records for health information such as past medical history and test results. He/she may also need to contact your family physician and your other health care providers to obtain additional medical information. The health information collected as part of this study will be kept confidential unless release is required by law, and will be used only for the purpose of the research study. By signing the consent form you give permission to the study staff to access any personally identifiable health information which is under the custody of other health care professionals as deemed necessary for the conduct of the research.

By signing the consent form you give permission for the collection, use and disclosure of your medical records. In Canada, study information is required to be kept for 7 years. Even if you withdraw from the study, the medical information which is obtained from you for study purposes will not be destroyed. You have a right to check your health records and request changes if your personal information is incorrect.

Withdrawal:
If you choose to participate, you may withdraw at any point in the study. You do not need to give a reason.

Contact:
Please be sure to ask the investigators any questions you have now or if you have any further questions about this study later on, please contact Dr. Boliek at (780) 492-0841.

If you have any concerns about the conduct of this study, please call Dr. Paul Hagler the Associate Dean of Research for the Faculty of Rehabilitation at (780) 492-9674.

UNIVERSITY OF ALBERTA

Assent Form

Project Title: *Neuroplasticity and functional outcomes in patients with facial paralysis following facial reanimation surgery.*

Investigator(s):

Co-supervisors: Carol Boliek, PhD and Jana Rieger, PhD
Melissa Harasem, BSc

Why have you been asked to do this:

You have had or will have smile surgery. We want to see how your brain and muscles change after surgery. We also want to see how your face moves, how you speak, how you chew food and how you drink.

How long will this take:

If you have had your surgery, we will test you 3 times. These tests will be about 6 months apart. If you have not had your surgery yet, we will test you once before surgery and 3 times after. These tests will be about every 6 months. It will take us about 4 hours every time we test you.

What will you have to do:

First, we will take a 3D picture of your head. A camera will move around your face for about 7 seconds. This will not hurt. The camera will then send this picture to a computer. We will use this picture to see how your face moves. You will only have to do this once.

Then we are going to take pictures of your brain using a big magnet called an MRI. You will lie down in a small space and the MRI will take pictures. This will not hurt, but you must lay still. It will take about 25 minutes. Sometimes the machine is loud, but you can wear headphones while it is taking the pictures.

Second, we want to see how well the muscles in your face are working. We will place 8 sticky metal dots on your face. These dots will measure how well your muscles are working. When these dots are on your face, we will get you to smile, frown, and pucker you lips. We will also get you to drink some juice, eat pudding and chew a piece of candy. You will also say some made up words that have different sounds in them.

Third, we are going to see how much your face is moving and take a movie while you are smiling, eating, and talking. Little lights will be attached to your face just next to the sticky metal dots. These lights are the size of the fingernail on your baby finger. The lights and the metal dots do not hurt. We will be taking your picture with a video camera so we can go back and look at your face and how it moves once you have gone home.

After this is done, we will look at how you chew, drink, and talk without the lights and dots. We will write down how well you can drink and eat. We will also write down any problems you have. We are going to look at your lips, tongue, and inside your mouth to see how everything there is working. We will get you to do a number of things with your mouth and tongue. For example, we will get you to stick out your tongue and move it from side-to-side and we will get you to puff out your cheeks. These tests only take a few minutes.

The last thing we are going to do is see how you talk. You will read a short story and say some made up words that have different sounds. We will also ask you some questions. For example, we might ask you what your favorite movie is. This is so we can see how you talk when you are just having a normal conversation. We will make a video and audio recording while you are doing all of these things.

Will it help?

By helping us out in this study we will learn about how you learn to smile and do other things with your face, lips, and mouth after you have had surgery. What you are able to show us will help the doctors and therapists do a better job with children and adults who will go through the same surgery in the future.

Will it hurt?

Nothing we are asking you to do will hurt. The MRI test will be the hardest because you have to be still on your back for 25 minutes and the noise will sound loud. Everything else is easy and will not be hard for you to do.

Can you quit?

You don't have to take part in the study at all and you can quit at any time. No one will be mad at you if you decide you don't want to do this or if you decide to stop part way through. You should tell the researchers or your parents that you want to quit.

Who will know?

No one except your parents, the researchers and the doctors will know you're taking part in the study unless you want to tell them. Your name and your information will not be seen by anyone except the researchers and doctors during the study.

Your signature:

We would like you to sign this form to show that you agree to take part. Your mom or dad will be asked to sign another form agreeing for you to take part in the study.

Do you have more questions?

You can ask your mom or dad about anything you don't understand. You can also talk to Carol, Jana, or Melissa.

I agree to take part in the study.

______________________________ Signature of Research Participant	____________________ Date
______________________________ Signature of Parent or Guardian	____________________ Date
______________________________ Signature of Parent or Guardian	____________________ Date
______________________________ Signature of Investigator	____________________ Date

APPENDIX C: CONSENT FORM

UNIVERSITY OF ALBERTA

Consent Form

Title of Project: *Neuroplasticity and functional outcomes in patients with facial paralysis following facial reanimation surgery.*

Principal Investigator(s):

Carol Boliek, PhD and Jana Rieger, PhD (Co-supervisors)
Melissa Harasem, BSc
Dr. Boliek's Contact Number: (780) 492-0841

Throughout this consent form the words "you" and "your" refer to the research subject.

	Yes	No
Do you understand that you have volunteered to be in a research study?	☐	☐
Have you read and received a copy of the attached information sheet?	☐	☐
Do you understand the benefits and risks involved in taking part in this research study?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Do you understand that you are free to withdraw from the study at any time? You do not need to give a reason and it will not affect your care.	☐	☐
Has the issue of confidentiality been explained to you? Do you Understand who will have access to your records/information?	☐	☐

This study was explained to me by: ______________________________

I agree to take part in this study.

