QUANTITATIVE ANALYSIS OF
ORAL PHASE DYSPHAGIA

by

CHAE-JOON LEE

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We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
AUGUST 1991
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Department of Mechanical Engineering

The University of British Columbia
Vancouver, Canada

Date August 20, 1991
I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.

- Lord Kelvin

So, also in deglutition; by the elevation of the root of the tongue and the compression of the mouth the food or drink is pushed into the fauces, the larynx is closed .... Yet, all these motions, though executed by different and distinct organs, perform harmoniously, and in such order, that they seem to constitute but a single motion and act, which we call deglutition.

- William Harvey
ABSTRACT

Swallowing disorders (dysphagia) are becoming increasingly prevalent in the health care field. Oral phase dysphagia specifically refers to swallowing difficulties encountered during the initial, voluntary segment of the swallowing process, where the ingested food material is prepared into a manageable food mass (bolus) and then propelled from the mouth to the pharynx.

Proper management (evaluation and treatment) of oral phase dysphagia poses a difficult task. The swallowing process is a complex sequence of highly coordinated events, while oral phase dysphagia can originate from a wide range of underlying causes. From a review of the literature, it is apparent that much of the current methods of management for oral phase dysphagia rely much on the subjective skills of the clinician in charge. In order to improve upon these methods as well as to gain a better understanding of the swallowing mechanism, the development of new, quantitative clinical methods are proposed.

A computer-aided tongue force measurement system has been developed that is capable of quantifying individual tongue strength and coordination. This strain gauge-based transducer system measures upward and lateral tongue thrust levels during a "non-swallowing" test condition. Clinical testing has been performed on 15
able-bodied control subjects with no prior history of swallowing difficulty and several patient groups (25 post-polio, 8 stroke, 2 other neuromuscular disorders) with or without swallowing difficulties. The results have demonstrated the system's potential as a reliable, clinical tool (repeatability: t-test, p < 0.01) to quantify variation in tongue strength and coordination between and within the control and patient groups.

In order to investigate the possible existence and role of a suction mechanism in transporting the bolus during the oral phase, a pharyngeal manometry setup has been utilized for oral phase application. This novel approach (oral phase manometry) would determine whether the widely-accepted tongue pressure mechanism is solely responsible for oral phase bolus transport. Based on extensive manometric data obtained from an able-bodied subject without any swallowing abnormality, no significant negative pressure or pressure gradients (suction) were found during the oral phase.

The pressure generated by the tongue acting against the palate in propelling the bolus during the oral phase has been utilized in the development of an oral cavity pressure transducer system. This computer-aided measurement system employs a network of ten force sensing resistors (FSR's) attached to a custom-made mouthguard transducer unit to record the wave-like palatal pressure pattern during an actual swallow. Clinical testing has been performed on 3 able-bodied subjects with no
swallowing abnormality, and their pressure data have been found to support the reliability of the device (repeatability: t-test, p < 0.01). The system has also been applied to study the effects of bolus size and consistency on the palatal pressure pattern during the oral phase.

The results of this investigation has confirmed the importance of the tongue during the oral phase of swallowing. It has been shown that deficiency in tongue strength or coordination is a primary factor in oral phase dysphagia. The new, quantitative clinical methods which were developed for this research has utilized these parameters to provide improved methods of evaluation and treatment for oral phase dysphagia.
# TABLE OF CONTENTS

**ABSTRACT** .................................................................................................................. ii

**TABLE OF CONTENTS** ................................................................................................. v

**LIST OF TABLES** ........................................................................................................ x

**LIST OF FIGURES** ....................................................................................................... xi

**ACKNOWLEDGEMENTS** ................................................................................................ xv

**CHAPTER 1 INTRODUCTION** ......................................................................................... 1

1.1 SWALLOWING PROCESS ............................................................................................. 2

1.2 DYSPHAGIA ................................................................................................................. 8

1.3 CURRENT STATE OF DYSPHAGIA MANAGEMENT .............................................. 12

1.4 RESEARCH OBJECTIVES ......................................................................................... 15

**CHAPTER 2 LITERATURE REVIEW** ............................................................................. 18

2.1 SWALLOWING PROCESS ............................................................................................. 18

2.2 ORAL PHASE DYSPHAGIA ......................................................................................... 22

2.3 EVALUATION OF ORAL PHASE DYSPHAGIA ..................................................... 28

2.3.1 QUALITATIVE SEGMENT .................................................................................. 29

2.3.2 QUANTITATIVE SEGMENT .............................................................................. 36

2.4 TREATMENT OF ORAL PHASE DYSPHAGIA ....................................................... 43

2.5 BIOMECHANICAL ANALYSIS OF THE ORAL PHASE OF SWALLOWING ............. 52

2.6 THE ROLE OF SUCTION DURING SWALLOWING .............................................. 64
# TABLE OF CONTENTS

3.5 DISCUSSION OF TOMS ................................................................. 112

CHAPTER 4 VERIFICATION OF AN ORAL PHASE SUCTION MECHANISM ................................................................. 118

4.1 INTRODUCTION AND BACKGROUND ........................................... 118

4.2 EXPERIMENTAL TESTING ........................................................... 121

4.2.1 MANOMETRIC MEASUREMENT SYSTEM #1 ......................... 122

4.2.1.1 SETUP - SYSTEM #1 ..................................................... 122

4.2.1.2 PROCEDURE - SYSTEM #1 .......................................... 124

4.2.2 MANOMETRIC MEASUREMENT SYSTEM #2 ......................... 125

4.2.2.1 SETUP - SYSTEM #2 ..................................................... 125

4.2.2.2 PROCEDURE - SYSTEM #2 .......................................... 125

4.2.3 SUBJECTS (SYSTEM #1, #2) ................................................ 126

4.3 RESULTS AND DATA ANALYSIS ............................................... 126

4.3.1 SYSTEM #1 ........................................................................... 126

4.3.2 SYSTEM #2 ........................................................................... 128

4.4 DISCUSSION OF ORAL PHASE SUCTION MECHANISM ........... 131

CHAPTER 5 ORAL CAVITY PRESSURE MEASUREMENT SYSTEM (OPTRANS) ................................................................. 134

5.1 INTRODUCTION AND BACKGROUND ........................................... 134

5.2 DEVELOPMENT OF OPTRANS ..................................................... 138

5.3 CLINICAL TESTING OF OPTRANS .............................................. 142

5.3.1 TESTING PROTOCOL ............................................................ 142
# TABLE OF CONTENTS

5.3.1.1 CALIBRATION OF OPTRANS ........................................... 143
5.3.1.2 SUBJECT QUESTIONNAIRE AND CUSTOMIZATION OF OPTRANS .................. 145
5.3.1.3 PALATAL PRESSURE MEASUREMENT .......... 146
5.3.1.4 TRANSDUCER STERILIZATION.............................. 149

5.3.2 SUBJECTS ................................................................. 149

5.4 RESULTS AND DATA ANALYSIS ..................................................... 149
5.4.1 REPEATABILITY OF OPTRANS' DATA ........................................... 149
5.4.2 ANALYSIS OF PALATAL PRESSURE DATA .................. 151

5.5 DISCUSSION OF OPTRANS ........................................................... 155

CHAPTER 6 GENERAL DISCUSSION OF EXPERIMENTAL RESULTS ..... 158
6.1 DEVELOPMENT OF NEW CLINICAL METHODS ......................... 158
6.2 ORAL PHASE SWALLOWING MECHANISM AND DYSPHAGIA .. 161

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS ...................... 163
7.1 CONCLUSIONS ................................................................. 163
7.1.1 DEVELOPMENT OF NEW CLINICAL METHODS .......... 164
7.1.2 ORAL PHASE SWALLOWING MECHANISM AND DYSPHAGIA ............................................. 166

7.2 RECOMMENDATIONS FOR FUTURE WORK .............................. 167

REFERENCES ........................................................................... 171

APPENDIX A SWALLOWING PHYSIOLOGY (ORAL/ PHARYNGEAL PHASE) ......................................................... 191

APPENDIX B SAMPLE DYSPHAGIA MANAGEMENT PROTOCOL .... 202
TABLE OF CONTENTS

APPENDIX C  PROS AND CONS OF VARIOUS EVALUATION METHODS .................................................. 210

APPENDIX D  CONSENT FORMS AND QUESTIONNAIRES FOR TEST SUBJECTS .................................................. 215

APPENDIX E  FORCE SENSING RESISTOR SPECIFICATIONS .................................................. 217

GLOSSARY ......................................................................................................................................... 218

BIOGRAPHICAL INFORMATION ........................................................................................................ 229
LIST OF TABLES

Table 1.1: Clinical and Radiographic Symptoms of Dysphagia .................. 10
Table 1.2: Prevalence of Dysphagia .................................................. 14
Table 2.1: Sample Protocol for Swallowing Physical Examination ............. 31
Table 2.2: Methods of Evaluation for Oral Phase Dysphagia ..................... 33
Table 2.3: Therapy Techniques for Dysphagia ...................................... 44
Table 2.4: Dietary Modifications for Problem Swallowing Phases ............... 50
Table 3.1: Repeatability of TOMS' Data ............................................. 97
Table 3.2: Mean Tongue Strength Data of Various Subject Groups ............. 98
Table 3.3: Mean Tongue Force Fatigue Rates of Tested Subjects ............... 101
Table 3.4: Sensitivity/Specificity of TOMS .......................................... 111
Table 5.1: OPTRANS Calibration Table .............................................. 145
Table 5.2: Repeatability of OPTRANS' Data ....................................... 150
Table A.1: Muscles of the Swallowing Process .................................... 191
Table A.2: Nervous System Control of the Swallowing Process ............... 199
LIST OF FIGURES

Figure 1.1: Anatomy of the Pharynx, Larynx and the Mouth ........................................ 3
Figure 1.2: The Three Phases of Swallowing ................................................................. 4
Figure 1.3: Physiology of Swallowing .............................................................................. 5
Figure 1.4: Five Physiological Events in Normal Swallow .............................................. 6
Figure 1.5: Different Types of Aspiration ........................................................................... 8
Figure 1.6: Multidisciplinary Organization of a Swallowing Center ................................ 13
Figure 2.1: Nasal Regurgitation of a Bolus ...................................................................... 23
Figure 2.2: Deviate Swallowing Pattern; Tongue Thrust Swallow .................................... 23
Figure 2.3: Compensation during the Oral Phase of Swallowing .................................... 24
Figure 2.4: Resection of Laryngeal Cancer Tumor ......................................................... 26
Figure 2.5: Patient with Thick Mucous Secretions Secondary to Radiotherapy (Tongue Cancer) ................................................................. 27
Figure 2.6: Fungal Inflammation of the Tongue .............................................................. 27
Figure 2.7: Swallowing Questionnaire for Dysphagia Evaluation ................................. 29
Figure 2.8: Numerical Scale Systems Used in Swallowing Evaluation ........................... 35
Figure 2.9: Videofluoroscopy ......................................................................................... 37
Figure 2.10: Intraluminal Manometry ............................................................................. 38
Figure 2.11: Ultrasonography ......................................................................................... 39
Figure 2.12: Electromyography ...................................................................................... 40
LIST OF FIGURES

Figure 2.13: Disadvantages of Videofluoroscopy; Oral Phase Imaging .......... 41
Figure 2.14: Simultaneous Videofluoroscopy and Manometry ....................... 42
Figure 2.15: Tongue Muscle Exercises ....................................................... 45
Figure 2.16: Biofeedback Instrument for Monitoring Oral Musculature Function ................................................................. 46
Figure 2.17: Various Oral Prostheses .......................................................... 49
Figure 2.18: Effect of Posture on Swallowing ............................................... 51
Figure 2.19: Early Device for Measuring Swallowing Pressures on Dentition ... 54
Figure 2.20: Strain Gauge-Based Transducer for Measuring Forces on Dentition by Lips, Cheek, and Tongue during Swallowing .......... 55
Figure 2.21: Intraoral Tongue Thrust Measurement Device .......................... 55
Figure 2.22: Transducer for Measuring Tongue Pressure near the Forepart of the Palate ................................................................. 56
Figure 2.23: Palatal Retainer Transducer I for Measuring Tongue Pressure on Palate .................................................................................. 57
Figure 2.24: Palatal Retainer Transducer II for Measuring Tongue Pressure on Palate ........................................................................ 58
Figure 2.25: Lingual Force Scale ................................................................. 59
Figure 2.26: Load Cell for Measuring Tongue Protrusion ............................... 60
Figure 2.27: Linguameter ........................................................................ 61
Figure 2.28: Introral Transducers ............................................................... 62
Figure 2.29: Headmount Used for Isolating Oro-Facial Muscles ..................... 62
Figure 2.30: Cantilever Beam Transducer .................................................... 63
Figure 2.31: Pharyngeal/Esophageal Manometric Swallowing Pattern I ....... 67
LIST OF FIGURES

Figure 2.32: Pharyngeal/Esophageal Manometric Swallowing Pattern II .......... 69
Figure 2.33: Pharyngeal/Esophageal Manometric Swallowing Pattern III ....... 71
Figure 3.1: TOMS Setup ........................................................................ 74
Figure 3.2: Anatomy of the Tongue ....................................................... 77
Figure 3.3: Schematic of TOMS Setup .................................................... 78
Figure 3.4: Beam Transducer Element ................................................... 79
Figure 3.5: Mouthblock ........................................................................ 81
Figure 3.6: Signal Processing Circuitry (Strain Gauge Amplifier) .............. 83
Figure 3.7: Transducer Calibration Curve .............................................. 85
Figure 3.8: Different Testing Protocols for TOMS (Able-Bodied Subjects) ..... 88
Figure 3.9: Visual Feedback during TOMS Measurement (30 Second Non-Cyclic Test) ................................................................. 93
Figure 3.10: Mean Tongue Strength Distribution (Able-Bodied vs. Post-Polio Patients) ................................................................. 99
Figure 3.11: Tongue Force Data from a Post-Polio Patient ...................... 104
Figure 3.12: Mean Tongue Strength Distribution (Able-Bodied vs. Stroke Patients) ................................................................. 106
Figure 3.13: Unilateral Tongue Weakness in Stroke Patients .................... 108
Figure 3.14: Tongue Force Data from Barlow [135] for Able-Bodied Subject and Parkinson’s Patient ................................................................. 115
Figure 4.1: Anatomical Seals Formed during the Oral Phase of Swallowing .... 120
Figure 4.2: Newly-Developed Manometry Setup ...................................... 122
Figure 4.3: Lingual and Labial Suction .................................................... 127
LIST OF FIGURES

Figure 4.4: Manometric Data (Able-Bodied) ......................................................... 129
Figure 5.1: OPTRANS Setup .............................................................................. 134
Figure 5.2: Palatal Pressure Distribution by Proffit [219] ........................................ 137
Figure 5.3: Schematic of OPTRANS Setup ........................................................... 139
Figure 5.4: Signal Processing Circuitry of OPTRANS ............................................ 142
Figure 5.5: Graphical Analysis of OPTRANS’ data ................................................. 147
Figure 5.6: Frame-by-Frame Analysis of a Normal Swallow (Able-Bodied) .............. 152
Figure 5.7: Effect of Bolus Volume on Swallowing Pressure ................................. 153
Figure 5.8: Effect of Bolus Consistency on Swallowing Pressure ........................... 154
Figure A.1: Segments of the Oral-Pharyngeal Food Pathway ................................. 194
Figure A.2: Pharyngeal and Laryngeal Muscles (Lateral View) ............................... 195
Figure A.3: Anterior Part of the Pharynx (Posterior View) ..................................... 196
Figure A.4: Frontal View of the Oral Cavity ......................................................... 197
Figure A.5: Nervous System Control of the Swallowing Process ........................... 200
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Finally, I would like to thank my family for all their love and understanding and my friends (many of whom “willingly” volunteered for the research experiments) for their support.
CHAPTER 1  INTRODUCTION

The act of swallowing (deglutition) is a habitual activity for most individuals, performed under minimal consciousness and effort. There is even evidence that the human fetus is able to swallow the amniotic fluid in the mother's womb [1-3]. Fortunately, this "ease" of swallowing facilitates some 600 swallows [4,5] that the average individual performs each day without physical and mental overexertion. The swallowed contents include saliva and all the liquid and solid foods that are consumed throughout the day (sleeping hours included).

In contrast to the relatively easy nature of the task, the swallowing process itself involves a highly complex and well-coordinated sequence of events that oversees the transport of the ingested food (ingesta - refer to GLOSSARY for medical terminology) from the time of intake into the mouth to the time of its arrival in the stomach. A disruption of this intricate process can seriously complicate the usually effortless swallowing task. Only upon encountering swallowing difficulties (dysphagia) does one become aware of how indispensable the swallowing process is in our daily lives.
1.1 SWALLOWING PROCESS

The swallowing process involves the participation of nearly 40 muscles distributed across the face, the oral cavity, the pharynx, and the esophagus [6-8] with various skeletal structures (bones and cartilages) acting as attachments to these muscles or as borders along the food pathway (see Figure 1.1, APPENDIX A). The process consists of both, voluntarily and involuntarily controlled mechanisms [6,8-11]. The activities in and around the oral cavity are predominantly performed under voluntary control, while the activities in the pharynx and the esophagus are under involuntary (subconscious) control.

Although the neural mechanism behind swallowing is not completely understood, the involvement of both the central and the peripheral nervous systems have been identified [12-19] (see APPENDIX A). These two networks primarily utilize the cranial nerves as sensory (afferent) and motor (efferent) neural pathways to coordinate the swallowing process. For example, proper functioning of the nervous system is essential in coordinating various physiological functions (e.g., swallowing, respiration, and speech) that share the pharyngeal lumen as a common pathway [5, 10,13,19-25].
INTRODUCTION

Figure 1.1: Anatomy of the Pharynx, Larynx and the Mouth (from [10])
The three principal sites of interest in the swallowing process are the oral cavity, the pharynx, and the esophagus (see Figure 1.2). These sites correspond to the standard classification of the process in terms of three sequential phases: the oral, the pharyngeal, and the esophageal phase, respectively [6,9,26-29] (Figure 1.3).

Figure 1.2: The Three Phases of Swallowing (from [6])
Figure 1.3: Physiology of Swallowing; a) Oral (Preparatory) Phase, b) Oral (Propulsive) Phase, c) and d) Pharyngeal Phase (from [9])
The oral phase is a voluntary, almost unconscious aspect of swallowing [6,9,26-29], comprised of a preparatory and a propulsive segment. The ingesta is "prepared" into a manageable food mass (bolus) of desired size and consistency by means of mastication (chewing), salivation, and manipulation by the tongue, lips, and cheeks. The bolus is then "propelled" from the anterior oral cavity towards the pharynx, as the tongue is raised and pressed firmly against the roof of the mouth (palate) (see Figure 1.3-1.4).

Figure 1.4: Five Physiological Events in Normal Swallow; 1) Tongue Lift, 2) Posterior Tongue Movement, 3) Soft Palate Elevation, 4) Laryngeal Protection, and 5) Movement of Hyoid Bone (from [6])
The pharyngeal phase is an involuntary, reflexive segment [6,9,26-29] consisting of a well-organized sequence of events which are triggered upon bolus detection at the entrance to the pharynx. The pharyngeal reflex mechanism then continues the transport of the bolus from the oral cavity through the pharynx to the esophagus via the sequential contraction of the pharyngeal muscles (pharyngeal peristalsis). It simultaneously facilitates the prevention of any undesired bolus escape into other channels (e.g., airway, oral cavity, and nasal cavity). The presence and function of the larynx at the pharyngeal level should also be noted in terms of its importance in airway protection from foreign material entry (aspiration of saliva, food residue, etc.).

The esophageal phase is also carried out under involuntary control [6,9,26-29]. Sphincters at each end of the esophageal tube control the inflow and outflow of food material. The bolus is propelled via esophageal peristalsis from the pharyngoesophageal sphincter (PES) located at the junction between the pharynx and the esophagus (Figure 1.1) down to the gastroesophageal sphincter (GES) located at the junction between the esophagus and the stomach.
1.2 DYSPHAGIA

Dysphagia is the medical term describing the condition in which the swallowing process is impaired. The word is derived from Latin: "dys-" meaning "difficult or bad" and "phagein" meaning "to eat" [30]. Dysphagia can exhibit a mild form, which presents minimal problems to the patient's swallowing ability (e.g., incidences of coughing due to minor aspiration - see Figure 1.5), while a severe form of dysphagia leads to stressful, painful, and even dangerous swallowing episodes (e.g., choking or massive aspiration) [7,8,31-35].

![Figure 1.5: Different Types of Aspiration: a) Before, b) During, and c) After the Swallow (from [9])](image-url)
Dysphagia can affect individuals of any age or sex [3,7,36,37], but it is most commonly associated with patients in the rehabilitative setting suffering from neuromuscular disorders [38-43].
The symptoms, indicative of dysphagia (e.g., prolonged time of bolus transit), allow the physician in charge to clinically detect its presence and assist in determining its underlying cause (see Table 1.1).