____

Signature of Research Participant   Date   Witness

____

Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

____________________________   ____________________

Signature of Investigator   Date

APPENDIX D: ORAL MECHANISM EXAM

Modified Oral Mechanism Exam

1. Instructions: Look straight at me

   Assess:

   - symmetry
   - flaccidity or spasticity
   - ptosis
   - lip drooping
   - drooling
   - mask like appearance

2. Instructions: Pucker your lips

   Assess:

   - range
   - symmetry

3. Instructions: Smack your lips like this: (model)

   Assess:

   - force

4. Instructions: close your teeth and use your lips to keep this tongue depressor in your mouth

   Assess:

   - strength on both sides

5. Instructions: Say ______, as many times as you can until I say stop. Ready?

   Assess:

   -pa

   -ta

   -ka

   -pataka

6. Instructions: Slowly open your jaw as wide as you can and close it three times. Like this (model).

   Assess:

   - TMJ
   - deviation
   - jerky movements

7. Instructions: Move your jaw forward an then backward three times. Like this (model).

   Assess:

   - range

8. Instructions: Move your jaw from side to side three times. Like this (model).

   Assess:

   - range

9. Instructions: Try to open your mouth against my hand.

   Assess:

   - strength

10. Instructions: Look straight at me and smile

Assess:

- range of motion

11. Instructions: Look straight at me and open your mouth as wide as you can

Assess:

-teeth

-gums

- hard palate

- tongue

- velum (when saying ah)

13. Instructions: Try to blow this balloon.

Assess:

-Lip closure and seal

14. Instructions: Puff out your cheeks

Assess:

-lip strength

15. Instructions: Try to whistle.

Assess:

-lip excursion

APPENDIX E: MASTICATION CHECKLIST

Compensatory Behaviors

Compensatory Behavior	Behavior present	Behavior present, but minimal	Behavior not present	Comments
Using hand during drinking				
Using hand during eating				
Drinking small amounts of liquids				
Eating small amounts of semi solid food				
Eating small amounts of solid food				
Slower drinking				
Slower eating of semi solid food				
Slower eating of solid food				
Adapted cup				
Cup on the non affected side				
Spoon on the non-affected side				

Adapted from:
de Swart, B.J.M., Jolien, M.A., Verheij, C.G.E., & Beurskens, C.H.G. (2003). Problems with Eating and Drinking in Patients with Unilateral Peripheral Facial Paralysis. *Dysphagia, 18,* 267-273.

Compensatory Behaviors Continued

Compensatory Behavior	Behavior present	Behavior present, but minimal	Behavior not present	Comments
Food on the non affected side				
Adapted head posture liquids				
Adapted head posture semi solids				
Adapted head posture solids				
Remove residual liquids				
Remove residual semi solids				
Remove residual solids				
Spoon on affected side				
Compensating with tongue				
Adapted consistency				

Adapted from:
de Swart, B.J.M., Jolien, M.A., Verheij, C.G.E., & Beurskens, C.H.G. (2003). Problems with Eating and Drinking in Patients with Unilateral Peripheral Facial Paralysis. *Dysphagia, 18,* 267-273.

Problems with Eating and Drinking

Problem	Problem present	Problem present, but minimal	Problem not present	Comments
Enclosing cup with lips				
Wet lips after drinking				
Residue of semi solid food on lips				
Residue of solid food on lips				
Residue of semi solid in cheek				
Residue of solid in cheek				
Residue of semi solid behind lip				
Residue of solid food lower lip				
Chewing: affected side open				
Serial drinking not possible				

Adapted from:
de Swart, B.J.M., Jolien, M.A., Verheij, C.G.E., & Beurskens, C.H.G. (2003). Problems with Eating and Drinking in Patients with Unilateral Peripheral Facial Paralysis. *Dysphagia, 18,* 267-273.

Problems with Eating and Drinking Continued

Problem	Problem present	Problem present, but minimal	Problem not present	Comments
Dribbling saliva				
Dribbling Liquids				
Dribbling semi solid food				
Dribbling solid food				
Chewing/biting cheek or lip				
Choking on liquids				
Choking on semi solids				
Choking on solids				
Coughing during drinking				
Coughing during semi solid foods				
Coughing during solid foods				

Adapted from:
de Swart, B.J.M., Jolien, M.A., Verheij, C.G.E., & Beurskens, C.H.G. (2003). Problems with Eating and Drinking in Patients with Unilateral Peripheral Facial Paralysis. *Dysphagia, 18,* 267-273.

APPENDIX F: OPEN ENDED QUESTIONS FOR SPEECH SAMPLE

1. If you could have dinner with anyone alive or dead, who would it be and why?
2. If you could have your ideal meal, which meal would it be and what would you eat?
3. What did you do this weekend/last night?
4. If you were king/queen of the world for one day, what would you do and why?
5. If you could have any job, what would you choose and why?
6. If you could go anywhere in the world, where would you go and why?
7. What would you do there?
8. Tell me about your favorite movie.
9. Tell me about your favorite vacation.
10. If you could be a super hero, what would your power be and why?
11. Tell me how to make your favorite sandwich/meal from start to finish.
12. Tell me about your family.
13. Tell me about your job.
14. Tell me a funny story about your children.

APPENDIX G: TABLES AND FIGURES FOR S1

The following appendix provides detailed tables and figures for the 2D kinematic and EMG data for S1. Please note: SRPS = surgically-repaired paralyzed side and NPS = non-paralyzed side.

2D Kinematic Measures

Eyebrows

Table 3.1: Asymmetries in movement between each side of the face at the eyebrows

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↔	↔
pucker	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.2: Activities that produced the largest maximum excursions at the eyebrows

SRPS	NPS
/wi/	/wi/

Cheeks

Table 3.3: Asymmetries in movement between each side of the face at the cheeks

Activity	Asymmetry	
	SRPS	NPS
/bi/	↑	↓
/pi/	↓	↑
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↓	↑
chewing winegum	↔	↔
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.4: Activities that produced the largest maximum excursions at the cheeks

SRPS	NPS
/fi/	/fi/
pucker	pucker
/bi/	Jack and Jill
/wi/	

Upper Lip

Table 3.5: Asymmetries in movement between each side of the face at the upper lip

Activity	Asymmetry	
	SRPS	NPS
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↓	↑
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.6: Activities that produced the largest maximum excursions at the upper lip

SRPS	NPS
Jack & Jill	Jack and Jill
pucker	pucker
/bi/	/wi/

Lip corners

Table 3.7: Asymmetries in movement between each side of the face at the lip corners

Activity	Asymmetry	
	SRPS	NPS
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.8: Activities that produced the largest maximum excursions at the lip corners

SRPS	NPS
/bi/	/bi/
/wi/	/wi/
pucker	pucker
/pi/	
/fi/	
Jack and Jill	

Lower Lips

Table 3.9: Asymmetries in movement between each side of the face at the lower lips

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	↓	↑
/fi/	↓	↑
/wi/	↓	↑
Jack and Jill	↓	↑
chewing winegum	↑	↓
smile	↑	↓
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.10: Activities that produced the largest maximum excursions at the lower lips

SRPS	NPS
/bi/	/bi/
/pi/	/pi/
/fi/	/fi/
/wi/	/wi/
Jack and Jill	Jack and Jill

Central Lip Marker

Table 3.11: Activities that Produced the Largest Maximum Excursions at the Central Lip

Central Lip Marker
/bi/
/pi/
/fi/
/wi/
Jack and Jill

Summary of 2D Kinematic Measures

Table 3.12: Summary of activities that produced large maximum excursions and the number of markers for which larger movements were observed

SRPS		NPS		Central Lip Marker
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
/bi/	4/5	/wi/	4/5	/bi/
/wi/	4/5	pucker	3/5	/pi/
/fi/	3/5	/bi/	2/5	/fi/
pucker	3/5	/fi/	2/5	/wi/
/pi/	2/5	/pi/	1/5	Jack and Jill

Table 3.13: Summary of activities that produced small maximum excursions and the number of markers for which smaller movements were observed

SRPS		NPS		Central Lip Marker
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
chewing winegum	4/5	chewing winegum	4/5	chewing winegum
smile	4/5	smile	4/5	smile
/bi/	1/5	/bi/	1/5	pucker
/pi/	1/5	/pi/	1/5	
/fi/	1/5	/fi/	1/5	
pucker	1/5	Jack and Jill	1/5	

EMG

Frontalis

Table 3.14: Asymmetries in peak EMG amplitude between each side of the face at the frontalis

Activity	Asymmetry	
	SRPS	NPS
/bi/	barely detectable	barely detectable
/pi/	barely detectable	barely detectable
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	↑	barely detectable
chewing winegum	barely detectable	barely detectable
smile	barely detectable	barely detectable
pucker	↑	barely detectable
chewing pudding	↑	barely detectable
drinking	↑	↓
press	↑	barely detectable
frown	↑	barely detectable
clench	barely detectable	barely detectable

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.15: Activities that produced peak EMG amplitudes in the frontalis

SRPS	NPS
Jack and Jill	drinking
pucker	
chewing pudding	
drinking*	
press	
frown*	

*Indicates an activity that produced some of the highest peak amplitudes in this muscle

Gracilis/Zygomatic Major

Table 3.16: Asymmetries in peak amplitude between each side of the face at the gracilis/zygomatic major

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	barely detectable	barely detectable
/pi/	barely detectable	barely detectable
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	↑	barely detectable
chewing winegum	barely detectable	↑
smile	barely detectable	barely detectable
pucker	barely detectable	barely detectable
chewing pudding	barely detectable	↑
drinking	↔	↔
press	barely detectable	barely detectable
frown	↑	barely detectable
clench	barely detectable	barely detectable

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.17: Activities that produced EMG amplitudes in the gracilis/zygomatic major

SRPS	NPS
Jack and Jill	chewing winegum*
drinking	chewing pudding
frown*	drinking

*Indicates an activity that produced some of the highest peak amplitudes at this muscle

Masseter

Table 3.18: Asymmetries in peak EMG amplitude between each side of the face at the masseter

Activity	Asymmetry	
	SRPS	NPS
/bi/	↑	barely detectable
/pi/	barely detectable	barely detectable
/fi/	↑	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	↑	barely detectable
chewing winegum	barely detectable	barely detectable
smile	barely detectable	barely detectable
pucker	↑	barely detectable
chewing pudding	↑	barely detectable
drinking	↑	barely detectable
press	↑	barely detectable
frown	↑	barely detectable
clench	↑	barely detectable

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.19: Activities that produced EMG amplitudes in the masseter

SRPS	NPS
/bi/	
/fi/	
Jack and Jill	
pucker*	
chewing pudding*	
drinking*	
frown*	
clench	

*Indicates an activity that produced some of the highest peak amplitudes at this muscle

Orbicularis Oris

Table 3.20: Asymmetries in peak EMG amplitude between each side of the face at the orbicularis oris

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	barely detectable	N/A
/pi/	barely detectable	N/A
/fi/	N/A	N/A
/wi/	barely detectable	↑
Jack and Jill	↓	↑
chewing winegum	barely detectable	barely detectable
smile	barely detectable	barely detectable
pucker	barely detectable	↑
chewing pudding	↓	↑
drinking	↓	↑
press	barely detectable	barely detectable
frown	barely detectable	↑
clench	barely detectable	barely detectable

↑ = higher; ↓ = lower; ↔ = no difference

Table 3.21: Activities that produced EMG amplitudes in the orbicularis oris

SRPS	NPS
Jack and Jill	/wi/
chewing winegum*	Jack and Jill*
chewing pudding	chewing winegum*
drinking	pucker
	chewing pudding
	drinking*
	frown

*Indicates an activity that produced some of the highest peak amplitudes at this muscle

Overall Impression of EMG

Table 3.22: Summary of activities that produced large peak EMG amplitudes and the number of muscles for which larger amplitudes were observed.