**Table 1.1: Clinical and Radiographic Symptoms of Dysphagia (from [9])**

<table>
<thead>
<tr>
<th>Patient Description</th>
<th>Clinical (Bedside) Symptom</th>
<th>Radiographic Symptom</th>
<th>Motility (Neuromuscular) Anatomic Disorder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cannot chew—avoids foods requiring mastication. None</td>
<td>Material remains midline on tongue or falls into sulcus. Material falls into sulci. Restricted mandibular movement. Cannot align mandible.</td>
<td>Material remains midline on tongue or falls into sulcus. Material falls into sulci. Restricted mandibular movement. Cannot align mandible and maxilla (A-P view).</td>
<td>Inability to laterize material with tongue. Reduced buccal tension. Inability to laterize mandible. Inability to align dentition.</td>
</tr>
<tr>
<td>Cannot “line up” teeth.</td>
<td>Material remains midline on tongue or falls into sulcus. Material falls into sulci. Restricted mandibular movement. Cannot align mandible.</td>
<td>Material remains midline on tongue or falls into sulcus. Material falls into sulci. Restricted mandibular movement. Cannot align mandible and maxilla (A-P view).</td>
<td>Inability to laterize material with tongue. Reduced buccal tension. Inability to laterize mandible. Inability to align dentition.</td>
</tr>
<tr>
<td>Material goes all over mouth. Food catches in mouth.</td>
<td>Material spreads throughout oral cavity.</td>
<td>Loss of bolus control: Material spreads around oral cavity. Material falls over base of tongue into the valleculae or the airway (aspiration before the swallow).</td>
<td>Reduced tongue coordination to form bolus (after mastication) Reduced oral sensation.</td>
</tr>
<tr>
<td>Coughing, choking before the swallow. Food catches in mouth. Slow eating, worse with solids. None</td>
<td>Coughing, choking before the swallow. Slowed oral transit times</td>
<td>Slowed oral transit times. Reduced tongue elevation. Collection of material on the hard palate.</td>
<td>Reduced tongue coordination to hold bolus (for liquids and paste materials). Reduced tongue elevation. Reduced anterior to posterior tongue movement.</td>
</tr>
<tr>
<td>Food catches in mouth. Slow eating, worse with solids. None</td>
<td>Slowed oral transit times</td>
<td>Slowed oral transit times.</td>
<td></td>
</tr>
</tbody>
</table>
Table 1.1 (continued)

<table>
<thead>
<tr>
<th>Patient Description</th>
<th>Clinical (Bedside) Symptom</th>
<th>Radiographic Symptom</th>
<th>Motility (Neuromuscular) Anatomic Disorder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Some food &quot;sticks&quot; high in the throat.</td>
<td>Coughing, choking</td>
<td>Residue of material on one side of valleculae and one pyriform sinus.</td>
<td>Unilateral pharyngeal paralysis.</td>
</tr>
<tr>
<td>Material catching at bottom of throat. Regurgitation of food. None.</td>
<td>Coughing, choking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coughing, choking.</td>
<td>Coughing, choking after swallow. Reduced laryngeal (thyroid) elevation. Coughing, choking during swallow. Hoarseness. None.</td>
<td>Aspiration after the swallow. Reduced thyroid elevation. Aspiration during the swallow. Reduced vocal cord adduction (A-P view). Collection of material in the cervical esophagus after the swallow.</td>
<td>Reduced laryngeal elevation. Reduced laryngeal adduction. Reduced esophageal peristalsis.</td>
</tr>
<tr>
<td>Material caught lower in the throat. None.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regurgitation of food. Coughing, choking after the swallow. None.</td>
<td>Regurgitation of food. Coughing, choking after the swallow.</td>
<td>Collection of material in a side pocket in the pharynx or esophagus.</td>
<td>Esophageal diverticulum.</td>
</tr>
<tr>
<td>Regurgitation of food. Coughing, choking after the swallow.</td>
<td>Regurgitation of food. Coughing, choking after the swallow.</td>
<td>Failure of food to pass through the esophagus. Aspiration after the swallow from esophageal &quot;overflow.&quot; Material passes from esophagus into trachea. Material leaks through skin.</td>
<td>Partial or total obstruction in pharynx or esophagus. Tracheoesophageal fistula. Pharyngocutaneous fistula.</td>
</tr>
<tr>
<td>Coughing, choking after the swallow. Material leaks out hole.</td>
<td>Material leaks out hole onto skin.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

None. Some patients are unaware of their swallowing disorder, and may not, therefore, describe any particular problem with eating or drinking.

2 As viewed laterally unless otherwise noted.
However, the etiology (cause) of dysphagia covers a very wide range of diseases and disorders; thus, it is no easy task to sort through the maze of overlapping, similar, and ambiguous symptoms to arrive at the correct etiology of the swallowing disorder. Overcoming this diagnostic difficulty is an important issue in the current state of dysphagia.

1.3 CURRENT STATE OF DYSPHAGIA MANAGEMENT

The general objectives of current management strategies for dysphagia are to identify (diagnose) and assess the dysphagic patient (i.e., evaluation) and to set up an appropriate treatment plan for the patient. Most of the strategies are based on a multidisciplinary team approach [6,9,44,45] (see Figure 1.6) in which the combined expertise of specialists in various traditional medical fields (e.g., radiology, gastroenterology, neurology) and other trained clinical staff (e.g., physiotherapist, speech therapist, physician, dietician, nurse) work together to provide the proper evaluation and treatment of dysphagic patients. This is an obvious improvement over past strategies, where dysphagia was often neglected due to a lack of swallowing specialists.
However, the proper management of dysphagia still poses difficulties, as one must deal with the complexity of the swallowing process and the diverse etiology of associated disorders. Although significant improvements have been made during the past decade [46-49] in terms of technology and clinical experience, much of today’s management methods still rely heavily on subjective, qualitative observations and clinical interpretations [47,50,51] (see APPENDIX B).
Further limitations of the current methods include, but are not limited to high costs, concerns for clinical safety, difficulty in application, lack of standardization, and shortage of specialized staff. With the growing prevalence of dysphagia (12-13% in hospitals [40], 30%+ in nursing homes [8,52]) (see Table 1.2), it seems clear that research on dysphagia must be continued to improve upon the current state of dysphagia management and understanding.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Subject of study</th>
<th>Setting</th>
<th>Population</th>
<th>Method</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trupe et al. (1984)</td>
<td>Overall prevalence</td>
<td>Nursing home</td>
<td>All residents</td>
<td>Questionnaire, chart review, physical exam</td>
<td>74% with feeding disorders; 59% with oral/pharyngeal dysphagia</td>
</tr>
<tr>
<td>Groher (1980)</td>
<td>Impression of staff</td>
<td>VA Hospital</td>
<td>All patients</td>
<td>Phone call to head nurse</td>
<td>6% with oral/pharyngeal dysphagia</td>
</tr>
<tr>
<td>Fleming (1985)</td>
<td>Impression of staff</td>
<td>Hospitals</td>
<td>All patients and residents</td>
<td>Questionnaire to allied health workers, medical personnel</td>
<td>43% judged prevalence to be less than 15%; 16% judged more than 15%; rest did not know or could not judge</td>
</tr>
<tr>
<td>Weinstein (1983)</td>
<td>Prevalence in specific diagnostic category</td>
<td>Rehab. hospital</td>
<td>Head injured</td>
<td>Retrospective chart review</td>
<td>25% of consecutive admissions had dysphagia</td>
</tr>
<tr>
<td>Pannell et al. (1984)</td>
<td>Prevalence in specific diagnostic category</td>
<td>Rehab. institute</td>
<td>Neurogenic disorders</td>
<td>Physical exam and chart review</td>
<td>42% with dysphagia</td>
</tr>
<tr>
<td>Echelard et al. (1984)</td>
<td>Prevalence in specific diagnostic category</td>
<td>Acute general hospital</td>
<td>Selected groups</td>
<td></td>
<td>Dysphagia in 25% of CVAs, 20% of pneumonias, 50% with head injuries, 30% with head/neck resections</td>
</tr>
<tr>
<td>Veis and Logemann (1985)</td>
<td>Prevalence in specific diagnostic category</td>
<td>Acute general hospital</td>
<td>Post CVA</td>
<td>Chart review of admissions in 1 year</td>
<td>28% with dysphagia</td>
</tr>
</tbody>
</table>
1.4 RESEARCH OBJECTIVES

The general purpose of the present investigation, therefore, is to complement and improve on the current, existing methods of evaluation and treatment of dysphagia by developing objective, quantitative methods that are clinically suitable and technically reliable. Such methods should be developed, taking into account issues of cost, ease of use, patient comfort, and safety.

The scope of the investigation is restricted to the study of the oral phase swallowing mechanism and its associated disorders for various reasons. The primary reason being that the oral phase represents the most accessible segment of the swallowing process, permitting expedient transducer setups with minimal invasiveness to the patient, as well as the potential for future application of prosthetic devices. The voluntary nature of the oral phase also enables the quantification of physiological, biomechanical parameters (e.g., tongue force) that effectively reflect an individual's swallowing functionality. For this research, particular focus is placed on the role of the tongue as a primary, propulsive agent of the bolus during the oral phase, while another possible propulsive mechanism (suction) is also considered. It should also be noted that research into the oral phase has been relatively scarce compared to the other phases of the swallowing process, leaving much to be investigated.
INTRODUCTION

To accomplish the tasks required for this research, the following objectives are defined:

Critically Review the Available Literature on Dysphagia-Related Research

The contributions and shortcomings of past and present research into the swallowing process, its associated disorders, and subsequent management are critically reviewed in CHAPTER 2. Particular attention is given towards literature dealing with the oral phase of swallowing to assist the present investigation.

Develop a Tongue Force Measurement System

The development of a Tongue Force Measurement System (TOMS), which quantifies an individual's tongue strength and coordination, is presented in CHAPTER 3. The system employs a strain gauge-based cantilever beam transducer to measure tongue force in three directions (up, left, and right). The experimental setup and protocol are described along with results and data analysis from able-bodied subjects and various patient groups, reporting of swallowing difficulties.

Verify the Role of Suction during the Oral Phase of Swallowing

The role of suction pressure (negative pressure gradient) in the propulsion of bolus has been in the past, and continues to be, an issue of controversy for researchers of the swallowing process. Research has been minimal, particularly in terms of the oral phase. Therefore, CHAPTER 4 describes an experimental attempt to verify the suction pressure hypothesis and its contribution to the oral phase swallowing mechanism.
INTRODUCTION

Develop an Oral Cavity Pressure Transducer System

The actual swallowing pressure profile generated by the tongue acting against the palate during the oral phase is recorded using a newly-developed Oral Cavity Pressure TRANsducer System (OPTRANS). The system represents a continuation of the research effort to utilize tongue force/pressure as a clinical indicator of swallowing functionality in able-bodied subjects and patient groups. The system setup, protocol, results, and data analysis are presented in CHAPTER 5.

Analyze the Clinical Data Obtained Using the Newly-Developed Transducer Systems

From the results obtained using the newly-developed transducer systems (CHAPTERS 3-5), CHAPTER 6 presents an overall discussion regarding the oral phase swallowing mechanism and its associated disorders. Also, the clinical feasibility of each transducer system is discussed.

Evaluate the Effectiveness of the Research Project

CHAPTER 7 presents a summary of the contributions and conclusions made by the present investigation and suggests a list of future recommendations, which will help to continue and upgrade the present research effort.
Chapter 2 LITERATURE REVIEW

Due to the multidisciplinary nature of the swallowing process, pertinent research literature has appeared in journals over a wide range of medical disciplines (e.g., neurology, anatomy, radiology, nursing, etc. [50,51,53-62]). Based on an extensive literature review, the relevant information for this research can be organized into four basic categories: 1) (normal) swallowing process, 2) oral phase dysphagia, 3) evaluation of oral phase dysphagia, and 4) treatment of oral phase dysphagia. Two additional topics of relevance need to be included in the literature review for this research: biomechanical analysis of the oral phase and the role of suction during swallowing. Each of these topics are further discussed in the following sections.

2.1 SWALLOWING PROCESS

The swallowing process has been studied since the time of the Greeks, with observations made by Hippocrates and Galen (cited in Bosma [63]). In the early 1800's, Magendie [26], a French physiologist, made a significant contribution by deriving the classical description of the swallowing mechanism in terms of the three sequential phases involving the mouth, the pharynx, and the esophagus. In fact, he was able to describe nearly all of the major swallowing events that are accounted for to date.
At the beginning of the 20th century, newly-developed radiographic technology (e.g., fluoroscopy) [64] enabled greater in-depth investigations, which confirmed past speculations on swallowing physiology. On the other hand, it also brought about much controversy as researchers disagreed over their results obtained using the new technique. Most of the discrepancy could be attributed to the infancy state of this visualization method, the lack of sufficient data, and the individual variations in data interpretation [64-68]. One of the controversial issues involved the propulsive mechanism of the bolus during the oral and pharyngeal phases. Barclay [65] stood out as an advocate of the hypothesis of negative suction pressure being the primary mechanism behind bolus transport from the oral cavity down to the esophagus (see also CHAPTER 2.6). While Barclay's theory only received the support of a few researchers [69], the majority of researchers seemed to support Magendie's traditional view of positive pressure, specifically pharyngeal muscular contraction (i.e., pharyngeal peristalsis), as the primary bolus propulsive mechanism for a solid or semisolid bolus [66,70,71]. For fluids and semi-fluids, Kronecker and Meltzer's (1880) theory of a "squirt" mechanism (cited in Wildman [68]), whereby oral musculature (i.e., tongue base) played the significant role in pushing the bolus from the oral cavity directly to distal esophagus ahead of the slower pharyngeal peristaltic activity, was widely supported [64,68].
Finally, in the 1950's, the use of improved radiographic methods led to the general acceptance of the positive muscular pressure theories over the suction theory. The improved techniques also led to a vast upgrading in the capabilities of swallowing research. Ardran and Kemp [72-74], in their significant radiographic investigations during the early 50's, gave an excellent account of the general swallowing process. They described the propulsive action of the tongue during the oral phase in terms of "toothpaste being pressed from a tube" and also clarified the airway protection mechanism during swallowing. Ramsey et al [75] defined the swallowing process in terms of an action-counteraction concept, orchestrated by means of expansion and contraction of the lumen (denoting a tubular space) ahead and behind the bolus, respectively. According to them, expansion of the lumen ahead of the bolus allowed for easy passage, while progressive narrowing (contraction) of the lumen behind the bolus (i.e., a "stripping wave") resulted in bolus propulsion. From an extensive review of the literature on human and animal swallowing physiology, Bosma [63] noted that the tongue was the principal mobile agent during the oral phase. In 1960, Shedd and associates [76,77] confirmed the theory of the "squirt" mechanism for fluid and semi-fluids, as previously found by Kronecker and Meltzer (cited in [64]), and they coined the phrase, "oropharyngeal force-pump action", to describe this mechanism. Wildman [68], in 1964, organized all prior theories of the swallowing mechanism into four distinct categories: 1) Theory of Constant Propulsion (Magendie), 2) Theory of Oral Expulsion (Kronecker and Meltzer), 3) Theory of Negative Pressure (Barclay), and 4)
Theory of Integral Function (Wildman). Similar to Magendie's theory, Wildman's Theory of Integral Function stressed the idea of a synergistic swallowing mechanism with various muscles and muscular valves involved interactively in the passage of the bolus. In 1977, Lederman [21] described the swallowing process in terms of sphincteric actions by various swallowing structures (e.g., soft palate/posterior pharyngeal wall, oral cavity, larynx, and cricopharyngeus - see GLOSSARY). In 1982, Miller [15] gave a comprehensive review of swallowing research to date, while recently, McConnel [79-83] reopened the earlier controversy on bolus propulsive mechanism with his support of a negative pressure gradient (suction) formed in the pharynx ahead of the bolus and a forceful tongue thrust mechanism applied behind the bolus as primary agents during the pharyngeal phase, rather than the pharyngeal peristalsis.

Since the 50's, most of the research into the normal swallowing process has involved some form of visualization technique. Although details of the process have been added with improved imaging and other techniques [55,78], the basic understanding of the swallowing physiology has not been significantly altered over the years. A detailed description of the swallowing process [5-10,12-17,19-29,36,39,42,50,51,55,62-85,87-95] is included in APPENDIX A.
2.2 ORAL PHASE DYSPHAGIA

The symptoms and underlying causes of oral phase dysphagia have been generally discussed in the same category with pharyngeal and esophageal dysphagia [8,32,38,39,41,42,50,51,62,96-98]. Some of the clinical and radiographic symptoms (see Table 1.1), indicative of oral phase dysphagia, include drooling of food material from the mouth and collection of food debris (pooling) in anatomical pockets (e.g., anterior and lateral sulcus) [6,9,39,99]. The duration of bolus transit during a phase may be abnormally prolonged [34,35,39,43,97,100,102], and a general difficulty in propelling the bolus may be encountered [34,39,53,103-105]. Problems in salivation to form a properly lubricated bolus may be observed [47,106-110], and signs of problems in airway protection (aspiration) are foretold by coughing, choking, or a gargly voice [6-9,31,35,38,111-113] (see Figure 1.5). Regurgitation (backflow) of food material into the oral and nasal cavity is a common symptom of oropharyngeal dysphagia [6,9,97] (Figure 2.1). A deviate swallowing pattern (e.g., the tongue thrust/infantile swallow) [11,27,68,87,114-119] (Figure 2.2) leading to swallowing difficulty may be detected in patients who attempt to compensate for anatomical or physiological abnormalities (e.g., orthodontic irregularities, lack of tongue control).
Figure 2.1: Nasal Regurgitation of a Bolus (from [7])

Figure 2.2: Deviate Swallowing Pattern; Tongue Thrust Swallow (from [116])
The determination of the underlying cause of oral phase dysphagia is a challenging task, considering the wide range of possibilities. Often symptoms, as well as their causes, can overlap and share similarities. They can also be "hidden" in cases where compensatory swallowing functions [20] are observed (see Figure 2.3).

Figure 2.3: Compensation during the Oral Phase of Swallowing; a) Normal, b) Compensation (from [20])

To simplify, the causes of oral phase dysphagia can be divided into those that lead to either neuromuscular or mechanical disorders [6]. The causes leading to
neuromuscular disorders fall into two categories. The first category includes causes which directly affect the muscles of swallowing such as myotonia/dystrophies [38,53, 97,103-105,120] and myasthenia gravis [38,39,120]. The second includes causes which directly affect the neural aspects of swallowing such as stroke [38,43,120,121- 124], brain trauma [34,38,125], Parkinson's disease [120,126-128], and poliomyelitis [129-132]. Also included in this category are amyotrophic lateral sclerosis (ALS) [38,120], Huntington's Chorea [38,61], multiple sclerosis (MS) [119], and peripheral neuropathies (e.g., diabetes, lymphoma, and carcinoma) [41,119,133,134]. These categories of causes contribute to some of the following dysphagic dysfunctions: 1) Reduction in control and range of movement of swallowing structures (e.g., tongue), 2) Reduction in muscle strength which results in ineffective propulsion of the bolus, 3) Diminishment of oro-pharyngeal sensation which could delay the triggering of the reflex swallowing mechanism, 4) Confused or hesitant mental state leading to various dysphagic symptoms, and 5) dysarthria (speech disorder), which may coexist and share similar symptoms with oral phase dysphagia [135,136].

Cancer is the primary cause leading to mechanical disorders of oral phase dysphagia [84,86,99,137-139], where lesions can develop anywhere around the oral cavity and the nearby pharynx. Cancer treatment can also aggravate the dysphagic condition. For instance, surgery to remove the tumor drastically alters the swallowing pattern [76,79,81,98-100,113,140,141] (Figure 2.4), while irradiation and chemotherapy
cause hyposalivation and loss of sensation in swallowing structures [47,100,106,108] (Figure 2.5). Inflammation is another cause leading to mechanical disorders (Figure 2.6).

Figure 2.4: Resection of Laryngeal Cancer Tumor (from [9])
Figure 2.5: Patient with Thick Mucous Secretions Secondary to Radiotherapy (Tongue Cancer) (from [6])

Figure 2.6: Fungal Inflammation of the Tongue (from [6])
Mechanical disorders [42,128,142-148] physically obstruct bolus passage and make the swallowing task difficult or impossible for the dysphagic patient. (Note: Swallowing difficulties may also be encountered due to mental stress [149-151])

In order to identify the correct dysphagia etiology, various methods of diagnosis and assessment (evaluation) have been developed, as revealed in the next segment.

2.3 EVALUATION OF ORAL PHASE DYSPHAGIA

The evaluation protocol of the swallowing process and its associated disorders has come a long way from its humble beginnings of the early investigators during the 18th century, like Harvey [152], Boerhaave and Haller (cited in Ramsey et al [75]), who had to rely solely on their speculative abilities to describe their observations of the swallowing physiology. Over time, clinical knowledge and experience have been accumulated and technology has progressed to enable swallowing investigators to expand and improve upon their evaluation methods. Thus, the current evaluation protocol for the oral phase has evolved into a two step process [6,9,28,29,43,48,50, 62,153,154] : 1) a qualitative segment, which depends largely on the clinical skills of the evaluator to collect and interpret relevant patient data (see APPENDIX B), followed by 2) a quantitative segment, which uses available technology to confirm and add to the information gathered during step 1).
2.3.1 QUALITATIVE SEGMENT [3, 6-9, 28, 29, 32, 44, 51, 155-160]

The evaluation protocol begins with the collection of all pertinent information on the patient that could roughly point to symptoms of oral phase dysphagia. This includes the subject’s swallowing history (e.g., complaints) and medical history (e.g., prior surgery, disease, medications, etc.) (see Figure 2.7).