SRPS		NPS	
Activity	**Number of Muscles**	**Activity**	**Number of Muscles**
frown	3/4	drinking	2/4
drinking	2/4	chewing winegum	2/4
chewing winegum	1/4	Jack and Jill	1/4
pucker	1/4		
chewing pudding	1/4		

APPENDIX H: TABLES AND FIGURES FOR S2

The following appendix provides detailed tables and figures for the 2D kinematic and EMG data for S2. Please note: NRPS = non-repaired paralyzed side and NPS = non-paralyzed side.

2D Kinematic Measures

Eyebrows

Table 4.1: Asymmetries in movement between each side of the face at the eyebrows

Activity	Asymmetry	
	NRPS	NPS
/bi/	↑	↓
/pi/	↑	↓
/fi/	↔	↔
/wi/	↓	↑
Jack and Jill	↓	↑
chewing winegum	↑	↓
smile	↔	↔
pucker	↔	↔

↑ = higher; ↓ = lower; ↔ = no difference

Note: There is no table for the activities that produced the largest maximum excursions at the eyebrows as movements were comparable across tasks.

Cheeks

Table 4.2: Asymmetries in movement between each side of the face at the cheeks

Activity	Asymmetry	
	NRPS	NPS
/bi/	↔	↔
/pi/	↔	↔
/fi/	↑	↓
/wi/	↓	↑
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.3: Activities that produced the largest maximum excursions at the cheeks

NRPS	NPS
chewing winegum	chewing winegum
/bi/	/wi/
	pucker

Upper Lip

Table 4.4: Asymmetries in movement between each side of the face at the upper lip

Activity	Asymmetry	
	NRPS	**NPS**
/bi/	↑	↓
/pi/	↓	↑
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↑	↓
pucker	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.5: Activities that produced the largest maximum excursions at the upper lip

NRPS	NPS
chewing winegum	chewing winegum
pucker	pucker
/bi/	/pi/
smile	

Lip corners

Table 4.6: Asymmetries in movement between each side of the face at the lip corners

Activity	Asymmetry	
	NRPS	NPS
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↑	↓
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.7: Activities that produced the largest maximum excursions at the lip corners

NRPS	NPS
/bi/	/bi/
/pi/	/wi/
chewing winegum	pucker

Lower Lips

Table 4.8: Asymmetries in movement between each side of the face at the lower lips

Activity	Asymmetry	
	NRPS	NPS
/bi/	↓	↑
/pi/	↓	↑
/fi/	↓	↑
/wi/	↓	↑
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↑	↓
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.9: Activities that produced the largest maximum excursions at the lower lips

NRPS	NPS
/bi/	/bi/
pucker	pucker
chewing winegum	/wi/

Central Lip Marker

Table 4.10: Activities that Produced the Largest Maximum Excursions at the Central Lip

Central Lip Marker
/bi/
/wi/
chewing winegum

Summary of 2D Kinematic Measures

Table 4.11: Summary of activities that produced the largest maximum excursions and the number of markers for which larger movements was observed

NRPS		NPS		Central Lip Marker
Activity	Number of Markers	Activity	Number of Markers	Activity
/bi/	4/4	pucker	4/4	/bi/
chewing winegum	4/4	/wi/	3/4	/wi/
pucker	2/4	/bi/	2/4	winegum
/pi/	1/4	/fi/	2/4	
smile	1/4	winegum	2/4	
		/pi/	1/4	

Note: The eyebrows were excluded from this analysis as movement was similar across tasks

Table 4.12: Summary of activities that produced small maximum excursions and the number of markers for which smaller movements was observed

NRPS		**NPS**		**Central Lip Marker**
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
/fi/	3/3	Jack and Jill	3/3	Jack and Jill
Jack and Jill	3/3	/fi/	2/3	smile
/pi/	1/3	smile	1/3	pucker

Note: The eyebrows and cheeks were excluded from this analysis as movement was similar across tasks

EMG

Frontalis

Table 4.13: Asymmetries in peak EMG amplitude between each side of the face at the frontalis

Activity	**Asymmetry**	
	NRPS	**NPS**
/bi/	barely detectable	barely detectable
/pi/	barely detectable	barely detectable
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	barely detectable	barely detectable
chewing winegum	barely detectable	barely detectable
smile	barely detectable	barely detectable
pucker	↓	↑
conversation	↓	↑
chewing pudding	barely detectable	↑
drinking	barely detectable	barely detectable
press	barely detectable	barely detectable
frown	barely detectable	↑
clench	barely detectable	barely detectable

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.14: Activities that produced the largest peak EMG amplitudes in the frontalis

NRPS	**NPS**
pucker	pucker
conversation	conversation
	drinking
	frowning

Gracilis/Zygomatic Major

Table 4.15: Asymmetries in peak amplitude between each side of the face at the gracilis/zygomatic major

Activity	Asymmetry	
	NRPS	**NPS**
/bi/	↓	↑
/pi/	NA	NA
/fi/	barely detectable	barely detectable
/wi/	NA	NA
Jack and Jill	↓	↑
chewing winegum	↓	↑
smile	barely detectable	↑
pucker	↓	↑
conversation	↓	↑
chewing pudding	barely detectable	↑
drinking	barely detectable	↑
press	barely detectable	↑
frown	barely detectable	↑
clench	barely detectable	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.16: Activities that produced the largest peak EMG amplitudes in the gracilis/zygomatic major

NRPS	NPS
conversation	conversation
	/bi/
	chewing winegum
	chewing pudding
	frown

Masseter

Table 4.17: Asymmetries in peak EMG amplitude between each side of the face at the masseter