Swallowing Questionnaire

Name: ___________________________ Age: ______
Date: ___________________________ Sex: ______

Check the statements that describe you:

1. ______ difficulty swallowing
2. ______ pain while swallowing
3. ______ "lump" in throat
4. ______ can't chew hard food
5. ______ can't chew fibrous or "crunchy" foods
6. ______ avoid foods like apples, nuts, and cookies

7. ______ avoid foods like celery
8. ______ food spreads all over mouth while eating
9. ______ food gets caught in cheek and is not swallowed
10. ______ food falls out of mouth before swallowing
11. ______ excessive saliva or mucus in mouth
12. ______ very dry mouth
13. ______ food comes out of mouth or nose while swallowing
14. ______ cough or choke before, during, or after swallowing
15. ______ food gets caught at base of tongue, high in throat
16. ______ food gets caught lower in throat
17. ______ slow eater
18. ______ food or water comes into mouth without vomiting, often while lying down
19. ______ more difficulty swallowing liquids than solids
20. ______ more difficulty swallowing solids than liquids

Figure 2.7: Swallowing Questionnaire for Dysphagia Evaluation (from [36])
Do you have:

1. ______ poorly fitting dentures
2. ______ dry mouth (xerostomia)
3. ______ frequent heartburn or indigestion
4. ______ hoarseness after swallowing
5. ______ decreased oral sensation
6. ______ paralysis of oral or facial muscles
7. ______ frequent pneumonia or respiratory problems

Have you ever had:

1. ______ surgery or radiation to the thyroid
2. ______ surgery or radiation of the face, head, neck, or mouth
3. ______ head trauma
4. ______ brain surgery
5. ______ cardiac surgery
6. ______ high blood pressure

Have you been told you have:

1. ______ dysphagia
2. ______ hiatal hernia
3. ______ gastric or peptic ulcer
4. ______ thyroid disorder
5. ______ amyotrophic lateral sclerosis (ALS)
6. ______ multiple sclerosis (MS)
7. ______ Parkinson’s disease
8. ______ muscular dystrophy
9. ______ dystonia
10. ______ myasthenia gravis
11. ______ dermatomyositis
12. ______ scleroderma
13. ______ rheumatoid arthritis
14. ______ cerebral palsy
15. ______ poliomyelitis
16. ______ dysautonomia
17. ______ Raynaud’s phenomenon (hands or feet turn red or blue)
18. ______ schizophrenia or other psychiatric disorder
19. ______ stroke
20. ______ cancer of the lips, mouth, throat, larynx, or neck
21. ______ structural abnormality of the face or mouth
22. ______ cleft lip/palate
23. ______ polymyositis
24. ______ diabetes

Have you taken or do you take:

1. ______ tranquilizers
2. ______ antacids
3. ______ cancer drugs
4. ______ ulcer drugs
5. ______ heart medications
6. ______ insulin

List all other medications you presently take (other than vitamins):

Food Preference/History:

Foods you avoid:

Foods you prefer:
The subsequent, physical examination (Table 2.1) is dictated by the initial information gathering session. It confirms some of the symptoms identified during the previous segment and provides further clues on the etiology of the swallowing disorder.

Table 2.1: Sample Protocol for Swallowing Physical Examination (from [50])

<table>
<thead>
<tr>
<th></th>
<th>On command</th>
<th>Present but not to command</th>
<th>Impaired</th>
<th>Absent</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Control</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>flexion</td>
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<tr>
<td>extension</td>
<td></td>
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<tr>
<td>turn R</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>turn L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>lateral flex R</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>lateral flex L</td>
<td></td>
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<tr>
<td>Jaw Control</td>
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<tr>
<td>close</td>
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<tr>
<td>open</td>
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<tr>
<td>lateral motion</td>
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<td>Lip Control</td>
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<tr>
<td>pursing</td>
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<tr>
<td>retraction</td>
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<tr>
<td>closure</td>
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<tr>
<td>Tongue Control</td>
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<td>protraction</td>
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<td>retraction</td>
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<td>to R</td>
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<td>to L</td>
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<tr>
<td>elevation</td>
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<tr>
<td>depression</td>
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<tr>
<td>Buccal Movements</td>
<td></td>
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</tr>
<tr>
<td>Suck</td>
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<tr>
<td>Chew</td>
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<tr>
<td>Swallow</td>
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</tr>
<tr>
<td>liquids-cup, straw</td>
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<tr>
<td>semi-solids</td>
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<tr>
<td>solids</td>
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</table>
### Table 2.1 (continued)

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<th>Sensory Present/Impaired</th>
<th>Absent</th>
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<th>Right 2</th>
<th>Left 3</th>
<th>Left 4</th>
<th>Comments</th>
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<tbody>
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<td><strong>Touch</strong></td>
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<td>lips</td>
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<td><strong>Temperature</strong></td>
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<td>tongue</td>
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<td>face</td>
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<td>lips</td>
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<tr>
<td><strong>Taste</strong></td>
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<tr>
<td>Present, Absent, Impaired</td>
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<td></td>
</tr>
<tr>
<td>Bitter</td>
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<td>Sour</td>
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<tr>
<td>Sweet</td>
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<td>(in all areas of tongue)</td>
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</tbody>
</table>

### Additional Observations
- tongue thrust
- food in side of mouth
- drooling
- facial weakness
- aspiration

### Recommendations

The Program:

Frequency of Treatment:

Patient Limitations:

Patient's Attitude Toward Program:

Nurse/Family Involvement:

Therapist:

Date:
This examination typically includes verbal and cognitive tests to determine the mental status of the patient, which, if impaired, could affect the voluntary aspect of swallowing. The strength and control of various muscles (orofacial, tongue, etc.) are checked through observation, palpation, and resistance tests (Table 2.2).

Table 2.2: Methods of Evaluation for Oral Phase Dysphagia (from [9])

<table>
<thead>
<tr>
<th>Factors Influencing Swallowing</th>
<th>Methods of Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral phase</td>
<td>Screen orientation, language, visual-motor perception, and memory</td>
</tr>
<tr>
<td>Mental status, judgment</td>
<td>Examine for symmetry at rest and during movement</td>
</tr>
<tr>
<td>Muscles of facial expression</td>
<td>Palpate and gently resist movement</td>
</tr>
<tr>
<td>Muscles of mastication</td>
<td>Inspect</td>
</tr>
<tr>
<td>Mucous membranes</td>
<td>Inspect</td>
</tr>
<tr>
<td>Dentition</td>
<td>Inspect at rest and on protrusion; resist movement</td>
</tr>
<tr>
<td>Lingual muscles</td>
<td>Subjective; identify stimulus qualities</td>
</tr>
<tr>
<td>Orofacial sensation</td>
<td></td>
</tr>
<tr>
<td>Pharyngeal phase</td>
<td>Observe at rest and during phonation; stimulate gag reflex</td>
</tr>
<tr>
<td>Palatopharyngeal closure</td>
<td>Stimulate gag; motion radiography</td>
</tr>
<tr>
<td>Pharyngeal constriction</td>
<td>Palpate larynx during swallow</td>
</tr>
<tr>
<td>Extrinsic laryngeal muscles</td>
<td>Indirect laryngeal inspection</td>
</tr>
<tr>
<td>Intrinsic laryngeal muscles</td>
<td>Motion radiography</td>
</tr>
<tr>
<td>Cricopharyngeus muscle</td>
<td></td>
</tr>
<tr>
<td>Esophageal phase</td>
<td>Motion radiography and endoscopy</td>
</tr>
<tr>
<td>Morphology of the esophagus</td>
<td>Manometry and cineradiography</td>
</tr>
<tr>
<td>Esophageal motility</td>
<td>Manometry, cineradiography, gastroesophageal scintiscanning, acid perfusion, pH monitoring, endoscopy, and biopsy</td>
</tr>
<tr>
<td>Gastroesophageal sphincter function, hiatal hernia, and reflux</td>
<td></td>
</tr>
</tbody>
</table>
For instance, the strength of the lips and tongue are assessed by subjectively interpreting the muscular resistance offered by the patient against a tongue depressor, held by the examiner. Lesions along the food pathway and structural irregularities, such as malocclusion and cleft palate, can often be discovered through direct observation. The patient's voice and articulation is checked as possible indicators of aspiration, and the level of oral sensation is examined by means of cotton swabs and taste stimulus. One of the most important components of the physical examination is the test swallow, which utilizes a small, "safe" bolus for clinical safety during the test. Employing this test, the examiner can roughly assess the person's ability to swallow, or identify possible abnormalities associated with a dysphagic condition.

Some dysphagia-associated clinics conclude their evaluation protocol after the physical examination for reasons of high cost, lack of facility, and lack of specialized staff. The result is a highly subjective, incomplete evaluation report, which is often based and interpreted in terms of a numerical scale system (see Figure 2.8), developed by the dysphagia staff [6,9,28,29,43,51,98,121,157,161,162].
Swallowing Ability Assessment

(7) No complaints.
(6) Minimal complaints and able to swallow without difficulty with the bolus.
(5) Minimal complaints and able to swallow without difficulty without the bolus.
(4) Moderate complaints and difficulty swallowing with the bolus.
(3) Severe complaints and difficulty swallowing with the bolus.
(2) Severe complaints and difficulty swallowing without the bolus.
(1) Severe complaints and unable to swallow.

Tongue Mobility Assessment

A. Mobility (+/- scoring)

POSITION SPONTANEOUS IMITATED

1. Straighten out
2. To upper teeth
3. To palate
4. Cured back
5. Laterize
6. Elevate
7. Depress
8. Clear palate of food

Excellent Poor

Figure 2.8: Numerical Scale Systems Used in Swallowing Evaluation (from [79,98])
2.3.2 QUANTITATIVE SEGMENT

Due to the shortcomings of the qualitative evaluation segment, advanced dysphagia-associated clinics also include a "quantitative" segment that utilizes up to date technology in evaluating a patient. This segment is recognized as being the most objective component of the current evaluation protocol, vital to effective, subsequent treatment. There are four techniques that are predominantly in use for this purpose (see APPENDIX C for detailed discussion on evaluation technology): cine/videofluoroscopy [8,9,47,48,55,58,79-83,93,111,118,124,158,163-170] (Figure 2.9), intraluminal manometry [32,46,56,79-83,96,163,171-175] (Figure 2.10), ultrasonography [36,47,49,84,176-183] (Figure 2.11), and electromyography [12-15,17,47,54,57,59,184-190] (Figure 2.12). While other methods (e.g., scintigraphy, x-ray pellet tracking, CATSCAN, etc. [25,47,49,125,170,171,176,191-193]) can be used, they only have special applications and are less frequently utilized.
Figure 2.9: Videofluoroscopy: a) Setup, b) Images of Various Dysphagic Conditions (from [9])
Figure 2.10: Intraluminal Manometry; a) Setup, b) Manometric Pressure Pattern for a Normal Swallow (from [173,235])
Figure 2.11: Ultrasonography; a) Setup, b) Image of Resting Tongue (from [47,179])
Figure 2.12: Electromyography; a) Setup, b) EMG Signals During a Swallow (from [59])
For oral phase evaluation, videofluoroscopy and ultrasonography has been primarily utilized to monitor tongue and bolus movement. Although these two methods are recognized as the "gold" standards of quantitative evaluation techniques, they only possess semi-quantitative, visual imaging capabilities. Except for the timing of swallowing events [176,186], both techniques offer little in terms of measurable, quantitative parameters and are prone to subjectivity in interpretation. Also, these methods are limited in their abilities to image different oral phase swallowing structures (e.g., bone, soft tissues), as well as the swallowed bolus (Figure 2.11, 2.13).

Figure 2.13: Disadvantages of Videofluoroscopy; Oral Phase Imaging (from [9])
High equipment cost, invasiveness of the test bolus, and radiation exposure are additional drawbacks of videofluoroscopy use. Finally, both methods require the assistance of a specialist.

To overcome the shortcomings of current evaluation methods, some of these techniques have often been combined (e.g., simultaneous videofluoroscopy and intraluminal manometry - Figure 2.14) to provide a more complete evaluation protocol.

Figure 2.14: Simultaneous Videofluoroscopy and Manometry (from [82])
Still, the present evaluation techniques offer little capability for true, quantitative evaluation of dysphagia, and a definite need exists to devise methods for such purpose to aid and complement the current protocol and improve the subsequent treatment methods.

2.4 TREATMENT OF ORAL PHASE DYSPHAGIA

The goals of the current treatment programs of oral phase dysphagia are generally similar, and they are as follows: 1) to maintain an adequate nutritional supply to the patient, 2) to minimize the risk of harmful effects (e.g., aspiration, choking) during the patient's meals, and 3) to help the patient quickly return, if possible, to normal oral feeding and achieve independence. The program needs to address the individual needs of the patient, yet still maintain some standard procedure to follow. Unfortunately, current treatment methods differ from one clinic to another [9, 44, 50, 51, 90, 157, 161, 194]. The inherent subjectivity in the evaluation methods correspondingly is reflected by the subjectivity in the subsequent treatment strategies (see APPENDIX B).

A treatment program consists of different methods to achieve its goals. The methods include swallow retraining [51, 90, 117, 142, 157, 195, 196], compensation of impaired swallowing mechanism [51, 60, 122, 157, 195, 196], surgery [98, 121, 141-143,
LITERATURE REVIEW

197], and alternate means of feeding [47,50,142,198]. Other methods such as medication [122,141], prosthesis [86,138,199-204], and thermal sensitization to elicit swallow reflex [158,196,205] only have special applications. For this investigation into the oral phase of swallowing, swallow retraining and prosthetic devices have most relevance and will be discussed in greater detail.

Table 2.3: Therapy Techniques for Dysphagia (from [51])

<table>
<thead>
<tr>
<th>Problem Area</th>
<th>Specific Deficit</th>
<th>Management Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaw control</td>
<td>Jaw motion</td>
<td>• Opening mouth</td>
</tr>
<tr>
<td></td>
<td>Closing mouth</td>
<td>• Closing mouth</td>
</tr>
<tr>
<td>Jaw motion</td>
<td>Poor mobility</td>
<td>• Poor mobility</td>
</tr>
<tr>
<td></td>
<td>Muscle weakness</td>
<td>• Muscle weakness</td>
</tr>
<tr>
<td></td>
<td>Poor rotary movement</td>
<td>• Poor rotary movement</td>
</tr>
<tr>
<td>Lip control</td>
<td>Weak closure</td>
<td>• Weak closure</td>
</tr>
<tr>
<td></td>
<td>Weak protraction</td>
<td>• Weak protraction</td>
</tr>
<tr>
<td></td>
<td>(puckering)</td>
<td>• Weak protraction</td>
</tr>
<tr>
<td>Tongue control</td>
<td>Poor control</td>
<td>• Poor control</td>
</tr>
<tr>
<td></td>
<td>Weakness</td>
<td>• Poor control</td>
</tr>
<tr>
<td>Laryngeal mobility</td>
<td>Weak elevation</td>
<td>• Weak elevation</td>
</tr>
</tbody>
</table>

  • Vibrating or pressing under lower lip
  • Vibrating or pressing above upper lip
  • Passive stretching
  • Repetitive resistance exercises
  • Chewing lemon swab or Sugar Daddy®
  • Passive rotary movement
  • Verbal coaching during chewing
  • Vibrating or quick stretching of orbicularis oris
  • Holding lemon swab or sucker between lips against increasing tension
  • Sucking exercise with lemon swab, Sugar Daddy®, Popsicle®, or straw
  • Exercise by smiling or showing teeth
  • Blowing bits of paper using a straw
  • Whistling
  • Pushing tongue to either cheek, protracting, and retracting
  • Licking jelly or toothpaste off lips
  • Pushing swab or sucker out of mouth or against hard palate; holding between tongue and hard palate against increasing tension
  • Vibrating under chin and down both sides of larynx
  • Upward stroking beneath chin or manually assisting laryngeal elevation during reflex or volitional swallowing
A dysphagic patient is trained to successfully regain the normal swallowing mechanism by exercising the involved muscles and relearning the swallowing process (Table 2.3). Muscle strengthening and movement exercises that involve the muscles of swallowing (see Figure 2.15), particularly those of oral phase, have been developed by numerous speech therapists and orthodontists [28,29,116,195,196]. They include isometric exercises, for instance, where the patient is required to exert his maximum tongue force against a tongue depressor (held by clinician) or against the cheeks. An exercise, requiring the specific movement of the tongue into various positions, is a way to improve voluntary tongue control. Other exercises involve the movement of
the soft palate and the elevation of the laryngeal structures (e.g., hyoid bone). The relearning of the swallowing process may involve the proper placement and movement of the bolus and surrounding oral structures, the formation of proper bolus size, and suspension of respiration during the swallow [51,90,122,157,196].

Figure 2.16: Biofeedback Instrument for Monitoring Oral Musculature Function (from [27])
Therapists are obviously required to carry out some of these exercises, but often they are performed by the patient alone. These exercises can become rather tedious, and a lack of enthusiasm may hinder the patient's progress. Thus, the need for stimulating feedback (e.g., audio, visual, tactile, etc. - see Figure 2.16) may be critical for a successful swallow training routine. A further drawback to this aspect of the treatment plan is that it is only applicable to patients with adequate cognitive and verbal skills, or with disorders where neuromuscular recovery is expected to some degree. It is also prone to much subjectivity, unless methods are devised to quantify the muscular strength and motility.

Prosthetic devices have been used exclusively for swallowing disorders following orofacial surgery to remove cancer tumors from the oral cavity [86,138,162,199,200,202-204]. The surgery may involve the tongue (glossectomy), the lower jaw (mandibulectomy), or the upper jaw (maxillectomy). Cantor et al (1969) [200] reported the results of lowering the posterior segment of the palate to accommodate swallowing and speech disorders. The prosthesis enabled improved contact between the tongue and the palate, but it also affected the normal swallowing mechanism. Tudor and Selley [203], in 1974, developed two intraoral training appliances for speech therapy to assist dysarthric (speech disorder) patients with soft palate function during the oral phase of swallowing. The appliances consisted of a U-shaped wire attached from an acrylic base plate and extended to touch the resting soft palate in the region of
maximum lift. In 1980, Wheeler and associates [204] formed customized maxillary prostheses (Figure 2.17a) and found that the contour of the palatal vault had to be compromised between the needs of speech articulation and swallowing. They noted definite improvements in the oral phase of swallowing (decreased bolus oral transit time) for all tested patients. Aramany et al (1982) [199] used two approaches, developing both a mandibular tongue prosthesis and a palatal augmentation prosthesis (Figure 2.17b). The mandibular prosthesis employed a silicone tongue replacement with different groove shapes for speech and swallowing, and it could be easily attached and removed from the floor of the mouth. Other variations of palatal appliances followed [86,124,138,162], which allowed stronger bolus propulsion during swallowing and better linguopalatal contact during articulation/swallowing (Figure 2.17c, d). The current state of prosthodontics has been well documented by Hurst (1988) [202].
Figure 2.17: Various Oral Prostheses; a) Wheeler et al [204], b) Aramany et al [199], c) Davis et al [138], d) Logemann et al [86]
Other treatment techniques include the compensation of the impaired swallowing mechanism by means of a safe, stimulating diet [161,194,198,206] to elicit the use of the undamaged swallowing mechanism (see Table 2.4).

Table 2.4: Dietary Modifications for Problem Swallowing Phases (from [62])

<table>
<thead>
<tr>
<th>Problem Phase</th>
<th>Diet modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 • Oral phase</td>
<td>• better with solid or soft; liquids cause problems</td>
</tr>
<tr>
<td>• Poor tongue control</td>
<td>• avoid small pieces of food</td>
</tr>
<tr>
<td>• No bolus formed</td>
<td>• do not give very hot foods; soft-textured foods and thickened foods and thickened liquids are best.</td>
</tr>
<tr>
<td>• Decreased sensation in the oral cavity</td>
<td></td>
</tr>
<tr>
<td>2 • Pharyngeal phase</td>
<td>• give consistency that can be swallowed in a single bolus; non-cohesive purees may be too hard to handle.</td>
</tr>
<tr>
<td>• Weak or absent swallowing</td>
<td></td>
</tr>
<tr>
<td>• Delayed swallowing reflex</td>
<td></td>
</tr>
<tr>
<td>• Incomplete closure of larynx</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• thicker foods are best; liquids almost always cause aspiration.</td>
</tr>
<tr>
<td></td>
<td>• use thicker foods</td>
</tr>
</tbody>
</table>

Also, a patient's posture may be adjusted (Figure 2.18) to better facilitate the swallow, or he or she may be instructed to concentrate on the swallowing task to increase the chances of a successful swallow [6,9,60,90].
Surgical intervention is performed in cases where significant improvements in the swallowing mechanism are expected as a result, or regular swallowing becomes too difficult [98, 121, 141-143, 197]. Surgery may involve the resection of lesions of cancer tumors (e.g., laryngectomy, glossectomy, etc.) (see Figure 2.4). It should be noted that surgery can result in further complications of dysphagia because of the altered swallowing anatomy, in which case, alternate feeding methods, prosthesis, or additional surgery is required [51, 79, 81, 98, 140, 141].

Figure 2.18: Effect of Posture on Swallowing (from [9])
If a dysphagic patient is unable to recover sufficient swallowing function and accept oral feeding, the only possible option is to use alternate feeding methods to provide the necessary nutrition [6,9,29,47,50,142,198]. Gastrostomy, jejunostomy, and intravenous methods (refer to GLOSSARY) are often preferred for permanent, fixed applications, while in rehabilitation settings, the use of nasogastric tube is prevalent for transient, recovering patients.

2.5 BIOMECHANICAL ANALYSIS OF THE ORAL PHASE OF SWALLOWING

Although the evaluation of the oral phase through the use of videofluoroscopy and ultrasound has been discussed in CHAPTER 2.3.2, a significant amount of literature has been produced by researchers in orthodontics [11,68,87,94,117,119,207-224] and speech therapy [135,136,156,225-233] on the biomechanical analysis of the oral phase. The researchers were interested in measuring oral musculature force and movement pertaining to their respective disciplines. Although clinical applications have been scarce (except by the investigators, themselves), these evaluation techniques have represented the only truly quantitative methods of oral phase biomechanical evaluation employed to date. Their significance as oral phase evaluation tools has serious implications for this research, and the following segment outlines their development and significance.
In 1937, Neumayer (cited in Palmer and Osborn [232]) took a mercury manometer, attached to it a small thick-walled rubber ball to be introduced into the subject's mouth. The subject was then asked to close the teeth, isolate the tongue muscle, and press up against the ball with the tongue. From his data, he noted tongue pressure differences among subjects of different age, sex, and between able-bodied and patient groups. Palmer and Osborn (1940) [232] gave a review of the few, previous attempts at measuring tongue strength, tracing back to the end of the 19th century. They also used a similar device to Neumayer's, but for speech defective patients. They showed that patients with a speech disorder exhibited low tongue strengths without any sex-linked differences. The 1950's brought about a surge in orthodontic research on orofacial biomechanics with the focus on measuring the forces on the dental arch. Alderisio and Lahr (1950) [208] developed a resistance strain gauge transducer setup capable of measuring seven pressures exerted by the lips, cheeks, and tongue on various areas of the dental arch (see Figure 2.19). The gauges, set up in a Wheatstone bridge configuration, were scanned with a switching circuitry, driven by a cam. Similar strain gauge technology continued to be used by researchers in measuring orofacial force [223,224] (Figure 2.20). However, these devices were insufficiently tested with clinical subjects and were inadequate for prompt data acquisition of swallowing pressures. Data was recorded on a single channel pen recorder, which was capable of charting the signals of the sensors only one at a time and not simultaneously.
Figure 2.19: Early Device for Measuring Swallowing Pressures on Dentition (from [208])
Kydd (1956) [210] devised a system, utilizing denture bases with mounted pressure transducers (cantilever beam type with strain gauges), to measure protruding and lateral tongue forces (see Figure 2.21).
Unfortunately, his study was limited to only one test subject. Kydd [211] then followed up with a thin, plastic, water-filled pressure device to obtain the maximum tongue forces exerted on the alveolar ridge just behind the upper incisors (Figure 2.22).

Figure 2.22: Transducer for Measuring Tongue Pressure near the Forepart of the Palate (from [211])

To measure the actual tongue pressures generated on the hard palate during the oral phase of swallowing, Kydd and Toda (1962) [212] measured 15 able-bodied subjects, using strain gauges attached to acrylic palatal retainers (Figure 2.23). To their credit, they put high priority on subject accommodation during test protocol. Their calibration unit consisted of a confined air bladder acting over the retainer, but this assumption that a completely uniform calibrated pressure distribution could be achieved over a complex contour such as the palate’s is questionable with limitations
of the air bladder to deform exactly to the palatal shape.

Figure 2.23: Palatal Retainer Transducer I for Measuring Tongue Pressure on Palate (from [212])

Significant studies involving different subject groups (e.g., young/old adults, children, palatal surgery patients) have been conducted by Proffit and his colleagues [216-221,231] over many years in their work covering orthodontics, plus speech and swallowing disorders. They developed a reusable, easy-fitting palatal retainer transducer (Figure 2.24), similar to the one used by Kydd and Toda, which could be calibrated by means of an closed air chamber. Subject comfort was ensured through the use of a customized palatal transducer. The transducer employed 5 strain gauges (cantilever beam type configuration), which were positioned flush against the retainer
at various points of the palate in contrast to Kydd's method. This transducer design may thus have problems in distinguishing between a singular tongue force at the sensor and a tongue pressure applied over a wider area around the sensor. Proffit still observed variations in swallowing patterns between individuals with an infantile (tongue thrust) and adult (normal) swallows, but further clinical data of patients with oral phase dysphagia were not presented.

Figure 2.24: Palatal Retainer Transducer II for Measuring Tongue Pressure on Palate; a) Transducer, b) Calibration Setup (from [217])
Abbs and Gilbert (1973) [225], in their paper, addressed critical design issues (e.g., structural loading) of a cantilever beam type strain gauge transducer. Dworkin (1979) [136,156] employed a "Lingual Force Scale" (see Figure 2.25), testing 45 normal and 45 lisping speakers to examine the relationship between tongue strength and articulation proficiency. But only protrusive tongue force measurements in the anterior direction were taken.

Figure 2.25: Lingual Force Scale (from [230])
In addition, Dworkin [230] devised another system, a load cell type held between the teeth, to measure anterior and lateral tongue forces exerted by normal and dysarthric patients (Figure 2.26). Porter and Lubker (1980) [233] applied a "Linguameter" to assess subjects' ability to accurately position their tongues along the antero-posterior direction (Figure 2.27). They noted that their setup presented an unrealistic task with respect to the oral phase swallowing mechanism, but they also found a potential use for the setup in assessing general motor control.
Barlow (1983-1986) [135,226-228], investigating speech disorders, developed various transducer systems to measure tongue, lip, and jaw movements (Figure 2.28), often interfacing with simultaneous electromyography and acoustic methods. His methods included the use of a new headmount to fix head position and isolate the oro-facial muscles (Figure 2.29). He used a cantilever-beam transducer (Figure 2.30), the one used by Abbs and Gilbert [225], to measure maximum as well as fine control forces during speech. Dysarthric patients (spastic cerebral palsy and Parkinson's) were unable to produce stable lingual muscle thrusts and generally showed a weaker muscle strength. Oddly, Barlow failed to present numerical results from his experiments and fully evaluate his device as a clinical tool.
Figure 2.28: Intraoral Transducers; a) Lip Force, b) Tongue Force (from [135])

Figure 2.29: Headmount Used to Isolate Oro-Facial Muscles (from [226])
Reddy (1985) [159,160] was the first investigator to purely address the orofacial biomechanics from the swallowing perspective. He measured six biomechanical parameters that characterized the swallowing mechanism and its disorders in the oral phase. His transducers included load cells, hydraulic pressure transducers, a plastic cantilever-beam strain gauge transducer, and an accelerometer. They enabled the measurement of lip/tongue strength, suction strength, and degree of laryngeal elevation (pharyngeal phase). Although he recorded differences in able-bodied tongue strength compared to dysphagic patients, Reddy failed to present detailed clinical results and data analysis from his experiments. His tongue force transducer, a plastic cantilever beam device, was also found to deflect too much when load was applied; thus failing to indicate one's maximum tongue strength. Finally, Reddy neglected to
discuss the clinical aspects of his experimental setup in terms of test subject comfort, safety, standardization of measurement protocol.

General improvements have been made over time in measuring the biomechanical parameters during the oral phase of swallowing. However, technical problems persist with regards to calibration, design of transducers, and recording instruments (e.g., recording chart pen), and often the sample of test subjects are limited. Particularly with the lack of research into the quantitative analysis of the oral phase, the feasibility of analyzing such neglected oral biomechanical parameters as tongue strength and coordination seems highly recommendable.

2.6 THE ROLE OF SUCTION DURING SWALLOWING

Along with the biomechanics of the oral phase of swallowing, another issue of interest for the present investigation is the role that manometric suction pressure (negative pressure gradient) plays in propelling the bolus from the front of the mouth to the entrance of the pharynx. While it is widely accepted that the tongue plays a critical role in propelling the bolus during the oral phase, the view of a suction mechanism in bolus propulsion has been in the past, and continues to be, an issue of controversy (see CHAPTER 2.1). Considering the formation and release of various "seals" around the oral cavity [21] (see Figure 4.1) during the swallowing process,
However, the theory of an oral phase suction mechanism should be investigated.

From the earliest to the latest research on the swallowing process, the topic of a suction mechanism has been consistently neglected, which suggests that either; 1) there really is no suction mechanism at all, 2) the mechanism has been completely overlooked or bypassed, 3) that suction has little effect on the swallowing process, or 4) or some combination of these. The first mention of a negative pressure gradient was made by Barclay [65] (see CHAPTER 2.1) in 1930, who proposed that suction is the mechanism by which a bolus is rapidly accelerated through the pharynx to the esophagus. He found that the expected, traditional peristaltic movements involved in bolus propulsion are only observable one-third the way down the esophagus. This led to his conclusion that, proximally, the bolus is transported by an initial, impulsive tongue thrust mechanism in the oral phase, followed by a suction mechanism through the pharyngeal phase. He based his interpretation on radiographic pictures, showing the obliteration of the pharyngeal space just before the bolus slipped over the back of the tongue. This observation was explained as being caused by the pressure exerted by the back of the tongue flattening the epiglottis upright against the posterior pharyngeal wall. The pharyngeal space reappeared eventually, and the bolus was then seen to enter this space. Barclay compared this phenomena to the formation of a vacuum when a closed space (obiterated pharyngeal space) is expanded (reappearance of pharyngeal space). Using simultaneous electromyography, Barclay
observed little, if any, sign of muscular activity through the pharyngeal portion of swallowing. The insignificant effect of gravity, along with the observed, rapid bolus transit, and the other aforementioned phenomena indicated to Barclay the presence of a suction mechanism. Barclay's findings have been refuted by later researchers, who have experimentally found no presence of the suction mechanism in the pharynx [66,70-75].

Fyke and Code [172], in 1955, measured the manometric pressure changes developed in the pharyngo-esophageal region of 15 healthy individuals during swallowing in order to determine whether a bolus was "squirted" [64,68,76,77] through the pharynx by positive pressures from above, e.g., tongue thrust, or sucked into the pharynx by negative pressure gradients originating from below. From their manometric analysis of different pressure profiles at the upper esophagus, pharyngoesophageal sphincter, and the pharynx (see Figure 2.31), they made the following observations.

Noting that the positive pressure wave, generated by pharyngeal peristalsis, did not travel as fast as a fluid bolus through the pharynx, Fyke and Code attributed the propulsion of a liquid bolus to a negative pressure gradient formed ahead of the peristalsis. The negative pressure gradient was developed during the first segment of the swallowing process, as the pharyngoesophageal sphincter, which was under
tonic contraction (high pressure) during resting periods, "relaxed" to drastically drop in pressure, even to negative levels. Sphincteric relaxation permitted easy passage of the arriving bolus, and after the bolus had passed, the sphincter recontracted to prevent bolus reflux back up to the pharynx.

Figure 2.31: Pharyngeal/Esophageal Manometric Swallowing Pattern I (from [172])
Meanwhile, the large negative pressure gradient was completed by a significant positive pressure wave that was simultaneously produced at the upper pharyngeal level. This wave represented the thrust by the posterior segment of the tongue against the posterior pharyngeal wall. In their investigation, Fyke and Code showed the importance of both the positive and the negative components of pressure changes as integral factors in swallowing. They clarified the previously mentioned conflict between Barclay and his counterparts by noting that the former only observed the large negative pressures at the sphincteric level, and that the latter recorded the purely positive pressures in the pharyngeal region.

The manometric measurements closest to the oral phase have been performed by Sokol et al [234], who recorded the pressures in the velopharynx located just behind the soft palate (see Figure 2.32). They also measured and identified three types of positive pressure waves involved in swallowing. The e (elevation) wave corresponded to the elevation of the laryngopharyngeal structures and occurred early in the swallowing process. The t (tongue) wave corresponded closely to the posterior motion of the back of the tongue towards the posterior pharyngeal wall. The distally-travelling p (peristalsis) wave, which was also the largest in magnitude, was coincident with the pharyngeal peristaltic activity. The existence of these three waves, along with a flow aspect (positive pressure plateau existing between the t and p waves - Figure 2.32), has been confirmed by other manometric studies [172,235,236].
Sokol et al.'s results showed that the e wave was most prominent in the oropharynx and almost non-existent in distal regions. Like Fyke and Code, Sokol et al. observed a period of relaxation by the sphincter accompanied by a large negative pressure drop. The resultant negative pressure gradient in the pharynx could be classified as suction, but Sokol et al. went on to state that it was not essential to
facilitate a successful swallow. The "force-pump", enforced by the t and p waves in the oropharynx, should be sufficient to carry out the swallowing process. In the velopharynx, Sokol et al observed a single positive pressure peak that could be correlated to the onset of the p wave.

McConnel [79-83], using his newly devised technique of manofluorography (an advanced version of simultaneous manometry and videofluoroscopy), challenged the traditional view of positive pharyngeal constrictor pressure as the chief driving force behind bolus propulsion. Instead, his results supported the significance of tongue driving pressure and the negative pressure gradient, developed in the pharyngeal and esophageal segments (see Figure 2.33). Pharyngeal constrictor activity was considered only as a clearing mechanism, occurring much too late to be a major factor in bolus transit. The tongue driving pressure (t wave) signified the posterior thrust by the back of the tongue against the posterior pharyngeal wall, i.e., the oropharyngeal force pump, previously noted as a squirt mechanism [64,68,76,77]. The negative pressure referred to the sphincteric relaxation, resulting in a negative pressure gradient ahead of the bolus. McConnel phrased this phenomena as a two-pump system with the tongue thrust and pharyngeal suction operating like pumps to propel the bolus. He, like previous researchers, observed three types of pressure waves: e, t, and c waves (c waves equivalent to p waves in other literature).
To the interest of this research, he recorded no pressure waves at all at the velopharyngeal level (near the junction between the oral cavity and the oropharynx). He stated that the bolus travelled past this point as a result of the tongue force acting against the palate during the oral phase. It should be noted that McConnel employed only liquid boluses which, as mentioned in CHAPTER 2.1, may emphasize the action of the tongue more than the pharyngeal peristalsis.
2.7 SUMMARY

The literature review, performed for this research, has confirmed the need for an improved understanding of the swallowing process and its disorders. In particular, the oral phase has yet to be investigated completely in regards to a bolus propulsion mechanism. Previous researchers into oral phase biomechanics have failed to develop transducer systems and test them for reliability and clinical applicability. Most of the dysphagia research presented in the literature depended heavily on visualization methods for evaluation and subsequent treatment. Thus, the possibility of developing quantitative methods of swallowing analysis should be investigated.

Improved understanding and management of oral phase dysphagia can only be attained through improvements in the methods of evaluation and treatment. The "new" methods must overcome the qualitative, subjective nature of the current methods in order to provide quantitative, objective results. These protocols must be more reliable, highly standardized, and thus would lead to a general upgrading of dysphagia management. For such purposes, three measurement systems have been incorporated in this research to study the oral phase swallowing mechanism and disorders: 1) a Tongue Force Measurement System (TOMS), 2) an intraluminal manometry setup, and 3) a Oral Cavity Pressure Transducer System (OPTRANS). TOMS and OPTRANS represent the two, primary measurement systems that have
been developed for this research at the Department of Mechanical Engineering at the University of British Columbia (UBC) and the Clinical Research Laboratory at the G.F. Strong Centre to measure tongue function (strength and coordination). The manometry testing, set up at the Gastroenterology Clinic at the University Hospital (UBC), was utilized to verify the possible role of suction pressure for the bolus propulsion during the oral phase. The following chapters describe in detail the quantitative analysis of the oral phase of swallowing and associated disorders by means of these three measurement systems.
CHAPTER 3  TONGUE FORCE MEASUREMENT SYSTEM (TOMS)

3.1 INTRODUCTION AND BACKGROUND

The first stage of the present investigation into the quantitative analysis of the oral phase swallowing mechanism and its associated disorders involved the development of a TOngue Force Measurement System (TOMS - see Figure 3.1).

Figure 3.1: TOMS Setup
This measurement system provides a new approach to the assessment of the oral phase swallowing mechanism through the use of a strain gauge-based cantilever beam-type transducer which is capable of measuring an individual's tongue force exerted in either upward or lateral (left and right) directions. The system is designed with special consideration for clinical safety, patient comfort, and standardization of the testing protocol. The incorporation of a microcomputer allows easy clinical use plus efficient data acquisition and handling, while providing excellent audio-visual feedback to the system user.

As mentioned in CHAPTER 2, much of the current dysphagia assessment techniques rely heavily on subjective, clinical observation and interpretation (e.g., medical history charts, questionnaires, physical examinations, or semi-quantitative analysis using imaging techniques like videofluoroscopy). However, with the clinical capabilities of TOMS, these techniques can now be complemented using a more objective, quantitative means of assessment. TOMS can be used to assist in the initial diagnosis of a dysphagic patient and also to monitor the patient's condition throughout the rehabilitation period. As well, TOMS has the potential to serve as an exercise therapy tool used to strengthen muscles in patients who have lost or diminished oral/pharyngeal neuromuscular function.
The underlying concept of TOMS is based on the fact that poor tongue strength and coordination are widely observed among dysphagic patients, especially those exhibiting oral phase disorders (e.g., stroke, poliomyelitis, etc.) [34,35,42,50,82,84,85,111,123,126,127]. This observation is understandable in view of the tongue’s critical role during the oral phase of the swallowing process [42,63,76,85,86,107,121]. Clearly, a certain level of tongue strength and coordination is necessary to the success of this swallowing segment (i.e., for manipulation and propulsion of bolus). Therefore, proper measurement of tongue force should provide a reliable parameter indicative of an individual’s tongue strength and coordination, as well as serving to evaluate the functionality of one’s oral phase swallowing mechanism. For example, maximally exerted tongue force should provide a measure of tongue strength, while target-oriented tongue force measurement should reflect the degree of tongue coordination for each tested subject.

Previous investigations into tongue function [6,14,27] have noted that the tongue consists of intrinsic (e.g., longitudinal, vertical, and transverse) and extrinsic muscles (e.g., genioglossus, hyoglossus, styloglossus, and palatoglossus) (see Figure 3.2, APPENDIX A). The intrinsic muscles determine the shape of the tongue, while the extrinsic muscles control the movements of the tongue. Genioglossus, for example, is mainly responsible for tongue protrusion, and palatoglossus is involved in tongue elevation.
However, Lowe [14] noted in his thorough paper on tongue anatomy, physiology, and neurology that proper functioning of the tongue does not depend solely on individual muscles, but instead, any lingual movement requires the combined actions of nearly all of the muscles.

Previous investigations into the quantitative analysis of tongue biomechanics have been mentioned in CHAPTER 2 (see Proffit [216-221], Dworkin [136,156,230], Barlow [135,226-228], and Reddy [159,160]). While past researchers were able to achieve a certain degree of success in quantifying tongue strength and coordination, the validity of their results are subject due to a lack of sufficient data, variations in
individual physiology, lack of proper instrumentation and protocol, and/or other technical and clinical difficulties. As a result, TOMS was developed specifically to avoid the shortcomings of these past investigations.

3.2 DEVELOPMENT OF TOMS

The development of TOMS is best discussed categorically in terms of its mechanical and electrical components (hardware) and measurement protocol (software).

Figure 3.3: Schematic of TOMS Setup (from [237])
Figure 3.3 depicts the basic setup of the system, which consists of a transducer, mouthblock, supporting structure, electronic signal processing unit, and a microcomputer.

The core of TOMS consists of a cantilever beam-type transducer (Figure 3.4), which can be oriented to measure tongue force in three directions (up, left, and right).
The transducer employs two active strain gauges (Micro-Measurements CEA-13 250UN-350), mounted on opposite sides near the base of the beam element, to measure the longitudinal strain generated by exerted tongue force at the end of the beam. These gauges make up the active components of a Wheatstone Bridge circuit that includes two passive dummy resistors for compensation of temperature-induced strains. The active strain gauges on the beam are protected from possible damage by encasing them with silicone rubber cement. The dimensions of the beam element were chosen to provide adequate deflection based on the expected maximum tongue force levels as determined by former investigators [136,159,160,237]. The current beam transducer is made out of a titanium alloy (Ti-6Al-4V: $\sigma_y = 1.07$ GPa, % elongation = 8), which possesses superior mechanical properties than the prototype version that was made out of aluminum alloy (2014: $\sigma_y = 97$ MPa, % elongation = 18). To ensure a consistent location for application of tongue force for all subjects, a tongue cup, molded out of dental impression putty (Coltene President), is fitted at the end of the beam (i.e., point of tongue force application).

The beam transducer is incorporated into a mouthblock (see Figure 3.5), consisting of two parallel plates of polypropylene material held together by a spring-loaded, adjustable screw-wing nut assembly. One end of the mouthblock, the oral segment which is placed into the subject's mouth, is formed into shape by heat application to fit an open-mouthed human dentition pattern, i.e., diverging and sloping
towards the molars. By adjusting the wing nuts, the mouthblock can accommodate a wide range of mouth sizes and therefore enables maximum dental contact for a firm grip.

Figure 3.5: Mouthblock

The size and shape of the mouthblock require the test subjects to open their mouths sufficiently wide to effectively isolate the tongue muscles from other muscles (e.g., orofacial and neck muscles) during the test protocol. Proper placement of the
oral segment of the mouthblock into the subjects’ mouth facilitates repeatable tongue force application on the transducer by preventing excessive tongue protrusion. In the case of upward tongue force, the mouthblock/transducer assembly is designed so that a close simulation to the actual tongue lifting action during the oral phase of swallowing is achieved.

The mouthblock assembly is placed in a small vice (Panavise) which firmly holds the assembly during the clinical tongue force measurements (see Figure 3.1). The vice is mounted on top of a nearly frictionless ball joint structure, thus allowing free movement of the subject’s head, a condition which is critical in preventing the introduction of extraneous forces (e.g., from neck and shoulder muscles). The ball joint design is an improvement over a previous setup which utilized a more restrictive head restraint device to control extraneous movements [237]. This assembly is then incorporated into a portable aluminum alloy supporting frame which can be affixed to a table and adjusted according to required subject height (Figure 3.1).

The measured voltage variation from the active strain gauges on the transducer (associated with force changes) are transmitted to a signal processing unit (Figure 3.3). Originally, this unit consisted of an aluminum box housing an amplifier (Intersil ICL 7605 chip), precision rectifier, comparator, and buffer circuitry, which supplied a suitable signal to a custom-built analog-to-digital (A/D) converter residing in a IBM-
compatible PC/XT [237]. The current signal processing unit consists of only the amplifier circuit (Figure 3.6), as an improved, commercially available A/D converter (Compumotion Inc. Model-AD08) is now employed. Residing in an IBM-compatible 386 microcomputer, the converter transmits the resulting tongue force signal to be stored in a file or to be graphically presented on the computer screen.

Figure 3.6: Signal Processing Circuitry (Strain Gauge Amplifier)
3.3 CLINICAL TESTING OF TOMS

3.3.1 TESTING PROTOCOL

The protocol used in the clinical testing of TOMS is segmented into four steps: 1) calibration of TOMS, 2) subject questionnaire and customization of TOMS, 3) tongue force measurement, and 4) transducer sterilization. These steps are carried out during all initial sessions and require a total of 45-50 minutes; however, in subsequent visits only steps 1, 3, and 4 (40 minutes) are required.

3.3.1.1 CALIBRATION OF TOMS

Prior to any tongue force measurement session, TOMS is calibrated by applying standard calibration weights of 100, 200, 300 up to 1000 grams to the end of the beam where the tongue cup is normally fitted (i.e., point of tongue force application). Through an external software program, the calibration process is repeated on each testing day, and the resulting, linear calibration curve (Figure 3.7) is incorporated into the main software program.
With each new test subject, a questionnaire and customization session is conducted in preparation of the actual tongue force measurement. First, a consent form (APPENDIX D) briefly outlining the test measurement protocol is signed by the
test subject and the investigator. Next, the subject's medical and swallowing histories are obtained in a 5 minute question/answer period, using a supplied questionnaire (APPENDIX D). This is a very important step, which can provide invaluable information as to the nature of the swallowing disorder and other relevant factors.