Activity	Asymmetry	
	NRPS	**NPS**
/bi/	NA	NA
/pi/	barely detectable	↑
/fi/	barely detectable	↑
/wi/	barely detectable	↑
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↑	↓
pucker	↑	↓
conversation	↑	↓
chewing pudding	↑	↓
drinking	↑	↓
press	barely detectable	barely detectable
frown	↑	↓
clench	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.18: Activities that produced the largest peak EMG amplitudes in the masseter

NRPS	NPS
conversation	conversation
frown	frown
Jack and Jill	chewing winegum
pucker	

Orbicularis Oris

Table 4.19: Asymmetries in peak EMG amplitude between each side of the face at the orbicularis oris

Activity	Asymmetry	
	NRPS	NPS
/bi/	↓	↑
/pi/	↓	↑
/fi/	barely detectable	↑
/wi/	↔	↔
Jack and Jill	↑	barely detectable
chewing winegum	↓	↑
smile	barely detectable	↓
pucker	↓	↑
conversation	↓	↑
chewing pudding	↑	barely detectable
drinking	↑	↓
press	↓	↑
frown	barely detectable	↓
clench	barely detectable	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 4.20: Activities that produced the largest peak EMG amplitudes in the orbicularis oris

NRPS	NPS
chewing winegum	chewing winegum
	pucker
	clench

Summary of EMG

Table 4.21: Summary of activities that produced large peak EMG amplitudes and the number of muscles for which larger amplitudes was observed

NRPS		NPS	
Activity	**Number of Muscles**	**Activity**	**Number of Muscles**
conversation	3/4	conversation	3/4
pucker	2/4	chewing winegum	3/4
Jack and Jill	1/4	frown	3/4
chewing winegum	1/4	pucker	2/4
frown	1/4	/bi/	1/4
		chewing pudding	1/4
		drinking	1/4
		clench	1/4

Table 4.22: Atypical EMG waveforms observed

Muscle	NRPS		NPS	
	Waveform	**Activity**	**Waveform**	**Activity**
Gracilis			Tremor	smile
			Tremor	frown
			Tremor	clench
Masseter			Abnormal	/bi/

APPENDIX I: TABLES AND FIGURES FOR S4

The following appendix provides detailed tables and figures for the 2D kinematic and EMG data for S4. Please note: NRPS = non-repaired paralyzed side and SRPS = surgically-repaired paralyzed side.

2D Kinematic Measures

Eyebrows

Table 5.1: Asymmetries in movement between each side of the face at the eyebrows

Activity	Asymmetry	
	NRPS	SRPS
/bi/	↓	↑
/pi/	↑	↓
/fi/	↑	↓
/wi/	↔	↔
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↑	↓
pucker	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.2: Activities that produced the largest maximum excursions at the eyebrows

NRPS	SRPS
/fi/	/bi/
chewing winegum	chewing winegum
smile	
pucker	

Cheeks

Table 5.3: Asymmetries in movement between each side of the face at the cheeks

Activity	Asymmetry	
	NRPS	SRPS
/bi/	↑	↓
/pi/	↓	↑
/fi/	↔	↔
/wi/	↑	↓
Jack and Jill	↓	↑
chewing winegum	↑	↓
smile	↓	↑
pucker	↔	↔

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.4: Activities that produced the largest maximum excursions at the cheeks

NRPS	SRPS
chewing winegum	chewing winegum

Upper Lip

Table 5.5: Asymmetries in movement between each side of the face at the upper lip

Activity	Asymmetry	
	NRPS	SRPS
/bi/	↑	↓
/pi/	↓	↑
/fi/	↑	↓
/wi/	↔	↔
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↑	↓
pucker	↔	↔

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.6: Activities that produced the largest maximum excursions at the upper lip

NRPS	SRPS
chewing winegum	chewing winegum
smile	

Lip corners

Table 5.7: Asymmetries in movement between each side of the face at the lip corners

Activity	Asymmetry	
	NRPS	SRPS
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↓	↑
pucker	↔	↔

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.8: Activities that produced the largest maximum excursions at the lip corners

NRPS	SRPS
chewing winegum	chewing winegum

Lower Lips

Table 5.9: Asymmetries in movement between each side of the face at the lower lips

Activity	Asymmetry	
	NRPS	SRPS
/bi/	↓	↑
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↑	↓
pucker	↔	↔

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.10: Activities that produced the largest maximum excursions at the lower lips

NRPS	SRPS
/wi/	/wi/
Jack and Jill	Jack and Jill
chewing winegum	chewing winegum

Central Lip Marker

Table 5.11: Activities that Produced the Largest Maximum Excursions at the Central Lip

Central Lip Marker
/wi/
/Jack and Jilli/
chewing winegum

Summary of 2D Kinematic Measures

Table 5.12: Summary of activities that produced the largest maximum excursions and the number of markers for which larger movements were observed

NRPS		SRPS		Central Lip Marker
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
winegum	5/5	winegum	5/5	winegum
smile	2/5	/bi/	1/5	/wi/
/wi/	1/5	/wi/	1/5	Jack and Jill
Jack and Jill	1/5	Jack and Jill	1/5	
/fi/	1/5			
pucker	1/5			

Note: A summary of the activities that produced the smallest maximum excursions is not listed as most tasks produced comparable excursions in the subject

EMG

Frontalis

Table 5.13: Asymmetries in peak EMG amplitude between each side of the face at the frontalis

Activity	Asymmetry	
	NRPS	**SRPS**
/bi/	barely detectable	barely detectable
/pi/	barely detectable	barely detectable
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	↑	barely detectable
chewing winegum	↓	↑
smile	barely detectable	barely detectable
pucker	↑	barely detectable
chewing pudding	↑	↓
drinking	↓	↑
press	↔	↔
frown	↔	↔
clench	↔	↔

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.14: Activities that produced the largest peak EMG amplitudes in the frontalis

NRPS	SRPS
chewing winegum	chewing winegum
chewing pudding	drinking

Gracilis/Zygomatic Major

Table 5.15: Asymmetries in peak amplitude between each side of the face at the gracilis/zygomatic major