TOMS is then customized for each test subject starting with the mouthblock. The first step is to obtain an initial estimate of the subject's mouth size by having the subject bite down on a slab of soft plasterscene thus leaving a recognizable dental impression. Using this dental impression, the oral segment of the mouthblock is then adjusted to provide maximal dental contact during the tongue force measurements. Next, four pieces of dental impression putty material (Coltene President) are formed and placed over the four corners of the oral segment of the mouthblock. The mouthblock is then carefully guided into the open mouth of the subject to the point where the top incisors comes in contact with a guide stopper. The stoppers are used to assist in reference positioning of the mouthblock in the subject's mouth. At this point, the subject is instructed to slowly close the mouth and "sink" their teeth into the impression putty pieces, leaving a recognizable impression after the release of the mouthblock. These customized impression pieces, now with embedded lower left/right molars' and top left/right molars' impressions (see Figure 3.5), are left to set for 5 minutes, after which they can be used repeatedly for subsequent measurements. It should also be noted that the oral segment of the mouthblock is grooved to enable
proper grip of the impression pieces during tongue force measurements and to provide easy, repeatable positioning of these impression pieces during future sessions.

3.3.1.3 TONGUE FORCE MEASUREMENT

Once the calibration, the initial questionnaire, and the customization segments are complete; the actual tongue force measurement protocol can begin. The protocol is centered around a menu-driven software program, which permits efficient data acquisition and analysis, instantaneous audio-visual feedback, and various other options. These options include the creation of patient record files, visit record files, and tongue force data files. (Note: all of TOMS software were written in Turbo Pascal Version 5.5., unless specified otherwise.)

In measuring tongue force, two distinct series of tests are utilized with TOMS; a series of 5-second duration tests designed to assess maximum tongue strength and a series of 30-second duration tests to determine the effect of fatigue on tongue strength and coordination. During the 5-second (non-cyclic) tests (see Figure 3.8a), subjects are instructed to exert and maintain their maximal tongue thrust on the tongue cup at the end of the beam for the duration of the test period. (Note: 5 seconds were determined to be adequate for individuals to easily achieve peak tongue force levels without inducing fatigue.) The measurements are repeated three times
in each direction (up, left, and right) with a 30-second resting period in between trials to avoid any muscle fatigue.

Besides the 5-second non-cyclic test, two distinct types of 30-second fatigue tests (non-cyclic and cyclic) are employed to study the effects of continued use on tongue strength and coordination.
Fatigue tests, it was theorized, may provide better indications of individual tongue strength and coordination than the relatively transient 5-second tests. The 30-second non-cyclic test (see Figure 3.8b) is similar in protocol to the 5-second test, but requires the subject to exert and maintain a maximum tongue thrust for a period of 30
seconds. In contrast, the 30-second cyclic test (Figure 3.8c) requires the subject to cyclically exert, relax, and re-exert a maximum tongue thrust at a preset target frequency (1 Hz) for a period of 30 seconds. Unlike the 5-second test, both fatigue tests require much greater physical effort, therefore are repeated only twice with a 4-minute rest period between each trial.

Figure 3.8 (continued)
Tongue force data is collected at a rate of 10 Hz during each trial. This sampling rate was found to provide sufficient resolution for the tongue force measurement protocol. For the benefit of the subject, audio cues are provided to acknowledge the start and the end of each measurement trial. Audio cues are also used to indicate the target frequency (1 Hz) during the 30-second cyclic test. Visual feedback is provided so that the system user and the test subject can monitor the tongue force versus time display (Figure 3.8, 3.9) on the computer screen during the measurement trial. In addition, the subject is provided with a visual "target force" level which can act as a motivational stimulus and a reference guide in performing the tongue thrust tasks. The target force level is determined for each subject during practice trials and set near the subject's maximum tongue force level.

Individual tongue strength is determined based on the average tongue force, as recorded during the time period between 1 and 5 seconds of the two non-cyclic tests (see Figure 3.8). The startup segment (0 to 1 second) is omitted from tongue strength analysis to allow for individual variations during the initial tongue force application and to provide individuals with sufficient time to achieve their maximum tongue force levels.

Tongue coordination is quantified using both non-cyclic and cyclic tests. During the non-cyclic tests, tongue coordination is reflected by the amount of variability (i.e.,
amplitude of tremor and fluctuation expressed in terms of percentage of maximum force level achieved by the subject, \( \% F_{\text{max}} \) in the subject’s tongue force level in maintaining a steady, smooth tongue thrust for the duration of the measurement trial (see Figure 3.8b). During the cyclic tests, tongue coordination is assessed by the subject’s ability to follow the preset, cyclic target frequency.

To study the effects of fatigue, two additional parameters, the force fatigue rate and the frequency fatigue rate, are calculated from the 30-second data. The former is calculated from the change in tongue force over time during the 30-second non-cyclic test (\( \geq 0 \): no fatigue, \( < 0 \): fatigue), and reflects the drop in tongue strength due to fatigue. The force fatigue rate represents the slope of the best-fit line (using a least squares analysis) through the average tongue force data points of six consecutive 5-second time intervals (see Figure 3.9). The frequency fatigue rate is calculated from the change in tongue thrust frequency over time during the 30-second cyclic test (\( \geq 0 \): no fatigue, \( < 0 \): fatigue), and it indicates the drop in tongue thrust frequency due to fatigue. The frequency fatigue rate represents the slope of the best-fit line (least squares analysis) through the average tongue frequency data points of six consecutive 5-second time intervals.
3.3.1.4 TRANSDUCER STERILIZATION

Of utmost importance to TOMS' clinical testing protocol is the cleaning and disinfecting of the system components which come in physical contact with the test subjects. The most obvious and problematic component to clean is the mouthblock and transducer assembly, especially the oral segment of the mouthblock and the
beam element. To ensure maximum clinical safety, rubber finger cots are wrapped around these parts, and the system user is required to wear medical gloves during the clinical testing of TOMS. As a secondary measure, the mouthblock and the transducer are carefully washed in liquid soap and then thoroughly rinsed. These components are then placed in a disinfectant bath (cold sterilant - Coldspore) and finally given another thorough rinse. This approved cleaning procedure is repeated after each measurement session.

3.3.2 SUBJECTS

Initially, TOMS was clinically tested with 15 able-bodied, control subjects (volunteers) without any symptoms of dysphagia to verify the system's repeatability in accurately measuring tongue force. The control subjects ranged in age from 20 to 45 and consisted of 10 males and 5 females. Subsequently, four potential dysphagic patient groups (25 post-polio sequelae, 8 stroke, 1 multiple sclerosis, and 1 amyotrophic lateral sclerosis - see GLOSSARY for definitions) were tested using TOMS to quantify variations in tongue strength and coordination between, and within, the control and the patient groups.

The post-polio patients ranged in age from 38 to 73 and consisted of 8 males and 17 females. Of the 25 post-polio patients, 9 reported varying levels of swallowing
difficulties (1 oral phase, 8 pharyngeal phase), while the others did not claim to have any difficulties at all. All of the post-polio patients had suffered acute poliomyelitis early in their lives and had encountered a recent onset of symptoms (e.g., muscle fatigue/weakness, joint/muscle pains, respiratory-, and/or swallowing difficulties) within the last few years [129-132,238-241]. The patients were selected for TOMS testing through the private referrals by Dr. Cecil Hershler, a post-polio specialist.

The 8 stroke patients (ages ranging from 42 to 67, 6 males and 2 females) tested with TOMS were recovering from cerebrovascular accidents (CVA) at the G.F. Strong Rehabilitation Centre. The initial stroke attack had left them hemiparetic (one-sided weakness), with impaired speech and swallowing mechanisms (8 oral and pharyngeal phase). The stroke patients were tested with TOMS at different stages of their recovery (from 2 to 16 weeks since the stroke onset).

The two other patients (1 amyotrophic lateral sclerosis, a 63 year-old female and 1 multiple sclerosis, a 44 year-old female) were referred to TOMS testing as subjects with potential swallowing difficulties (pharyngeal phase).
3.4 RESULTS AND DATA ANALYSIS

3.4.1 REPEATABILITY OF TOMS' DATA

Before TOMS could be utilized to assess an individual's tongue function, the system's capability to provide accurate and consistent tongue force data had to be verified. For this purpose, TOMS' data (i.e., mean tongue strength) from an initial sample of 5 able-bodied, control subjects were statistically analyzed for within-day and day-to-day repeatability using a two-way analysis of variance (ANOVA) [237]. Calculated F-test values (p < 0.005) indicated that the data were not significant, thus leading to failure in rejecting the Ho hypothesis (Ho: μ₁ = μ₂) for both, within-day and day-to-day repeatability. To determine the degree of repeatability, Intraclass Coefficients (ICC - 0: no repeatability, 1: perfect repeatability) were calculated. The results show that even for the initial analysis with the small sample of subjects, a relatively high degree of repeatability was achieved (r = 0.32-0.66) [237].

For further verification of the initial repeatability results, TOMS' mean tongue strength data obtained from 15 able-bodied, control subjects were analyzed using a simple paired t-test (Table 3.1). As before, the calculated t-test values (p < 0.01) failed to reject the Ho hypothesis (Ho: μ₁ = μ₂) for within-day and day-to-day repeatability. The subsequent, high levels of correlation coefficients (r = 0.86-0.99)
reaffirmed TOMS capability in providing repeatable tongue force data.

Table 3.1: Repeatability of TOMS' Data

<table>
<thead>
<tr>
<th>Force Direction</th>
<th>Within-day</th>
<th>Day-to-day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>1.943 (0.978)</td>
<td>0.274 (0.865)</td>
</tr>
<tr>
<td>Left</td>
<td>1.950 (0.991)</td>
<td>-2.050 (0.978)</td>
</tr>
<tr>
<td>Right</td>
<td>2.296 (0.912)</td>
<td>0.495 (0.903)</td>
</tr>
</tbody>
</table>

- using average tongue force, 15 able-bodied subjects
- student's t-test (p < 0.01), Pearson Correlation Coefficient shown in parenthesis.

3.4.2 ANALYSIS OF TONGUE FORCE DATA

3.4.2.1 TONGUE FORCE DATA OF ABLE-BODIED SUBJECTS

Examination of the mean tongue strength data, obtained using TOMS, revealed that the able-bodied, control subjects without any complaints of swallowing difficulties
exhibited a range of tongue strengths in each of the three tongue thrust directions (up, left, and right) (see Table 3.2), representing a relatively normal distribution (Figure 3.10). Upon comparison, it was also found that the mean lateral tongue strength of the able-bodied subjects were weaker (15-25%) than the upward tongue strength. Although a relatively small difference (12% maximum) in mean left and right directional tongue strength was measured (Table 3.2), analysis of individual subjects failed to indicate any definite pattern of unilateral strength.

**Table 3.2: Mean Tongue Strength Data of Various Subject Groups**

<table>
<thead>
<tr>
<th></th>
<th>Able-Bodied Subjects (n=15)</th>
<th>Post-polio Patients (n=25)</th>
<th>Stroke Patients (n=8)</th>
<th>MS patient (n=1)</th>
<th>ALS patient (n=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>σ</td>
<td>mean</td>
<td>σ</td>
<td>mean</td>
</tr>
<tr>
<td>Up</td>
<td>10.50</td>
<td>2.76</td>
<td>4.10</td>
<td>2.49</td>
<td>5.38</td>
</tr>
<tr>
<td>Left</td>
<td>9.04</td>
<td>3.34</td>
<td>3.95</td>
<td>2.60</td>
<td>3.48</td>
</tr>
<tr>
<td>Right</td>
<td>7.98</td>
<td>2.94</td>
<td>3.86</td>
<td>2.37</td>
<td>4.71</td>
</tr>
</tbody>
</table>

- unit is in Newtons
Meanwhile, tongue coordination was found to be excellent for all of the able-bodied subjects, showing only traces of tremor and fluctuations (<25% maximum force level = Fmax) in maintaining a steady, smooth tongue thrust during the non-cyclic tests in all three directions (see Figure 3.8b). It should be noted that the value of 25%
Fmax was chosen to be the dividing line between high and low levels of tongue coordination, as it indicated the critical level of tongue coordination observed based on TOMS results in subjects complaining of swallowing difficulty and those without any complaints. During the 5-second non-cyclic test, the subjects were able to exert and maintain a tongue thrust within 15% of the preset target force levels (Figure 3.8a). This was also true for the initial 10 second period of the 30-second non-cyclic test (Figure 3.8b). Although the tongue force levels declined gradually with time due to fatigue, significant tremors and fluctuations were still not observed. During the 30-second cyclic test, the able-bodied subjects were able to closely follow the required cyclic loading task (i.e., ± 15% target frequency), further confirming a high degree of tongue coordination (Figure 3.8c).

In terms of fatigue effects, the able-bodied subjects showed a range of force fatigue rates (change in force over time) during the 30-second non-cyclic test in all tongue thrust directions (See Table 3.3). The fatigue data generally indicated that there is a small drop (<25% Fmax) in tongue force level over the test duration. As for the frequency fatigue rate (change in cyclic frequency over time) during the 30-second cyclic test, all of the subjects were able to follow the cyclic target frequency (1 Hz) for the full test duration without showing signs of significant fatigue. In comparison to the patient data, able-bodied subjects generally exhibited larger (absolute) fatigue rates (Table 3.3); however, this should be viewed in terms of % change in tongue force and
frequency over time (relative fatigue rates) to indicate a true comparative means of fatigue. Relative fatigue rate comparison results in similar values for able-bodied and patient groups (15-30% drop in tongue force and frequency).

Table 3.3: Mean Tongue Force Fatigue Rates of Tested Subjects  
* a) Able-Bodied and Post-polio, b) Stroke and Others.

<table>
<thead>
<tr>
<th></th>
<th>Able-Bodied Subjects (n=15)</th>
<th>Post-polio Patients (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>force fatigue (N/sec)</td>
<td>freq'y fatigue (Hz)</td>
</tr>
<tr>
<td>Up</td>
<td>-0.11 ± 0.11</td>
<td>-0.03 ± 0.05</td>
</tr>
<tr>
<td>Left</td>
<td>-0.12 ± 0.09</td>
<td>-0.06 ± 0.04</td>
</tr>
<tr>
<td>Right</td>
<td>-0.11 ± 0.07</td>
<td>-0.06 ± 0.05</td>
</tr>
</tbody>
</table>

a)
Table 3.3 (continued)

<table>
<thead>
<tr>
<th></th>
<th>Stroke Patients (n=8)</th>
<th>MS Patient (n=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>force fatigue (N/sec)</td>
<td>force fatigue</td>
</tr>
<tr>
<td>Up</td>
<td>-0.07 ± 0.03</td>
<td>-0.25 ± 0.03</td>
</tr>
<tr>
<td>Left</td>
<td>-0.09 ± 0.04</td>
<td>-0.11 ± 0.02</td>
</tr>
<tr>
<td>Right</td>
<td>-0.05 ± 0.04</td>
<td>-0.17 ± 0.03</td>
</tr>
</tbody>
</table>

3.4.2.2 TONGUE FORCE DATA OF POST-POLIO PATIENTS

The post-polio patient group, like the able-bodied control group, exhibited a near normal distribution in the range of tongue strengths in all of the tested tongue thrust directions (see Table 3.2, Figure 3.10). However, this patient group (including patients with and without complaints of swallowing difficulty) had a significantly weaker mean tongue strength (Table 3.2), as is evident by their tongue strength distribution which overlaps only the lower value range of the able-bodied distribution (Figure
Similar to the able-bodied subjects' data, the mean lateral strengths of the post-polio patients were found to be slightly weaker (4-6%) than their upward strength. Analysis of individual post-polio lateral tongue strength data indicated an asymmetrical pattern with noticeable differences (>25%) observed between the left and right directional tongue strength in 11 of the 25 tested post-polio patients. This correlated well with the medical history and physical examination findings of these patients, whose orofacial/neck muscles were affected by their poliomyelitic condition, leading to unilateral weakness.

Tongue coordination of the post-polio patients was found to be generally poorer and much more variable in all tongue thrust directions, when compared to the able-bodied subjects. During the non-cyclic tests, they showed significant fluctuations (25-75% Fmax) in their attempts to exert and maintain a steady, smooth tongue thrust for the test duration (see Figure 3.11a). During the cyclic test, the post-polio patients also showed increased difficulty in performing the repeated loading task, often deviating from the preset target frequency during the measurement trial (Figure 3.11b).
TONGUE FORCE VS. TIME (PPS PATIENT)
NON-CYCCLIC 30-SECOND TEST, UPWARD FORCE

Figure 3.11: Tongue Force Data from a Post-Polio Patient; a) Non-Cyclic Test, b) Cyclic Test
The force fatigue rates of the post-polio patients for the 30-second tests in all tested directions were relatively similar in range to the able-bodied subjects' results (see Table 3.3). Both groups generally showed a small drop in tongue force level (<25% Fmax) over the test duration. The relative frequency fatigue rates, obtained from the cyclic tests, also corresponded to the range of values observed for the able-bodied subjects, showing minimal effects of fatigue on the cyclic loading task (Table 3.3).
3.4.2.3 TONGUE FORCE DATA OF STROKE PATIENTS

In comparison to the able-bodied and post-polio subject groups, the stroke patient group (all with varying degrees of swallowing difficulty) exhibited a much wider range of mean tongue strength for all test tongue thrust directions (see Table 3.2).

Figure 3.12: Mean Tongue Strength Distribution (Able-Bodied vs. Stroke Patients)
Instead of the relatively normal distributions observed with the two previous subject groups, the mean tongue strength data of the stroke patients were found to be scattered over the range of tongue force levels (Figure 3.12), i.e., with the lowest near 0 N and the highest comparable to the maximum tongue force level achieved by able-bodied subjects (near 15 N). The variability in mean tongue strength of this group correlated well with, and was reflective of, the level of recovery for each stroke patient as noted in their medical history. For example, patients who suffered a stroke attack recently (e.g., 2 weeks) showed a distinctly weaker tongue strength when compared to patients who had the stroke attack 8 weeks ago. Furthermore, one patient who was monitored over a period of 4 months using TOMS showed a continuous improvement in tongue strength from near 0 N (at 2 weeks since stroke onset) to 15 N (at 16 weeks since stroke onset). Generally, a stroke patient’s mean tongue strength, as expected, was weaker (see Table 3.2, Figure 3.12) than those of able-bodied subjects. In contrast to the other subject groups, the lateral tongue strengths observed in individual stroke patients were found to be highly asymmetrical (Figure 3.13). Identifiable differences in lateral tongue strengths (mean difference 27%) were noted, as the stroke-affected, weaker (hemiparetic) side of the body significantly diminished the tongue strength to that side. Even with the recovery of a certain amount of tongue strength over time, the asymmetry was still observed.
Tongue coordination of stroke patients in all tongue thrust directions was also found to be dependent on the individual patient's recovery stage since the stroke onset, i.e., the longer recovery time corresponded to improved tongue coordination based on TOMS results. In general, the stroke patients showed marked difficulty in the tongue control tasks required by the non-cyclic tests when compared to the able-bodied subjects. During these tests, the fluctuation in maintaining a steady, smooth
tongue thrust was found to be of greater magnitude (>25-75% Fmax). At the time of report, no cyclic data had been obtained for stroke patients.

The force fatigue rates calculated for the stroke patient group (in the 30-second non-cyclic tests) failed to reveal any distinct differences in comparison to the other subject groups' data (see Table 3.3). A majority of the patients revealed the pattern of a small decrease in tongue force level (<25% Fmax) over time as seen previously with other subject groups.

3.4.2.4 TONGUE FORCE DATA OF OTHER PATIENTS

For the single cases of the multiple sclerosis (MS, a 44 year-old female) and amyotrophic lateral sclerosis (ALS, a 63 year-old female) patients with potential swallowing difficulty, tongue strengths were found to be comparable to the able-bodied subjects' data in all of the tongue thrust directions (see Table 3.2). Similar to the able-bodied subjects, the mean lateral tongue strengths of the MS patient were weaker (<19-28%) than the mean upward tongue strength. In contrast, the ALS patient, tested using only the 5-second non-cyclic test due to time limitations, exhibited extremely high tongue strength levels (comparable to able-bodied mean tongue strengths). In these tests, the lateral tongue strengths were actually stronger than the upward tongue strength (Table 3.2). For both patients, no clear asymmetrical pattern
was observed between the left and right directional tongue strengths.

During the non-cyclic tests, the MS and ALS patients revealed lower levels of tongue coordination (>25% Fmax) compared to the able-bodied subjects in maintaining a smooth, steady tongue thrust over the test duration. However, during the 30-second cyclic test (MS patient only), the patient exhibited little difficulty following the cyclic loading task.

The calculated force fatigue rate (MS patient only) obtained from the 30-second non-cyclic test in all tested directions showed that this particular patient fatigued more markedly compared to the able-bodied subjects and other patient groups (see Table 3.3). On the other hand, the frequency fatigue rate (MS patient only) obtained from the 30-second cyclic test was comparable in value to those of able-bodied subjects (Table 3.3), indicating little fatigue effects on the cyclic loading task.

3.4.3 SENSITIVITY/SPECIFICITY OF TOMS

Finally, from the tongue force data of various subject groups obtained using TOMS, the sensitivity and specificity of TOMS in clinically evaluating tongue dysfunction (i.e., tongue weakness and/or lack of tongue coordination) were calculated and presented in Table 3.4. While the sensitivity denotes TOMS’ ability to positively
detect tongue dysfunction in patients with reported swallowing difficulty, the specificity denotes TOMS' ability to identify subjects without complaints of swallowing difficulty as having no tongue dysfunction.

Table 3.4: Sensitivity/Specificity of TOMS

<table>
<thead>
<tr>
<th></th>
<th>Presence of oral phase dysphagia</th>
<th>Absence of oral phase dysphagia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive diagnostic test</td>
<td>17  a</td>
<td>8 b</td>
</tr>
<tr>
<td>Negative diagnostic test</td>
<td>1  c</td>
<td>24 d</td>
</tr>
<tr>
<td>a+c</td>
<td>18</td>
<td>b+d 32</td>
</tr>
<tr>
<td>N = 50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sensitivity = \( \frac{a}{a+c} = \frac{17}{18} = 0.944 \)
Specificity = \( \frac{d}{b+d} = \frac{24}{32} = 0.75 \)
Thus, the high sensitivity (17/18) and specificity (24/32) of TOMS (n = 50) indicate the system’s potential as a clinical, diagnostic tool. It was also found that these results correlated well with the findings obtained from the subjects' medical history (questionnaire, n = 50) and a limited number of videofluoroscopy results (n = 2). The 8 subjects, who have been positively diagnosed with TOMS as having oral phase dysphagia but did not report any swallowing difficulty, may have tongue deficiencies without being aware of them. This shows TOMS’ potential in indicating and forewarning patients and clinicians of the impending dysphagic condition.

3.5 DISCUSSION OF TOMS

Many advantages over previous tongue force measurement methods can be observed through the use of TOMS. Components of the TOMS design, such as the tongue cup, the custom-fit dental impression pieces, and the adjustable mouthblock clearly assist in patient comfort and repeatability of the test data. Variations in individual orofacial anatomy are accommodated, and chance of clinical mishaps (e.g., slippage) are minimized. Instead of simulating Reddy’s long, flexible plastic beam transducer (isotonic) [159,160], the dimensions and material of the beam transducer were chosen to elicit a nearly isometric effort from the test subject, in a similar fashion to the current tongue strength resistance test. Also, the application of a target force level and instantaneous audio-visual feedback serves to focus the task at hand and
personalize the measurement procedure for each test subject. Often, individuals closed their eyes to further enhance their concentration levels.

TOMS' clinical testing experience has also provided additional improvements in its physical design and protocol. To remove the effect of any directional bias, it was noted that consecutive tongue force measurement trials should be conducted in the various tongue thrust directions in random order. It was also recognized that mean tongue force values should be used in tongue force data analysis instead of the maximal force values to remove any impulsive, singular peak values which may distort the true tongue force levels that are achieved. Furthermore, the similarity in test protocols between the 5-second non-cyclic test and the 30-second non-cyclic test led to the eventual replacement of the former by the latter test. Also, manual calibration tasks were replaced by an option in the TOMS' software to computerize the procedure.

A few issues of concern still remain in the clinical application of TOMS. First, TOMS unfortunately is confined to measuring only a lumped tongue force in three discrete force directions. Second, TOMS' trials are performed under a non-swallowing condition (i.e., with mouth open and no bolus introduced), which discredits TOMS' clinical validity as a true swallowing assessment tool. Third, a successful tongue force measurement requires a highly-concentrated, cognitive effort by the test subject.
Thus, some patients with neuromuscular dysfunctions (e.g., spasticity) experienced difficulties in performing the TOMS protocol. Based on the clinical tests, however, it was recognized that these drawbacks are not as critical as initially thought. For instance, instead of viewing the limitation of discrete tongue force measurement as a problem, it is seen as a lumped measure of the coordinated efforts of all lingual muscles presented in a much simpler manner than trying to isolate any particular muscle. In this manner, the three force directions were deemed sufficient to test all lingual muscles involved in the oral phase of swallowing, as the downward tongue force is of minimal importance during the swallowing process. As well, since it was initially theorized as a basis for TOMS' development, that tongue force measurements would be reflective of the individual swallowing (tongue) function regardless of the test protocol, the non-swallowing condition in which TOMS is utilized fails to become a significant factor. Lastly, the requirement for concentration and cognition for TOMS protocol can be viewed as an asset to assist in the clinical evaluation of the test subject's motor control and cognitive sense.

Overall, the clinical testing of TOMS has shown the system's functionality as an effective assessment tool for oral phase dysphagia with a potential to be used for treatment (therapy) purposes. Statistical analysis has revealed significant repeatability for within-day and day-to-day tongue force data of test subjects. TOMS' use of the tongue force as an indicator to individual oral swallowing functionality proved to be
successful, and the system was found to be highly effective in distinguishing the
tongue strength and coordination between able-bodied subjects and various dysphagic
patient groups. Interestingly, a few subjects without any complaints of swallowing
difficulty were also diagnosed as having tongue weakness and relatively poor levels
of tongue coordination. These subjects may not be aware of their potentially deficient
oral phase swallowing mechanisms, because of the existence of a compensatory
swallowing mechanism [20].

Figure 3.14: Tongue Force Data from Barlow [135] for Able-Bodied
Subject and Parkinson's Patient
On average, the able-bodied subjects exhibited significantly stronger tongue strengths and better tongue coordination than the patient groups. This agreed with findings from previous research [135] (see Figure 3.14). Also, upward tongue strengths were found to be usually stronger than the lateral tongue strengths, likely due to the frequency of upward tongue movements involved in the oral phase of swallowing. It was also apparent that tongue coordination plays a major role in the success of oral phase of swallowing, as all subjects with poor tongue coordination were found to have corresponding difficulty during the oral phase. All subjects with relatively weak tongue strength but good tongue coordination, reported no swallowing difficulty. Only a certain level of tongue strength, therefore, seems to be required for a proper swallow, if accompanied by a well-coordinated tongue movement. It was also noted, that the 30-second tests often proved to be more suited for identifying individual differences in tongue coordination and lateral tongue strengths, compared to the more transient 5-second tests.

While TOMS' sensitivity and specificity to tongue dysfunction (oral phase dysphagia) were comparable to those of carefully-conducted, bedside examination methods (80% sensitivity [144]), TOMS offers clear advantages in terms of quantification of results. In comparison with videofluoroscopy, TOMS represents a less invasive, harmless, quantitative method, which enables detailed analysis of the tongue function during the oral phase. It is envisioned that TOMS will continue to be
clinically tested with more subjects (able-bodied and patient groups), possibly in conjunction with these currently-used methods, to form a basis for improved assessment of oral phase swallowing mechanism and its associated disorders.
CHAPTER 4 VERIFICATION OF AN ORAL PHASE SUCTION MECHANISM

4.1 INTRODUCTION AND BACKGROUND

The second stage of the present investigation was an attempt to verify the presence of a suction mechanism during the oral phase of swallowing. It was expected that identification of such a mechanism and its contribution to the transport of bolus during the oral phase could be determined using oral/pharyngeal manometry. This segment follows the initial investigation using TOMS, which centers around the critical role of tongue strength and coordination in propelling a bolus by means of positive lingual pressure exerted against the palate. The suction hypothesis was based on the principle that various seals are established and broken during the swallowing process within the oral cavity and oropharynx [21,68] (see Figure 4.1), suggesting the possible formation of pressure gradients that might be sufficient to propel a bolus.

Research into the role of suction pressure in the transport of a bolus during the oral phase has been virtually non-existent (see CHAPTER 2.6), as pressure/suction measurements have been limited to the pharyngeal and esophageal regions. The reason for the neglect of oral manometry is attributable to its technical and clinical difficulties, compared to the ease and confidence in the well-established manometric techniques and experience for the pharyngeal and esophageal regions. As noted
earlier (CHAPTER 2.6), previous pharyngeal manometric studies [79-83,172,234,236] positively identified a negative pressure gradient that is formed from the upper pharynx down to the upper esophagus during the swallowing process (Figure 2.31-2.33). Positive manometric pressure peaks were recorded near the upper pharynx due to the posterior movement of the tongue against the posterior pharyngeal wall (see APPENDIX A for swallowing physiology), while simultaneous negative pressures were recorded near the upper esophagus due to a sudden relaxation of the pharyngoesophageal sphincter from its contracted tonic state. While manometric studies have generally agreed in identifying various positive pressure waves (e, t, p waves - see CHAPTER 2.6), disagreements still exist over the contribution of the negative (suction) pressure gradient in pharyngeal bolus transport.

Based on the reported pharyngeal manometric measurements, any existing oral phase suction mechanism was expected to be related to the aforementioned pharyngeal suction mechanism, whereby the pharyngeal negative pressure gradient reaches superiorly into the oral cavity. Moreover, the oral phase suction mechanism was expected to occur near the junction between the oral cavity and the pharynx, where two significant swallowing events occur. At this point in the swallowing process, the peripheral seal that is formed around the bolus during the preparatory segment of the oral phase is broken posteriorly (i.e., separation of the soft palate from the posterior segment of the tongue), allowing easy bolus passage into the pharynx.
In addition, the propulsive segment of the oral phase is initiated with the tongue pushing up against the palate and squeezing the bolus posteriorly. It was thus theorized that the combination of these two events could lead to the formation of a significant negative pressure gradient (i.e., positive tongue pressure applied behind the bolus and sudden expansion of lumen ahead of the bolus). By being able to
identify the oral phase suction mechanism and distinguish it from the traditionally accepted tongue pressure propulsive mechanism, clinical applications may be found in the evaluation of a dysphagic patient and the recommendation of an appropriate treatment procedure.

4.2 EXPERIMENTAL TESTING

To investigate the hypothesis that suction assists in bolus propulsion, two experimental setups were proposed. These included a newly developed suction pressure measurement system (System #1 - see Figure 4.2) and a standard intraluminal manometry system (System #2 - see Figure 2.10). The latter setup was made available by the Gastroenterology (GE) Clinic at the University Hospital (UBC). The purpose of these measurement systems were to accurately record the manometric data during both the oral and pharyngeal phases of swallowing, with particular focus on negative pressure gradients that are formed. By introducing the transducer catheters through the mouth in contrast to the commonly practised nasal insertion, verification of the oral suction mechanism was expected. Unfortunately, when initial attempts with the first setup (System #1) proved to be unsuccessful due to deficiencies in transducer design and signal processing (see CHAPTER 4.3.1), the intraluminal manometry protocol had to be exclusively used to obtain manometric data.
However, due to the extensive effort and time that were invested, as well as important, clinical observations that were made during experimental testing, both measurement systems are described here for reference.

4.2.1 MANOMETRIC MEASUREMENT SYSTEM #1

4.2.1.1 SETUP - SYSTEM #1

The first suction pressure measurement system (see Figure 4.2) utilized a

Figure 4.2: Newly Developed Manometry Setup
strain gauge air pressure transducer (Cobe), developed and donated by Professor N.P. Reddy (University of Akron) to measure positive and negative air pressure during the oral phase of swallowing. Professor Reddy had previously used the transducer to measure the lip suction created when sucking a liquid through a straw [159,160]. For the purpose of the present research, the transducer was connected to a fine-diameter (<2mm), clear, flexible tube (Tygon) that was fed into the subject's mouth. The small size allowed the subject to easily close one's mouth around the tube, as well as to create a lingual seal around the bolus against the palate in a preparatory position during the oral phase. The subject's swallowing mechanism would thus be minimally affected by the presence of the tube.

Measured voltage changes (manometric pressure) from the transducer were then amplified and transmitted to an analog-to-digital converter, residing in an IBM PC/XT. A customized software program was developed to facilitate data acquisition and file management in a similar manner to TOMS. Once the existence of an oral phase suction mechanism could be established, its contribution and importance to the bolus transport would be determined by removing the suction effect. This was achieved by slowly feeding positive pressure air into the oral cavity through a second, small tube (<2mm diameter) connected to a medical air tank, equipped with a flow rate regulator and pressure gauge. The air input was expected to indicate a subject's ability to swallow even with one's oral phase suction disabled by the incoming air. It
was theorized that the positive pressure air input would cancel out any negative pressure gradients formed within the oral cavity during the propulsive segment of the oral phase.

4.2.1.2 PROCEDURE - SYSTEM #1

For the first suction pressure measurement system, the data measurement protocol consisted of three trials measured at each of the three standardized locations along the dorsal length of the tongue, e.g., front, middle, and back of the tongue. The back location corresponded to the junction between the oral cavity and the oropharynx (i.e., the oral-pharyngeal junction). Tape markings were made on the tube for locating these reference positions, with the assumption that the subjects' variability in oral, anatomical dimensions were relatively small. The trials were of three seconds in duration, in which time the subjects were asked to perform a "regular" saliva swallow. The choice of a three-second duration allowed for some lag in the response while still capturing the full range of swallowing activities during the oral phase (i.e., duration of the oral phase < 1 sec. [55]). In order to trigger swallows, subjects were instructed to prepare themselves, such that upon notice, they were ready to promptly start the swallowing process. The manometric data at each dorsal location along the tongue were averaged for 3 trials, and these values were then stored in a data file for future analysis.
4.2.2 MANOMETRIC MEASUREMENT SYSTEM #2

4.2.2.1 SETUP - SYSTEM #2

The second suction pressure measurement system (see Figure 2.10) utilized the traditional intraluminal manometry technique. Using a standard hydraulic capillary water manometer unit (Beckman Model 4-727 I), pressure measurements were obtained through a multi-tube (3) catheter with laterally oriented sensors, located at 50 mm intervals. The sensors were connected to externally located pressure transducers which employed strain gauges to measure the manometric data. The measurement system's catheter was water-infused to prevent it from being obstructed by accumulated saliva. Finally, the manometric data from the 3 sensors were graphed on a chart using a dynagraph/recorder (Beckman Model R611), running at 50 mm/sec.

4.2.2.2 PROCEDURE - SYSTEM #2

For the second suction pressure measurement system, the manometric transducer catheter was inserted orally and pressure data were recorded at various levels from the central oral cavity down to the pharyngoesophageal sphincter level (3-20 cm from the incisors). 20 saliva swallows were performed for analysis during each of the two separate visits. Local throat anesthetic spray was used to prevent gagging
reflexes during the tests.

4.2.3 SUBJECTS (SYSTEM #1, #2)

Initially, 3 able-bodied male subjects, ranging in age from 20 to 24, were tested employing System #1. Further clinical testing of System #1 was discontinued after encountering technical difficulties (see CHAPTER 4.3). Due to the invasive, uncomfortable nature of the intraluminal manometry protocol which easily induced gagging reflexes, only one volunteering subject (24-year old, able-bodied male) was tested for the second segment of this investigation.

4.3 RESULTS AND DATA ANALYSIS

4.3.1 SYSTEM #1

During the experimental testing of the newly-developed oral-pharyngeal manometric setup (System #1), two previously-known sources of suction pressure [32,63,67,87] were identified during the oral phase through clinical observation: One was lingual suction produced as the tongue "sucked" the bolus against the palate, thus creating a high pressure, peripheral seal around the bolus (see Figure 4.3). This suction was found to alter the preparatory position of the bolus prior to the propulsive
segment with the bolus being held further back in the oral cavity between the posterior segment of the hard palate and the tongue. This was expected to result in a swallow that required less tongue thrust, because the bolus now had to travel a shorter distance to the back of the mouth (Figure 4.3a). However, when one attempted to initiate a swallow, the high pressure, lingual seal could not be maintained and had to be partially relieved in order to facilitate the oral phase. Thus, lingual suction appeared to be an insignificant factor in the actual bolus propulsion during the oral phase.
Another possible source of suction came from the buccal-labial (cheek-lip) musculature (Figure 4.3b), i.e., as in sucking a fluid through a straw, where the formation of a labial seal was required. It was observed that this mechanism only served to ingest a (semi) fluid bolus and contributed little to the oral phase propulsive mechanism.

Unfortunately, after initial experiments with 3 able-bodied subjects, several critical flaws were detected in the newly-developed manometric setup and protocol (System #1). Technical difficulties, such as saliva clearance from the small tubes, tendency to occlude the tubes with teeth and lips, and the inadequacy of the pressure transducer (e.g. problems of output signal magnitude and drift) all forced the abandoning of System #1 without useful results. Instead, the standard manometric setup of System #2 was utilized to provide the most reliable measure of swallowing pressures.

4.3.2 SYSTEM #2

The swallowing manometric data, obtained using the standard manometry setup (System #2), failed to indicate the existence of a suction mechanism in the actual propulsion of the bolus during the oral phase.
Distance from front incisors (mm)

- From Sokol et al (1966)
- From Lee et al (1991)

Figure 4.4: Manometric Data (Able-Bodied); a) Sokol et al [234], b) Results from this research
As seen from Figure 4.4, the manometric data showed that no significant negative pressures were recorded near the critical oral-pharyngeal junction (i.e., 8-11 cm from the incisors), at any time during the swallowing process. The recorded manometric data from this site exhibited relatively similar manometric pressure patterns, as those recorded by Sokol et al [234] and McConnel [79-83] (see Figure 2.33).

At the oral-pharyngeal junction, the patterns revealed a single positive peak of small magnitude (<100 mmHg - Figure 4.4), which resulted from the pressure exerted by the tongue against the soft palate during the transition from lingual (oral phase) to pharyngeal peristalsis (i.e., a form of p wave - see CHAPTER 2.6). The e wave did not appear, indicating that the elevation of laryngeal structures did not affect this region. The t wave was also missing, since this junction was located slightly superior to the t wave source (i.e., the back of the tongue acting against the posterior pharyngeal wall). In the oral cavity, positive pressure peaks were mostly observed, and the only negative pressure components were in the form of small "dips" (<5 mmHg - Figure 4.4), which were probably caused by sudden initial or concluding movements of swallowing structures before or after bolus (pressure wave) passage. These were found to be not of any significance in the active bolus propulsion. The relaxation of the pharyngoesophageal sphincter (20 cm from incisors) and the simultaneous thrust by the posterior segment of the tongue against the posterior...
pharyngeal wall (10-13 cm from incisors) resulted in a negative pressure gradient of 100 mmHg (Figure 4.4), and were comparable to other investigators' results [79-83, 172, 234, 235]. As expected in comparing to Sokol et al [234] and McConnel [79-83], the standard manometric pressure patterns involving the elevation, tongue, and peristalsis (e, t, p) waves were all observed at various locations, with p waves being the largest in magnitude (100+ mmHg - Figure 4.4).

4.4. DISCUSSION OF ORAL PHASE SUCTION MECHANISM

There has not been a uniformly accepted explanation for the role that suction plays in the oral phase propulsion of a bolus. Applying the intraluminal manometry technique to the oral phase, especially to measure swallowing pressures at the oral-pharyngeal junction, showed that positive lingual pressures played an integral part in propelling the bolus from the oral cavity to the oropharynx. The negative pressure gradient, observed through the pharynx and the upper esophagus, only served to rapidly transfer the bolus (i.e., saliva, liquid) during the pharyngeal phase, but it did not affect the bolus transport during the oral phase. The gradient was only effective within the zone bounded by the pharyngoesophageal sphincter distally and the level of the posterior segment of the tongue (oropharynx) proximally. The hypothesized oral phase suction mechanism was not observed, since the effect of this large, negative pressure gradient did not continue into the oral cavity and coincide with the
onset of the propulsive segment of the oral phase (i.e., the breaking of the velolinguinal seal by the downward and forward movement of the back of the tongue away from the soft palate).

Thus, the widely-accepted view of pharyngeal peristaltic activity as the main propulsive agent for the transport of a solid bolus, is supported in this investigation. This slower, muscular activity appears to be essential in transporting the more difficult, especially larger solid boluses. Although the two aforementioned bolus transport mechanisms (pharyngeal peristalsis and suction) are distinctly different, they can be traced back to a common reference point. Namely, the posterior thrust of the back of the tongue against the posterior pharyngeal wall (t wave) signifies the start of the pharyngeal peristaltic activity, and it also provides the positive pressure component in the formation of the negative pressure gradient.

Despite the affirmative indications for the absence of a critical, oral suction mechanism, the results of this manometry experiment have to be carefully interpreted. Foremost, this experiment did not use high fidelity manometry equipment, as advocated by Dodds and others [46,56,174] for optimal pharyngeal manometry. In addition, the catheter sensors were oriented radially rather than distally, which made the recordings subject to directional variations. However, it was shown that the recorded pressure data throughout the pharyngeal lumen were comparable to other
investigators' results. And for this investigation, this conventional manometry setup (System #2) was deemed adequate to provide data for the verification of the hypothetical suction mechanism (i.e., a large negative pressure gradient). The manometric data obtained, although limited to a single able-bodied subject, combined with noted previous investigation results [56,81,172,234] and the additional manometric data supplied by the GE Clinic at the University Hospital, proved sufficient for such "verification" purposes. The present investigation's approach in introducing the manometry transducer catheter orally allowed for a rare observation of manometric data in the oral phase of the swallowing process.
CHAPTER 5  ORAL CAVITY PRESSURE TRANSUDER SYSTEM (OPTRANS)

5.1 INTRODUCTION AND BACKGROUND

The final stage of the present investigation into the oral phase swallowing mechanism and its associated disorders consisted of the development of an Oral Cavity Pressure Transducer System (OPTRANS - see Figure 5.1).

Figure 5.1: OPTRANS Setup; a) Mouthguard Transducer, b) Measurement System
Figure 5.1 (continued)
The OPTRANS system is based on a modified mouthguard unit with a network of FSR's (force sensing resistors - Interlink Inc.), placed in a pattern to measure the palatal pressure distribution generated by the tongue acting against the palate during the oral phase of swallowing. This sensor design not only allows the system to reliably measure tongue pressure exerted against the palate in the act of swallowing but also provides the opportunity to indirectly monitor tongue coordination (positioning). Like the previously described TOMS, the design of OPTRANS is optimized for clinical safety, patient comfort, and test data repeatability. It also incorporates the use of a microcomputer for valuable audio-visual feedback, fast and precise data acquisition, and clinical ease of use.

OPTRANS is the obvious "successor" to TOMS in the study of the lingual propulsive mechanism of the bolus in the oral phase. Although TOMS addresses many of the technical and clinical shortcomings of past investigations (See CHAPTER 3), it still possesses a few inherent problems (e.g., the non-swallowing condition under which TOMS' tests are conducted). OPTRANS is designed to address some of these shortcomings, thereby complementing TOMS and other existing assessment protocols. OPTRANS appears to be the ideal, quantitative method of evaluation to complement the current ultrasound method, which is primarily used to visualize tongue function during the oral phase, with corresponding analytical capabilities of capturing the swallowing process (in terms of palatal pressure for OPTRANS and visual images for
ORAL CAVITY PRESSURE MEASUREMENT

ultrasound) at specified time intervals (frame-by-frame analysis)(see CHAPTER 2.3). The system also has potential for practical therapy applications in tongue strengthening and coordination exercises.