Activity	Asymmetry	
	NRPS	SRPS
/bi/	barely detectable	↑
/pi/	barely detectable	NA
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	↓	↑
chewing winegum	↓	↑
smile	barely detectable	↑
pucker	barely detectable	barely detectable
chewing pudding	↑	↓
drinking	barely detectable	↑
press	↓	↑
frown	↑	↓
clench	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.16: Activities that produced the largest peak EMG amplitudes in the gracilis/zygomatic major

NRPS	SRPS
chewing winegum	chewing winegum
	drinking

Masseter

Table 5.17: Asymmetries in peak EMG amplitude between each side of the face at the masseter

Activity	Asymmetry	
	NRPS	SRPS
/bi/	barely detectable	NA
/pi/	barely detectable	NA
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	barely detectable	↑
chewing winegum	↓	↑
smile	barely detectable	↑
pucker	barely detectable	↑
chewing pudding	↑	↓
drinking	barely detectable	↑
press	barely detectable	↑
frown	↑	↓
clench	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.18: Activities that produced the largest peak EMG amplitudes in the masseter

NRPS	SRPS
chewing pudding	chewing pudding
frown	chewing winegum
clench	Jack and Jill
	drinking
	press

Orbicularis Oris

Table 5.19: Asymmetries in peak EMG amplitude between each side of the face at the orbicularis oris

Activity	Asymmetry	
	NRPS	**SRPS**
/bi/	barely detectable	NA
/pi/	↑	barely detectable
/fi/	barely detectable	barely detectable
/wi/	barely detectable	barely detectable
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	↑	↓
pucker	↑	barely detectable
chewing pudding	↑	↓
drinking	barely detectable	↑
press	↑	↓
frown	↑	↓
clench	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 5.20: Activities that produced the largest peak EMG amplitudes in the orbicularis oris

NRPS	SRPS
chewing winegum	chewing winegum
chewing pudding	Jack and Jill
	drinking

Summary of EMG

Table 5.21: Summary of activities that produced large peak EMG amplitudes and the number of muscles for which larger amplitudes were observed

NRPS		SRPS	
Activity	**Number of Muscles**	**Activity**	**Number of Muscles**
chewing winegum	3/4	chewing winegum	4/4
chewing pudding	3/4	drinking	4/4
frown	1/4	Jack and Jill	2/4
clench	1/4	press	1/4
frown	1/4		

Table 5.22: Atypical EMG waveforms observed

Muscle	NRPS		SRPS	
	Waveform	**Activity**	**Waveform**	**Activity**
Gracilis			Abnormal	chewing winegum
Masseter	Abnormal	chewing winegum		
Orbicularis Oris	Abnormal	drinking	Abnormal	drinking
	Abnormal	/pi/		

APPENDIX J: TABLES AND FIGURES FOR S5

The following appendix provides detailed tables and figures for the 2D kinematic and EMG data for S5. Please note: SRPS = surgically-repaired paralyzed side and NPS = non-repaired paralyzed side.

2D Kinematic Measures

Eyebrows

Table 6.1: Asymmetries in movement between each side of the face at the eyebrows

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↓	↑
/pi/	↓	↑
/fi/	↓	↑
/wi/	↓	↑
Jack and Jill	↑	↓
chewing winegum	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.2: Activities that produced the largest maximum excursions at the eyebrows

SRPS	NPS
Jack and Jill	/bi/
	/pi/
	/fi/

Cheeks

Table 6.3: Asymmetries in movement between each side of the face at the cheeks

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	↑	↓
/fi/	↓	↑
/wi/	↔	↔
Jack and Jill	↓	↑
chewing winegum	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.4: Activities that produced the largest maximum excursions at the cheeks

SRPS	NPS
Jack and Jill	Jack and Jill
	/bi/
	chewing winegum
	pucker

Upper Lip

Table 6.5: Asymmetries in movement between each side of the face at the upper lip

Activity	Asymmetry	
	SRPS	NPS
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.6: Activities that produced the largest maximum excursions at the upper lip

SRPS	NPS
/pi/	/pi/
/fi/	/fi/
Jack and Jill	pucker

Lip corners

Table 6.7: Asymmetries in movement between each side of the face at the lip corners

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	↓	↑
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.8: Activities that produced the largest maximum excursions at the lip corners

SRPS	NPS
/fi/	chewing winegum
pucker	pucker
Jack and Jill	

Lower Lips

Table 6.9: Asymmetries in movement between each side of the face at the lower lips

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.10: Activities that produced the largest maximum excursions at the lower lips

SRPS	NPS
/fi/	/bi/
/wi/	chewing winegum
pucker	pucker
Jack and Jill	

Central Lip Marker

Table 6.11: Activities that Produced the Largest Maximum Excursions at the Central Lip

Central Lip Marker
/bi/
/pi/
Jack and Jill

Summary of 2D Kinematic Measures

Table 6.12: Summary of activities that produced the largest maximum excursions and the number of markers for which larger movements were observed

SRPS		NPS		Central Lip Marker
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
Jack and Jill	5/5	pucker	5/5	/bi/
/fi/	3/5	winegum	3/5	/pi/
pucker	2/5	/bi/	3/5	Jack and Jill
/pi/	1/5	/pi/	2/5	
		/fi/	2/5	
		Jack and Jill	1/5	

Note: A summary of the activities that produced the smallest maximum excursions is not listed as those tasks that did not produce the largest excursions generated comparable excursions.

EMG

Frontalis

Table 6.13: Asymmetries in peak EMG amplitude between each side of the face at the frontalis

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↑	↓
/pi/	barely detectable	barely detectable
/fi/	↔	↔
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↔	↔
pucker	barely detectable	barely detectable
chewing pudding	↑	↓
drinking	↑	↓
press	barely detectable	barely detectable
frown	barely detectable	barely detectable
clench	↑	barely detectable

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.14: Activities that produced the largest peak EMG amplitudes in the frontalis

SRPS	NPS
/wi/	/wi/
chewing winegum	chewing winegum
chewing pudding	chewing pudding
Jack and Jill	
Drinking	

Gracilis/Zygomatic Major

Table 6.15: Asymmetries in peak amplitude between each side of the face at the gracilis/zygomatic major

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↑	barely detectable
/pi/	barely detectable	barely detectable
/fi/	↔	↔
/wi/	↑	↓
Jack and Jill	↓	↑
chewing winegum	↓	↑
pucker	barely detectable	barely detectable
chewing pudding	↓	↑
drinking	↓	↑
press	↓	↑
frown	↑	barely detectable
clench	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.16: Activities that produced the largest peak EMG amplitudes in the gracilis/zygomatic major

SRPS	NPS
chewing pudding	chewing pudding
/wi/	

Masseter

Table 6.17: Asymmetries in peak EMG amplitude between each side of the face at the masseter

Activity	Asymmetry	
	SRPS	NPS
/bi/	↑	NA
/pi/	barely detectable	NA
/fi/	↑	NA
/wi/	↑	↓
Jack and Jill	↑	NA
chewing winegum	↑	NA
pucker	↑	NA
chewing pudding	↑	NA
drinking	↑	NA
press	NA	NA
frown	↑	NA
clench	↑	NA

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.18: Activities that produced the largest peak EMG amplitudes in the masseter

SRPS	NPS
/wi/	
chewing pudding	
drinking	
clench	

Orbicularis Oris

Table 6.19: Asymmetries in peak EMG amplitude between each side of the face at the orbicularis oris

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	barely detectable	↑
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↔	↔
chewing winegum	↑	↓
pucker	↑	↓
chewing pudding	↑	↓
drinking	↑	↓
press	↑	↓
frown	↑	↓
clench	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 6.20: Activities that produced the largest peak EMG amplitudes in the orbicularis oris

SRPS	NPS
chewing winegum	chewing winegum
chewing pudding	chewing pudding
/wi/	/bi/
drinking	Jack and Jill

Summary of EMG

Table 6.21: Summary of activities that produced large peak EMG amplitudes and the number of muscles for which larger amplitudes were observed

SRPS		NPS	
Activity	Number of Muscles	Activity	Number of Muscles
chewing pudding	4/4	chewing pudding	3/3
/wi/	4/4	chewing winegum	2/3
drinking	3/4	/bi/	1/3
chewing winegum	2/4	/wi/	1/3
Jack and Jill	1/4	Jack and Jill	1/3
clench	1/4		

Note: The masseter was not included in this analysis on the NPS as data recorded from this side was unusable.

Table 6.22: Atypical EMG waveforms observed

Muscle	SRPS		NPS	
	Waveform	**Activity**	**Waveform**	**Activity**
Frontalis	Abnormal	/fi/		
	Abnormal	Jack and Jill		
	Abnormal	drinking		
	Abnormal	clench		
Gracilis	Abnormal	/bi/		
	Abnormal	/fi/		
	Abnormal	Jack and Jill		
	Abnormal	chewing pudding		
	Abnormal	drinking		
Masseter	Abnormal	/bi/		
	Abnormal	/fi/		
	Abnormal	Jack and Jill		
	Abnormal	chewing pudding		
	Abnormal	drinking		
	Abnormal	frown		
	Abnormal	clench		
Orbicularis Oris	Abnormal	/bi/		
	Abnormal	/fi/		
	Abnormal	Jack and Jill		
	Abnormal	drinking		

APPENDIX K: TABLES AND FIGURES FOR S6

The following appendix provides detailed tables and figures for the 2D kinematic and EMG data for S6. Please note: SRPS = surgically-repaired paralyzed side and NPS = non-paralyzed side.

2D Kinematic Measures

Eyebrows

Table 7.1: Asymmetries in movement between each side of the face at the eyebrows.

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↑	↓
/pi/	↑	↓
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↑	↓
pucker	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.2: Activities that produced the largest maximum excursions at the eyebrows

SRPS	NPS
/bi/	/bi/
pucker	pucker
/fi/	/pi/

Cheeks

Table 7.3: Asymmetries in movement between each side of the face at the cheeks

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↓	↑
/pi/	↑	↓
/fi/	↓	↑
/wi/	↑	↓
Jack and Jill	↓	↑
chewing winegum	↑	↓
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.4: Activities that produced the largest maximum excursions at the cheeks

SRPS	NPS
/bi/	/bi/
/pi/	pucker

Upper Lip

Table 7.5: Asymmetries in movement between each side of the face at the upper lip

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↓	↑
/pi/	↓	↑
/fi/	↑	↓
/wi/	↑	↓
Jack and Jill	↓	↑
chewing winegum	↑	↓
smile	↔	↔
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.6: Activities that produced the largest maximum excursions at the upper lip

SRPS	NPS
/bi/	/bi/
chewing winegum	pucker

Lip corners

Table 7.7: Asymmetries in movement between each side of the face at the lip corners

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↓	↑
/pi/	↓	↑
/fi/	↓	↑
/wi/	↓	↑
Jack and Jill	↓	↑
chewing winegum	↓	↑
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.8: Activities that produced the largest maximum excursions at the lip corners

SRPS	NPS
/bi/	/bi/
	Jack and Jill
	pucker

Lower Lips

Table 7.9: Asymmetries in movement between each side of the face at the lower lips

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↓	↑
/pi/	↓	↑
/fi/	↓	↑
/wi/	↓	↑
Jack and Jill	↓	↑
chewing winegum	↓	↑
smile	↓	↑
pucker	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.10: Activities that produced the largest maximum excursions at the lower lips

SRPS	NPS
/bi/	/bi/
/pi/	/pi/*
	/wi/
	Jack and Jill*
	pucker

* Activities which produced slightly lower maximum excursions when compared to /bi/, /wi/, and pucker