As previously discussed in CHAPTER 2, the concept of measuring palatal pressure has been studied by only a few researchers, most notably by the research teams led by Proffit [216-219] and Kydd [211,212]. Both researchers employed customized palatal restrainers with small mounted strain gauges (cantilever beam type sensor), that were placed onto discrete locations on the palate (See Figure 2.23, 2.24, 5.2). They conducted tests with limited application as to the effects of bolus consistency or size and concentrated mainly on obtaining maximum pressure values rather than the full palatal pressure profile during the oral phase.

![Figure 5.2: Palatal Pressure Distribution by Proffit [219]](image-url)
At the time performed, these studies with limited clinical data and data analysis did not have the benefits of using high performance microcomputers which currently allow for superior measurement setups.

OPTRANS represents an improved method of analysis, whereby the full palatal pressure profile at any given time and location can be obtained. The transducer system thus facilitates the accurate assessment of any tongue deficiencies (e.g., lack of appropriate tongue thrust levels and mispositioning of the tongue) during the oral phase of swallowing.

5.2 DEVELOPMENT OF OPTRANS

The core of OPTRANS is the mouthguard transducer, a modified mouthguard supplied by Vanguard Inc., with a network of ten 1/4 inch circular FSR’s fitted over the palatal region (See Figure 5.1,5.3). Initially, the mouthguard is flattened, after softening it in boiling water, to a very thin layer (< 1 mm) and then reshaped using a prefabricated orthodontic impression of a "flat" palatal arch. The thin FSR’s are then placed onto the lingual (facing the tongue) side of the mouthguard palate in a standardized pattern (See Figure 5.1, 5.3) to obtain the most revealing pressure profile.
Figure 5.3: Schematic of OPTRANS

ORAL CAVITY PRESSURE

TRANSDUCER SYSTEM

ORAL CAVITY PRESSURE MEASUREMENT
Force sensing resistors (FSR) are comprised of two thin polymer sheets (total thickness < 0.5 mm) laminated together, where one sheet is coated with interdigitating electrodes and the other with semiconductive material. With a load applied normally to the FSR surface, the semiconductive material shunts the interdigitating electrodes to various degrees, thereby decreasing in resistance with any increase in applied load. The two sheets are held together by thin spacer adhesives around the edges except for a small air gap near the terminal ends of the FSR. The small air gap allows clear separation between the two sheets when no load is applied, as well as nearly instantaneous response when a small load is detected. Electrical connections are achieved by means of solder tabs attached to the FSR terminals. FSR's show relatively good repeatability, mechanical-, electrical characteristics (See APPENDIX E) for the purpose of OPTRANS application.

The terminal ends of the FSR's are pushed through slits made on the mouthguard palate to the palatal (upper) side. Thin wires (32 gauge) are soldered onto the solder tabs of the FSR, linking the sensors to two small, customized printed circuit boards (See Figure 5.3). The thin (1 mm) circuit boards, which are inserted through a slit made at the front of the mouthguard, provide structural rigidity to the transducer unit and external connection for pressure signal output. During the actual pressure measurement, the boards' small size causes only a slight parting of the lips; thus minimally affecting the swallowing process. The boards' shape also provides
adequate strain relief at the front edge of the mouthguard (Figure 5.3). The board is externally connected to a ribbon cable 30 mm in front of the leading edge of the mouthguard using small pin connectors. The mouthguard transducer is completed by attaching an overlayer of mouthguard material (i.e., flattened sheet) on the upper side of the mouthguard to enclose the transducer circuitry. The entire transducer unit, up to and including the external connections to the ribbon cable, is then coated with a thin layer of transparent dental impression gel (Viscogel) to provide water and chemical resistance. Further precautions to ensure patient safety and transducer protection are provided by using silicone rubber sealant and applied heat to seal the mouthguard. In order to facilitate multiple subject measurement sessions in a day, three mouthguard transducer units, as described above, are pre-assembled prior to clinical testing.

The resistance output from FSR's is transmitted via connected wires, printed circuit boards, pin connectors, and ribbon cables directly to a custom-built data acquisition board (Figure 5.4) residing in an IBM compatible 386 microcomputer. The input signals into the data acquisition system consisting of a 16-channel multiplexer, amplifier, analog-to-digital converter, and other signal processing circuitry are then sampled using a customized software program, which either stores the data in a file, or displays it on the screen. The signal processing circuitry is designed to provide optimal sensitivity and resolution of the pressure data from the FSR's.
Figure 5.4: Signal Processing Circuitry of OPTRANS

5.3 CLINICAL TESTING OF OPTRANS

5.3.1 TESTING PROTOCOL

As with TOMS, the clinical testing protocol for OPTRANS follows four steps: 1) calibration of OPTRANS, 2) questionnaire and customization of OPTRANS, 3) actual
palatal pressure measurement, and 4) transducer sterilization. Completion of the protocol requires around 30 minutes. These steps are described in the following paragraphs.

5.3.1.1 CALIBRATION OF OPTRANS

Before each palatal pressure measurement session, OPTRANS is calibrated utilizing a 1.6 m (6 ft) column of water as a reference pressure source, providing a maximum calibration pressure of 15.7 kPa. The column of water is stored in a 127 mm (5 inch) diameter, hollow plexiglass cylinder with one end sealed and the depths graduated along the cylinder height (Figure 5.1b). The cylinder is placed in a level aluminium base for stability. The available height of water column was initially estimated to be sufficient for this study's purpose, based on previously recorded maximal swallowing pressure values mentioned in the literature (90 mmHg = 12.0 kPa [219]). This method of calibration differs from those used by Proffit [216-219] and Kydd [211,212], whose techniques employed air chamber or air bladder (see Figure 2.24), respectively, to apply calibrated pressures on rigid palatal restrainer type transducers. Proffit's technique of placing just the actual sensing portion of the transducer and fitting it over one end of a pressure regulated air chamber would present problems in OPTRANS application due to the elasticity of the mouthguard material. Kydd's method of calibration, employing a pliable air bladder which is held
within a fixed chamber and then pressurized, would overcome Proffit's problem. However, his claim that he was able to obtain uniform pressure distribution is questionable over an irregular contour such as the palate. Although the water column calibration used in this research involves a comparatively less refined technique, it was seen as a functional prototype method of calibration.

In order to perform the actual sensor calibration for this study, the mouthguard transducer and the connected ribbon cable (3 m in length) are dropped using a hanging weight (800 g) attached to a guiding rod to preset depths at 50 mm intervals. At each interval, marked off along the height of the cylinder, the pressure values from the ten sensors are sampled nearly simultaneously by means of the OPTRANS software, thereby creating a calibration table (See Table 5.1). The creation of a calibration table is necessary to deal with the non-linearity of the FSR's, as seen in APPENDIX E. Calibration is required for each measurement session, and either an updated calibration table can be created or the most recent calibration table can be recalled at the beginning of each session.
5.3.1.2 SUBJECT QUESTIONNAIRE AND CUSTOMIZATION OF Optrans

Once calibration is completed, the questionnaire and customization session is conducted in a similar manner to TOMS (See CHAPTER 3). While the questionnaire
segment is identical to TOMS (i.e., consent forms, medical/swallowing history), OPTRANS requires a different customization procedure to accommodate the variation in dental and palatal shape found in test subjects. A comfortable and relatively accurate fit is imperative to allow the test subjects to perform swallows that follow their "usual" swallowing patterns and thus avoid any variation resulting from the presence of the transducer. This is achieved by filling the upper side of the mouthguard transducer with dental impression material (Dentsply Jetrate Plus) and fitting the mouthguard onto the subjects' palate. Then, by pushing the transducer firmly against the palate, the dental impression material deforms to fill in any void space between the transducer and the palate/dentition, thus providing a tight fit. After the impression material sets for 5 minutes, palatal pressure measurements can then be conducted.

5.3.1.3 PALATAL PRESSURE MEASUREMENT

Similar to TOMS protocol, the OPTRANS measurement protocol is based on a menu-driven software program which provides accurate, high-speed data acquisition and storage plus other options. Of note, an assembler language procedure, utilizing Turbo Assembler, is incorporated to allow for nearly instantaneous sampling of signals from the 10 FSR's at a frequency of 50 Hz. OPTRANS' main program also creates, modifies, and stores patient and visit records for each test subject, while calibration and data analysis options are also available. Using the data analysis option, palatal
pressure data can be analyzed on a frame-by-frame or sensor-by-sensor basis, involving a 3-dimensional color graphics capability (See Figure 5.5). The frame-by-frame analysis, showing the pressure distribution across the FSR network at given time frame, can be performed on a continuous (i.e., moving frames - Figure 5.5) or individual frame basis. The sensor-by-sensor analysis allows for a number of sensors (five maximum) to be analyzed simultaneously (Figure 5.5).

Figure 5.5: Graphical Analysis of OPTRANS Data
The actual pressure measurement test protocol used is comprised of two trials, each lasting 5 seconds in duration. This duration provides ample time for the subject to produce a successful, representative swallow. In preparation of the measurement, a bolus of defined size and consistency is placed onto the forepart of the tongue, and the subjects are asked to close their mouths and hold the bolus in the resting position (i.e., tongue resting on the floor of the mouth and not touching the palate). The subjects are given an audio cue at the start of the trial, instructed to perform a single swallow in 5 seconds without chewing, and then given another audio cue to denote the end of the trial. Swallows involving different bolus sizes (10, 20, 30 mL) and consistencies (saliva - dry, liquid, paste, solid) are tested. The dry swallow does not involve an introduced bolus, but instead, the subject is required to "dry" swallow without the aid of saliva. While one specific type of swallow can be tested using OPTRANS, a complete set of measurement was recognized as consisting of two trials of saliva, liquid (10, 20 mL), and paste (10, 20 mL) swallows (i.e., ten swallows in total). 30 seconds are provided for rest between trials in order to prevent fatigue. Appropriate bolus size and consistency are selected for testing subjects exhibiting signs of dysphagia such as the presence of aspiration identified during the subject questionnaire session.
5.3.1.4 TRANSDUCER STERILIZATION

Finally, the OPTRANS transducer is subjected to a rigorous cleaning (disinfecting) process, identical to that of TOMS. The procedure consists of a liquid soap wash/rinse step, followed by a cold sterilant (Coldspore) bath/rinse step. The transducer is cleaned immediately after a test session in preparation for the next test session.

5.3.2 SUBJECTS

Only preliminary data have been taken with OPTRANS from 3 able-bodied subjects for repeatability analysis of the palatal pressure data. The subjects consisted of 3 males ranging in age from 20 to 26, and all of them did not report any swallowing difficulties.

5.4 RESULTS AND DATA ANALYSIS

5.4.1 REPEATABILITY OF OPTRANS’ DATA

Utilizing the recorded palatal pressure data obtained from 3 able-bodied subjects, the repeatability of OPTRANS’ data was initially verified prior to any clinical
testing of the system on patients.

Table 5.2: Repeatability of OPTRANS' Data

- using the maximum palatal pressure obtained during a dry swallow at four sensors, for 3 able-bodied subjects
- student's t-test (p < 0.01), Pearson Correlation Coefficient shown in parenthesis

<table>
<thead>
<tr>
<th>Sensor #</th>
<th>1</th>
<th>5</th>
<th>7</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within-day</td>
<td>0.479</td>
<td>-0.280</td>
<td>-0.438</td>
<td>-0.287</td>
</tr>
<tr>
<td></td>
<td>(0.502)</td>
<td>(0.521)</td>
<td>(0.769)</td>
<td>(0.828)</td>
</tr>
</tbody>
</table>

The maximum pressure values generated by the tongue against sensors 1, 5, 7, and 9 (see Figure 5.3) during the swallow were analyzed for within-day repeatability using a paired student's t-test (p < 0.01). These sensors were selected on the basis of their distinct palatal locations (front, back, left, and right). Table 5.2 shows that the t-test failed to reject the Ho hypothesis (Ho: $\mu_1 = \mu_t$), thus indicating no difference for within-day pressure values. The calculated Pearson Correlation Coefficients (0.5-0.82)
further indicate a relatively high level of repeatability in OPTRANS data.

5.4.2 ANALYSIS OF PALATAL PRESSURE DATA

Figure 5.6, shows the frame-by-frame palatal pressure profiles, generated by an able-bodied subject in performing a saliva swallow. The tongue was firstly raised to the alveolar ridge, just behind the upper front incisors (sensor 1,5,7) and then pushed progressively against the palate in a manner of a distally moving wave. As the anterior segment of the tongue moved upwards towards the palate, the posterior segment was found to exert minimal pressure on the palate, which correlates well with the separation of the soft palate and the posterior segment of the tongue to allow the bolus to pass easily into the pharynx. Maximum pressures were produced at sensor 1 (anterior center of palate), while smaller maximum pressure values were recorded (< 25% difference in magnitude) at the laterally and posteriorly located sensors.
Figure 5.6: Frame-by-Frame Analysis of a Normal Swallow (Able-Bodied); a) Time Frame 1, b) Frame 6, c) Frame 12, d) Frame 18
Corresponding to the repeatability results, the test subjects were able to exhibit repeatable swallowing patterns regardless of bolus volume or consistency. Although individual differences in palatal pressure values were observed, increase in bolus volume generally resulted in higher swallowing pressures (20-30% increase from 10-30 mL bolus) (see Figure 5.7).

**Figure 5.7: Effect of Bolus Volume on Swallowing Pressure**
This correlates well with clinical observations that more effort is required in swallowing a larger bolus. In comparison, variation in bolus consistency (Figure 5.8)
did not indicate a clear pattern with regards to swallowing pressures. However, saliva and liquid swallows generally resulted in lower swallowing pressures (5-15%) than a solid bolus.

5.5 DISCUSSION OF OPTRANS

The design and development of OPTRANS overcomes many of the limitations and problems that were observed in TOMS and experienced by previous investigators in measuring oral phase biomechanical parameters. For example, OPTRANS testing is conducted under actual swallowing conditions using a bolus, allowing the quantification of a true swallowing parameter. The bolus can be varied in size and consistency, depending on the information desired. Either a "stress" test can be performed using a large, difficult-to-swallow bolus to elicit swallowing deficiencies, or a "safe" bolus can be used to reduce the possibility of aspiration and other harmful effects during clinical testing. As mentioned in CHAPTER 3, tongue force measurement using TOMS is limited to a single, discrete tongue force vector during a trial. In comparison, OPTRANS is able to generate the full swallowing pressure pattern, simultaneously indicating multiple load vectors, for the oral phase of swallowing. The network of ten FSR's provides significantly more information on palatal pressure distribution compared to the 3-5 sensors used by Proffit [216-219] and Kydd [211,212]. The comfort of the test subject is ensured by using a minimally
transducer along with the use of dental impression material. Finally, OPTRANS requires minimal concentration and cognitive ability on the part of the test subject, who is only instructed to perform a normal, simple swallow during the measurement trial. This relatively effortless protocol reduces or eliminates any concerns regarding physical and mental fatigue.

Despite all of these advantages in using OPTRANS for the assessment of oral phase swallowing mechanism, some disadvantages still exist. The required effort and time to properly construct a transducer unit is currently a major problem, especially if individuals are to be fitted with their own customized mouthguard transducer. If palatal restrainers are desired for maximum custom-fit and sturdier transducers in the future, external assistance from dentists and orthodontists is required. Although the mouthguard transducer units are more than sufficient for prototype purposes, their reliability is of some concern if they are to see regular clinical use. Of particular concern are the connections between the individual components (e.g., FSR, solder tabs, wires, and printed circuit board) and the technical limitation of the FSR (e.g., problem with the curved contour of the mouthguard palate). Of utmost importance to OPTRANS' reliability is the protection of the transducer from water and saliva and its disinfection in between test subject use. These two tasks require maximum care on the part of the clinician.
The clinical testing of OPTRANS has confirmed the system's capability to aid in the evaluation of oral phase dysphagia. Statistical analysis of palatal pressure data obtained from able-bodied subjects resulted in significantly high levels of within-day repeatability. Although the test subject sample data was limited, OPTRANS was able to clearly indicate normal swallowing palatal pressure pattern. It is expected that clinical differences would appear in pressure patterns during the oral phase between the able-bodied subjects and dysphagic patients (e.g., weaker pressure values and variations in swallowing patterns - asymmetrical behaviour).

In comparison to the widely used videofluoroscopy, OPTRANS represents a less invasive, more comfortable technique of assessment without the dangers of radiation exposure. It is superior to both, videofluoroscopy and ultrasound, in quantifying tongue force and movement, and in "3-dimensional" visualization (VF and US employ 2-dimensional slices). Prospects of utilizing OPTRANS with its frame-by-frame analysis capabilities in conjunction with the other evaluation techniques are excellent. In a similar manner to TOMS, this evaluation method appears to have wider application such as in monitoring tongue function for recovering patients, as well as in their treatment through tongue strengthening and coordination exercises.
CHAPTER 6 GENERAL DISCUSSION OF EXPERIMENTAL RESULTS

The three stages of this investigation, as outlined in the previous chapters, have combined to generate a much clearer understanding of the oral phase of swallowing and its associated disorders. The investigation has led to the development of new devices and clinical methods, which enable accurate assessment of individual swallowing function. As well, the investigation has provided meaningful information regarding normal oral phase swallowing physiology.

6.1 DEVELOPMENT OF NEW CLINICAL METHODS

Three new clinical methods of assessment for oral phase swallowing mechanism have been developed corresponding to the three experimental stages of this investigation. Two of these methods involved the development of new transducer systems (TOMS and OPTRANS), which effectively utilize tongue force/pressure as a suitable parameter to reflect individual swallowing function. A third method of assessment involved the development of a pressure transducer system, capable of measuring the manometric swallowing pressures during the oral phase. Due to technical difficulty in transducer setup, however, this method was replaced by a well-established pharyngeal intraluminal manometry setup.
In developing TOMS and OPTRANS systems, every effort was made to improve on previous attempts at quantifying tongue biomechanics and addressing the shortcomings of current techniques of evaluation of oral phase swallowing mechanism and treatment of its associated disorders. As noted previously in CHAPTER 2, OPTRANS was built to complement and improve upon the previously developed TOMS. The development of both systems paid close attention to the limiting constraints, which exist when dealing with the soft tissues (e.g., tongue) of the oral environment, the variability of individual oral anatomy, the need for transducer protection (i.e., from water, saliva entry), and the safety of the test subjects (i.e., disinfecting of transducers). In designing efficient clinical devices, low-cost and clinically user-friendly solutions were considered (e.g., computer-aided with graphical or audio-visual feedback). Additional steps to optimize the systems included standardization of test protocol and patient comfort (e.g., use of dental supplies).

As mentioned in CHAPTERS 3 and 5, TOMS and OPTRANS have been shown to be reliable in facilitating the quantitative analysis of the oral phase of swallowing. Both systems can be clinically implemented in a diagnostic role during the initial assessment of possible dysphagic patients, for instance, replacing the tongue blade depressor resistance test (tongue strength) during the physical examination segment of the evaluation. Another application for these systems may involve the continuous monitoring of tongue (swallowing) function in patients recovering from neuromuscular
6.2 ORAL PHASE SWALLOWING MECHANISM AND DYSPHAGIA

Besides developing new, quantitative methods of assessment for oral phase dysphagia, one of the goals of this research was to obtain a better understanding of the swallowing physiology. With the emphasis being placed on the oral phase for this investigation, a major portion of research revolved around the role of the tongue in controlling and propelling the bolus from the mouth to the pharynx. As well, another potential mechanism of bolus propulsion, namely suction, was investigated.

Based on clinical results obtained using TOMS, the importance of tongue strength and coordination for proper oral phase swallowing function has been reaffirmed. Weaker tongue strength and poorer tongue coordination were observed prevalently in dysphagic patient groups (e.g., post-polio, stroke) in comparison to able-bodied subjects reporting of no swallowing difficulty. Similar results are also expected from clinical testing using OPTRANS. It also has become evident that tongue coordination rather than absolute tongue strength is more important to a successful swallow. This was observed in a number of individual subjects (able-bodied and patients), who reported of no swallowing difficulty despite of their relatively weak tongue strengths. Since the swallowing act usually requires only a small application of an individual’s full tongue strength, it was recognized that the high level of tongue coordination found in these subjects was sufficient to allow a successful swallow. This
Additional support for the importance of tongue strength and coordination during the oral phase came from the investigation into the oral phase suction mechanism. Based on manometric data obtained using intraluminal manometry in the oral phase, suction (i.e., negative pressure gradient) was not observed. Thus, it was determined that the bolus is transported during the oral phase by the positive pressure generated by the tongue acting against the palate behind the bolus, rather than by a negative pressure gradient ahead of the bolus.
CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The general purpose of the present investigation, as mentioned in CHAPTER 1, was to develop objective, quantitative methods of evaluation and treatment for oral phase dysphagia. In order to develop these quantitative methods, three experimental stages were proposed for this research, which deal with three different aspects of the oral phase swallowing mechanism:

1) Tongue force measurement to study the role of tongue strength and coordination in oral phase of swallowing (under a non-swallowing condition).

2) Suction pressure measurement to investigate the existence and role of a possible suction mechanism (negative pressure gradient) in oral phase bolus propulsion.

3) Oral cavity pressure measurement to study the role of tongue (pressure and movement during the oral phase (under a swallowing condition).
These experiments have resulted in the development of new clinical methods of evaluation for oral phase dysphagia, as well as providing valuable data about the oral phase swallowing physiology.

7.1.1 DEVELOPMENT OF NEW CLINICAL METHODS

From the review of available literature (See CHAPTER 2), it has been demonstrated that there is a shortage of reliable, objective methods of evaluation and treatment for oral phase dysphagia. Much of today's subjective methods are prone to inaccuracy and inconsistency and do not result in objective, quantitative data. Instead of "semi-quantitative" imaging methods that are currently used (e.g., videofluoroscopy or ultrasound), techniques are required that can quantify oral phase parameters on which individual swallowing function can be assessed.