Central Lip Marker

Table 7.11: Activities that Produced the Largest Maximum Excursions at the Central Lip

Central Lip Marker
/bi/
/pi/
/wi/
Jack and Jill

Summary of 2D Kinematic Measures

Table 7.12: *Summary of activities that produced large maximum excursions and the number of markers for which larger movements were observed*

SRPS		NPS		Central Lip Marker
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
/bi/	5/5	/bi/	5/5	/bi/
/pi/	2/5	pucker	5/5	/pi/
/fi/	2/5	Jack and Jill	2/5	/wi/
pucker	1/5	/pi/	1/5	Jack and Jill
Jack and Jill	1/5			

Table 7.13: Summary of activities that produced small maximum excursions and the number of markers for which smaller movements were observed

SRPS		NPS		Central Lip Marker
Activity	**Number of Markers**	**Activity**	**Number of Markers**	**Activity**
chewing winegum	3/5	winegum	5/5	smile
Jack and Jill	3/5	/fi/	2/5	pucker
smile	2/5	smile	2/5	
/pi/	1/5	/wi/	1/5	
/wi/	1/5			
pucker	1/5			

EMG

Frontalis

Table 7.14: Asymmetries in peak EMG amplitude between each side of the face at the frontalis

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↑	↓
/pi/	barely detectable	barely detectable
/fi/	barely detectable	barely detectable
/wi/	↑	barely detectable
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	barely detectable	barely detectable
pucker	↓	↑
chewing pudding	↑	↓
drinking	barely detectable	barely detectable
press	barely detectable	barely detectable
frown	barely detectable	↑
clench	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.15: Activities that produced the largest peak EMG amplitudes in the frontalis

SRPS	NPS
/bi/	/bi/
Jack and Jill	Jack and Jill
chewing winegum	chewing winegum
chewing pudding	chewing pudding
/wi/	clench

Gracilis/Zygomatic Major

Table 7.16: Asymmetries in peak amplitude between each side of the face at the gracilis/zygomatic major

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	↓	↑
/fi/	N/A	N/A
/wi/	↓	↑
Jack and Jill	↑	↓
chewing winegum	↓	↑
smile	barely detectable	↑
pucker	barely detectable	↑
chewing pudding	↑	↓
drinking	N/A	N/A
press	barely detectable	↑
frown	barely detectable	↑
clench	↑	↓

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.17: Activities that produced the largest peak EMG amplitudes in the gracilis/zygomatic major

SRPS	NPS
Jack and Jill	Jack and Jill
chewing winegum	chewing winegum
chewing pudding	chewing pudding
	/bi/

Masseter

Table 7.18: Asymmetries in peak EMG amplitude between each side of the face at the masseter

Activity	Asymmetry	
	SRPS	**NPS**
/bi/	↓	↑
/pi/	↔	↔
/fi/	↔	↔
/wi/	↔	↔
Jack and Jill	↑	↓
chewing winegum	↑	↓
smile	↔	↔
pucker	↔	↔
chewing pudding	↑	↓
drinking	N/A	N/A
press	↔	↔
frown	↔	↔
clench	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.19: Activities that produced the largest peak EMG amplitudes in the masseter

SRPS	**NPS**
/bi/	/bi/
Jack and Jill	Jack and Jill
chewing winegum	chewing winegum
chewing pudding	chewing pudding
clench	clench

Orbicularis Oris

Table 7.20: Asymmetries in peak EMG amplitude between each side of the face at the orbicularis oris

Activity	Asymmetry	
	SRPS	NPS
/bi/	↓	↑
/pi/	↓	↑
/fi/	↓	↑
/wi/	↓	↑
Jack and Jill	↓	↑
chewing winegum	↓	↑
smile	↓	↑
pucker	↓	↑
chewing pudding	↓	↑
drinking	↓	↑
press	↓	↑
frown	↓	↑
clench	↓	↑

↑ = higher; ↓ = lower; ↔ = no difference

Table 7.21: Activities that produced the largest peak EMG amplitudes in the orbicularis oris

SRPS	NPS
chewing Winegum	chewing Winegum
chewing Pudding	chewing Pudding
press	press
drinking	/bi/
	Jack and Jill
	smile
	pucker
	clench

Summary of EMG

Table 7.22: Summary of activities that produced large peak EMG amplitudes and the number of muscles for which larger amplitudes were observed

SRPS		NPS	
Activity	**Number of Muscles**	**Activity**	**Number of Muscles**
chewing winegum	4/4	chewing winegum	4/4
chewing pudding	4/4	chewing pudding	4/4
Jack and Jill	3/4	Jack and Jill	4/4
/bi/	2/4	/bi/	4/4
/wi/	1/4	clench	3/4
drinking	1/4	smile	1/4
press	1/4	press	1/4
clench	1/4	pucker	1/4

Table 7.23: Summary of EMG signals < 0.001 mV

Muscle	Activity	Side of the face
Frontalis	/pi/	both
	/fi/	both
	/wi/	NPS
	smile	both
	drinking	both
	press	both
	frown	SRPS
Gracilis/Zygomatic Major	smile	SRPS
	pucker	SRPS
	press	SRPS
	frown	SRPS
Orbicularis Oris	frown	NPS

Table 7.24: Atypical EMG waveforms observed

Muscle	SRPS Waveform	SRPS Activity	NPS Waveform	NPS Activity
Frontalis	Abnormal	/bi/	Abnormal	Jack and Jill
		/pi/		
		/wi/		
		smile		
Gracilis	Abnormal	/wi/	Abnormal	pucker
		smile		
			Tremor	/fi/
			Fires inappropriately	/bi/
Masseter	Abnormal	/wi/	Abnormal	/pi/
		press		/wi/
				pucker
			Tonic Firing	press
			Fires inappropriately	/bi/
Orbicularis Oris	Abnormal	/wi/	Abnormal	chewing winegum