Three new clinical methods (measurement systems) have been developed for each of the aforementioned experimental stages. Two methods were based on the important role that tongue force plays during the oral phase of swallowing:

Development of a tongue force measurement system

- A computer-aided tongue force measurement system (TOMS) has been developed, which is capable of reliably measuring tongue force in three directions. This strain gauge based system utilizes a cantilever beam type transducer to measure applied tongue force at the end of the beam
element. The system is capable of quantifying individual tongue strength and coordination by means of different test protocols.

- The system's reliability as a clinical tool has been statistically verified using able-bodied subject and patient group data. The system's high sensitivity and specificity to oral phase dysphagia reflect its potential as a clinical, diagnostic device. Further applications of the system are foreseen in tongue muscle strengthening and control exercises.

**Development of an oral cavity pressure transducer system**

- A computer-aided oral cavity pressure transducer system has been developed, which is capable of reliably measuring the pressure distribution generated by the tongue acting against the palate during the actual oral phase of swallowing. The system uses a mouthguard transducer unit with a network of force sensing resistors (FSR's) positioned along the mouthguard palate.

- The system's reliability has been statistically verified using preliminary data from able-bodied subjects. Potential applications are foreseen in clinical diagnosis of oral phase dysphagia, tongue muscle strengthening and control exercises.

A third clinical method was developed for the purpose of recording the manometric pressure pattern generated during the oral phase. The method was intended to verify the existence and role of a suction mechanism for oral phase bolus propulsion, but it was aborted due to technical difficulties encountered with the experimental setup. Instead, a well-established pharyngeal/esophageal manometry setup was used and effectively applied to the oral phase (see CHAPTER 7.1.2).
7.1.2 ORAL PHASE SWALLOWING MECHANISM AND DYSPHAGIA

Based on the experimental results obtained using the various transducer systems, the following conclusions about the oral phase swallowing mechanism and its associated disorders could be made:

Clinical test results of tongue force measurement

- In able-bodied subjects reporting of no swallowing difficulty, mean tongue strength was found to be the greatest among the test groups in all tongue thrust directions. The tongue strength data reflected a nearly normal distribution, spread over a relatively small range. Also, upward tongue strength was usually greater compared to lateral tongue strength. Tongue coordination was found to be excellent for this test group compared to other patient groups. The able-bodied subjects were able to closely coordinate their tongue according to a non-cyclic (target holding) and a cyclic thrust protocol.

- In post-polio patients, the mean tongue strength data reflected a similar distribution as the able-bodied subjects' (nearly normal within a small force range), but with a significantly weaker mean tongue strength. The degree of tongue coordination was generally poorer than the able-bodied subjects. Those patients complaining of swallowing difficulty exhibited both weak tongue strength and poor tongue coordination.

- In stroke patients, tongue strength depended on individual level of recovery from the initial stroke onset. A patient with a recent stroke attack showed much weaker tongue strength and poorer tongue coordination than a patient after 4 months of recovery. Thus, the mean tongue strength distribution was scattered over a wide range of tongue force values. Unilateral tongue weakness and lack of coordination were evident, correlating well to the stroke patients' hemiparetic condition.
CONCLUSIONS AND RECOMMENDATIONS

Clinical test results of oral cavity pressure measurement

- Although between subject variability existed, able-bodied subjects were able to perform the oral phase swallow in a repeatable manner. The palatal pressure data indicated that each subject placed their tongue just behind the upper front incisors to initiate the wave-like tongue movement from the front to the back of the mouth. Highest pressure levels were recorded at posteriorly and laterally located sensors.

- Increase in bolus volume, as well as bolus consistency, generally led to an increase in oral phase palatal pressure levels. This finding correlates well with the observation that greater muscular effort is required in swallowing a larger, "harder to swallow" bolus.

Clinical test results of suction pressure measurement

- Obtained manometric data has verified that no significant negative pressure or pressure gradient (suction) forms during the oral phase of swallowing.

- The negative pressure gradient, confined to the region near the hypopharynx (150-200 mm distally from the front incisors), has confirmed the existence of pharyngeal suction mechanism.

This absence of an oral phase suction mechanism has reaffirmed the importance of the tongue as the principal agent of bolus propulsion during the oral phase.

7.2 RECOMMENDATIONS FOR FUTURE WORK

The findings of the present investigation mentioned in the previous section lead to a natural course for continued research into the oral phase swallowing mechanism
and its associated disorders.

Optimization of newly-developed clinical methods

- The design and protocol of the newly-developed clinical methods (TOMS and OPTRANS) should be optimized with considerations for patient safety and comfort, low setup cost, ease of use, and protocol standardization.

Along with the optimization of the clinical methods, clinical test data should be continuously collected to verify the reliability of the utilized measurement device and determine its capabilities for oral phase dysphagia evaluation and treatment.

Clinical testing of newly-developed clinical methods

- Extensive clinical testing using TOMS and OPTRANS should be performed on able-bodied subjects and various patient groups of interest (e.g., dysphagic patients suffering from neuromuscular or mechanical disorders). This would provide valuable clinical database for diagnostic purpose.

- Further clinical testing should be performed to study the effects of age and sex on tongue force/palatal pressure. Also, the new, clinical methods should be utilized to monitor the effects of various treatment strategies (e.g., posture, tongue exercise/speech therapy, diet, prosthetics, etc.) on oral phase swallowing function.

As mentioned in CHAPTER 5, the OPTRANS system has been designed with considerations for simultaneous application of current evaluation methods.
Application of OPTRANS with other evaluation methods

- Simultaneous application of OPTRANS with videofluoroscopy and ultrasound techniques should result in improved swallowing evaluation. OPTRANS' capability of frame-by-frame analysis was intended for such a purpose.

With respect to actual treatment of oral phase dysphagia, the two newly-developed measurement systems in this investigation appear to be applicable as training (e.g., regaining tongue strength and control) or monitoring devices (e.g., evaluating the effectiveness of various treatment methods). Presently, the only orthotic/prosthetic devices used to assist the oral phase of swallowing are various anatomical prostheses (i.e., for replacement of tongue, palate, etc. lost due to cancer tumor resections).

Development of an oral phase orthotic/prosthetic device

- Based on the obtained results on the importance of tongue strength and coordination, as well as the actual oral phase swallowing mechanism, an oral phase orthotic/prosthetic device should be developed to aid patients with oral phase dysphagia.

The present investigation comprises only a small part of a multidisciplinary effort by health care professionals and other researchers to better understand and manage the increasingly prevalent condition of dysphagia. The results of this investigation should serve to clearly upgrade the present methods of evaluation and
CONCLUSIONS AND RECOMMENDATIONS

treatment of oral phase dysphagia. However, additional research should be conducted to continue to improve upon current, existing methods.
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APPENDIX A: SWALLOWING PHYSIOLOGY (ORAL/PHARYNGEAL PHASE)

The oral phase begins as the ingesta is taken into the mouth. With the mouth closed, a bolus of proper size and consistency is formed in the oral cavity by means of the interaction among the dentition, the maxilla and the mandible (upper and lower jaw), and the muscles of the tongue, face, and mastication (see Table A.1, Figure A.1- A.5 for swallowing anatomy).

Table A.1: Muscles of the Swallowing Process (from [27]); a) Muscles of the Face, b) Mastication, c) Tongue (Extrinsic), d) Tongue (Intrinsic), e) Soft Palate, and f) Suprahyoid

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbicularis oris</td>
<td>None. Derives fibers from other muscles in the area. Encircles mouth.</td>
<td></td>
<td>Closes mouth: compresses or puckers lips</td>
</tr>
<tr>
<td>Quadratus labii superior</td>
<td>Frontal process of maxilla; lower border of orbit; zygomatic bone</td>
<td>Upper lip, laterally from midline</td>
<td>Elevates upper lip</td>
</tr>
<tr>
<td>Caninus</td>
<td>Canine fossa of maxilla</td>
<td>Upper lip, at angle of mouth</td>
<td>Elevates outer end of upper lip</td>
</tr>
<tr>
<td>Zygomatic</td>
<td>Zygomatic bone</td>
<td>Upper lip, at angle of mouth</td>
<td>Pulls corner of mouth up and back</td>
</tr>
<tr>
<td>Buccinator</td>
<td>Alveolar processes of maxilla and mandible; pterygomandibular raphe</td>
<td>Fibers of other labial muscles</td>
<td>Compresses cheek; unifies action of interconnecting muscles</td>
</tr>
<tr>
<td>Risorius</td>
<td>Fascia over masseter</td>
<td>Skin at angle of mouth</td>
<td>Retracts angle of mouth</td>
</tr>
<tr>
<td>Triangularis</td>
<td>Oblique line of mandible</td>
<td>Lower lip at angle of mouth</td>
<td>Depresses angle of mouth</td>
</tr>
<tr>
<td>Quadratus labii inferior</td>
<td>Oblique line of mandible</td>
<td>Integument of lower lip</td>
<td>Draws lower lip down and back</td>
</tr>
<tr>
<td>Mentalis</td>
<td>Incisive fossa of mandible</td>
<td>Integument of chin</td>
<td>Raises and protrudes lower lip</td>
</tr>
<tr>
<td>Platysma</td>
<td>Fascia covering thoracic muscles</td>
<td>Skin and tissue of lower face; mandible below oblique line</td>
<td>Depresses mandible; wrinkles skin of neck and chin; depresses outer end of lower lip</td>
</tr>
</tbody>
</table>

*All innervated by cranial nerve VII.*
Table A.1 (continued)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masseter</td>
<td>Superficial: lower border of zygomatic arch</td>
<td>Superficial: outer surface of lower ramus and angle of mandible</td>
<td>Lifts mandible vertically</td>
</tr>
<tr>
<td></td>
<td>Deep: medial surface of zygomatic arch</td>
<td>Deep: outer surface of upper ramus and coronoid process</td>
<td></td>
</tr>
<tr>
<td>Temporalis</td>
<td>Temporal fossa of skull</td>
<td>Coronoid process and anterior margin of upper ramus</td>
<td>Elevates and retracts mandible</td>
</tr>
<tr>
<td>Internal pterygoid</td>
<td>Lateral pterygoid plate; palatine and maxillary bones</td>
<td>Lower margin of inner surface of ramus</td>
<td>Elevates and protrudes mandible</td>
</tr>
<tr>
<td>External pterygoid</td>
<td>Upper head: greater wing of sphenoid</td>
<td>Neck of condyle and articular disc of TMJ</td>
<td>Draws mandible forward; depresses mandible; moves mandible to side</td>
</tr>
<tr>
<td></td>
<td>Lower head: outer surface of lateral pterygoid plate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*All innervated by the mandibular branch of cranial nerve V.

b)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Cranial nerve</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genioglossus</td>
<td>XII</td>
<td>Inner surface of mandible near symphysis</td>
<td>Median septum of tongue; body of hyoid bone</td>
<td>Various fibers protrude and retract tongue; depress midline of tongue; elevate hyoid bone</td>
</tr>
<tr>
<td>Hyoglossus</td>
<td>XII</td>
<td>Body and greater cornu of hyoid bone</td>
<td>Side of the tongue, posterior half</td>
<td>Depresses and retracts tongue; depresses side of tongue</td>
</tr>
<tr>
<td>Styloglossus</td>
<td>XII</td>
<td>Styloid process of temporal bone</td>
<td>Lateral margin, full length of tongue</td>
<td>Draws tongue upward and backward; elevates side of tongue</td>
</tr>
<tr>
<td>Palatoglossus</td>
<td>X</td>
<td>Anterior surface of velum</td>
<td>Side of posterior tongue</td>
<td>Constricts faucial isthmus, elevates posterior tongue</td>
</tr>
</tbody>
</table>

c)
Table A.1 (continued)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior longitudinal</td>
<td>Submucosa near epiglottis; median septum of tongue</td>
<td>Edges of tongue</td>
<td>Shortens, widens tongue; turns tip and sides up, forming concave dorsum</td>
</tr>
<tr>
<td>Inferior longitudinal</td>
<td>Lower portion of root of tongue</td>
<td>Apex (tip) of tongue</td>
<td>Shortens, widens tongue; depresses tip, forming convex dorsum</td>
</tr>
<tr>
<td>Transverse Vertical</td>
<td>Median septum of tongue</td>
<td>Mucosa at side of tongue</td>
<td>Narrows, elongates tongue</td>
</tr>
<tr>
<td></td>
<td>Upper surface of tongue</td>
<td>Lower surface of tongue</td>
<td>Flattens, widens tongue tip</td>
</tr>
</tbody>
</table>

*All innervated by cranial nerve XII.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Cranial nerve</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uvula</td>
<td>X</td>
<td>Posterior nasal spine; palatal aponeurosis</td>
<td>Body of uvula</td>
<td>Elevates uvula</td>
</tr>
<tr>
<td>Tensor veli palatini</td>
<td>V (mandibular branch)</td>
<td>Scaphoid fossa; spine of medial pterygoid plate; posterior border of hard palate</td>
<td>Palatal aponeurosis; cartilage of eustachian tube</td>
<td>Tenses velum: opens eustachian tube during deglutition</td>
</tr>
<tr>
<td>Levator veli palatini</td>
<td>X</td>
<td>Lower surface; petrous portion of temporal bone; side of eustachian tube</td>
<td>Throughout velum to midline</td>
<td>Elevates velum toward posterior pharyngeal wall; dilates orifice of eustachian tube</td>
</tr>
<tr>
<td>Palatopharyngius</td>
<td>X</td>
<td>Lower: mucous membrane along posterior border of velum</td>
<td>Posterior thyroid cartilage; aponeurosis of pharynx</td>
<td>Depresses velum; constricts faucial isthmus; elevates pharynx</td>
</tr>
<tr>
<td>Palatoglossus (see also: “Extrinsic muscle of tongue”)</td>
<td>X</td>
<td>Upper: midline of velum</td>
<td>Side of posterior tongue</td>
<td>Constricts faucial isthmus; elevates tongue</td>
</tr>
<tr>
<td>Velopharyngeal sphincter</td>
<td>X</td>
<td>Midline of velum</td>
<td>Posterior median raphe of pharynx</td>
<td>Aids in moving velum posteriorly; creates ridge on posterior pharyngeal wall</td>
</tr>
</tbody>
</table>

d)
Table A.1 (continued)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Cranial nerve</th>
<th>Origin</th>
<th>Insertion</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digastric</td>
<td>V</td>
<td>Interior mandible near midline</td>
<td>Body and greater cornu of hyoid bone, via intermediate tendon</td>
<td>Depresses mandible or elevates hyoid bone</td>
</tr>
<tr>
<td>Anterior belly</td>
<td>VII</td>
<td>Inner surfaces of mastoid process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior belly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mylohyoid</td>
<td>V</td>
<td>Mylohyoid ridge of mandible</td>
<td>Body of hyoid bone and midline raphe</td>
<td>Lifts hyoid bone and base of tongue up and forward</td>
</tr>
<tr>
<td>Geniohyoid</td>
<td>XII (aided by first cervical)</td>
<td>Inferior mental spine at symphysis of mandible</td>
<td>Body of hyoid bone, anterior surface</td>
<td>Draws hyoid bone and base of tongue forward</td>
</tr>
<tr>
<td>Stylohyoid</td>
<td>XII</td>
<td>Styloid process of temporal bone</td>
<td>Body of hyoid near greater cornu</td>
<td>Lifts hyoid bone up and backward</td>
</tr>
</tbody>
</table>

Figure A.1: Segments of the Oral-Pharyngeal Food Pathway (from [10])
Figure A.2: Pharyngeal and Laryngeal Muscles (Lateral View) (from [10])
Figure A.3: Anterior Part of the Pharynx (Posterior View) (from [10])
Salivation to aid in the bolus formation and transport is accomplished via the three salivary glands situated around the oral cavity. In preparation of the bolus propulsion, the formed bolus is placed centrally on the dorsum of the tongue (refer to Figure 1.2,1.3). The tip of the tongue is raised to the alveolar ridge of the hard palate, just behind the upper front incisors. The posterior segment of the tongue is raised ahead of the bolus in apposition to the depressed soft palate, while the posterior faucial pillars are contracted to constrict the lumen ahead of the bolus. The lateral portions of the tongue are raised against the region behind the upper molars to
establish a functional seal around the bolus. The tongue "cups" the bolus in this preparatory position before the propulsive segment is initiated. The seal, enhanced by small lingual suction, effectively prevents any premature or unwanted bolus escape into the pharynx, the floor of the mouth, or the anterior and lateral sulcus (see Figure A.4).

With the onset of the propulsive segment, masticatory (chewing) and respiratory (breathing) activities are suspended until the completion of the swallow. Selley [22-25] has noted that most individuals swallow during the expiratory phase of their breathing cycles. The onset of the propulsive segment is also marked by the upward movement of the forepart of the tongue towards the hard palate. Simultaneously, the posterior segment of the tongue is separated from the soft palate and lowered to form a "grooved chute", and the posterior faucial pillars separate for the effortless passage of the bolus through the faucial isthmus. In a wave of peristaltic-like motion (lingual peristalsis), the tongue then squeezes and progressively "strips" the bolus along the hard/soft palate, thereby propelling it from the oral cavity towards the oropharynx.

The reflexive, pharyngeal phase of the swallowing process (see Figure 1.2,1.3) is triggered as the passing bolus reaches the sensory receptors located near the anterior faucial pillars. The process now comes under the control of the "swallowing center" (a "central pattern generator") which accepts the afferent stimuli (e.g., bolus
size and consistency) primarily via cranial nerves VII, IX, and X and generates the appropriate swallowing pattern via the motoneurons of the cranial nerves IX, X, and XII (Table A.1, A.2, Figure A.5).

Table A.2: Sensory/Motor (Afferent/Efferent) Controls of the Swallowing Process
(from [61])

<table>
<thead>
<tr>
<th>Sensory Function</th>
<th>Innervation</th>
</tr>
</thead>
<tbody>
<tr>
<td>General sensation, anterior two-thirds of tongue</td>
<td>Lingual nerve, trigeminal (V)</td>
</tr>
<tr>
<td>Taste, anterior two-thirds tongue</td>
<td>Chorda tympani, facial (VII)</td>
</tr>
<tr>
<td>Taste and general sensation, posterior one-third of the tongue</td>
<td>Glossopharyngeal (IX)</td>
</tr>
<tr>
<td>Mucosa of vallecula</td>
<td>Internal branch of SLN (vagus)</td>
</tr>
<tr>
<td>Primary afferent</td>
<td>Glossopharyngeal (IX)</td>
</tr>
<tr>
<td>Secondary afferent</td>
<td>Pharyngeal branch of vagus (X)</td>
</tr>
<tr>
<td>Tonsils, pharynx, soft palate</td>
<td>Glossopharyngeal (IX)</td>
</tr>
<tr>
<td>Pharynx, larynx, viscera</td>
<td>Vagus (X)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Efferent/Stage</th>
<th>Innervation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral</td>
<td></td>
</tr>
<tr>
<td>Masticatory, buccinator, floor of mouth</td>
<td>Trigeminal (V)</td>
</tr>
<tr>
<td>Lip sphincter</td>
<td>Facial (VII)</td>
</tr>
<tr>
<td>Tongue</td>
<td>Hypoglossal (XII)</td>
</tr>
<tr>
<td>Pharyngeal</td>
<td></td>
</tr>
<tr>
<td>Constrictors and stylopharyngeus</td>
<td>Glossopharyngeal (IX)</td>
</tr>
<tr>
<td>Palate, pharynx, larynx</td>
<td>Vagus (X)</td>
</tr>
<tr>
<td>Tongue</td>
<td>Hypoglossal (XII)</td>
</tr>
<tr>
<td>Esophageal</td>
<td></td>
</tr>
<tr>
<td>Esophagus</td>
<td>Vagus (X)</td>
</tr>
</tbody>
</table>
Figure A.5: Neural Control of the Swallowing Process (from [6])
The reflex mechanism prevents the bolus from escaping into improper channels (e.g., nasal cavity, airway, back to oral cavity) through the functional closing of these passages. For example, the laryngeal structures are lifted upwards to lie under the projection of the tongue base and to facilitate the epiglottic closure of the airway entrance. The reflex mechanism also coordinates the propulsion of the bolus through the pharynx by means of the sequential contraction of the pharyngeal constrictors (pharyngeal peristalsis). This action is the apparent continuation of the lingual peristalsis from the oral phase. Finally, the bolus passes into the esophagus through a sphincter, the PES, which relaxes from its tonic contracted state (part of the reflex mechanism) to allow easy bolus passage into the esophagus.
APPENDICES

APPENDIX B: SAMPLE DYSPHAGIA EVALUATION PROTOCOL

DYSPHAGIA EVALUATION FORM

Jill S. Steefel, M.A.

PATIENT: ___________________________ EXAMINATION DATE __________
BIRTHDATE: ___________________________ DATE OF ONSET: __________
PHYSICIAN: ___________________________ TELEPHONE: __________
MEDICAL DIAGNOSIS: ___________________________
OTHER MEDICAL PROBLEMS: ___________________________
DIETARY RESTRICTIONS (Medical): ___________________________
CURRENT DIET ORDERED: ___________________________

IF PATIENT “NPO,” CURRENT METHOD OF NOURISHMENT:
— I.V. — GASTROSTOMY — NG TUBE — TUBE SIZE
LIQUID RESTRICTIONS: _ YES _ NO; _ MAX CC _ MIN CC
PER DAY
DOES PATIENT HAVE TRACHEOSTOMY TUBE? _ YES _ NO
REPORTED CRANIAL NERVE IMPAIRMENT: ___________________________

INFORMATION FROM ENT REPORT: ___________________________

DOES PATIENT WEAR DENTURES? _ YES _ NO; _ PARTIAL
— COMPLETE
DOES PATIENT DROOL? _ YES _ NO; _ SITTING _ LYING DOWN
— CHOKES ON SALIVA
DOES PATIENT NEED SUCTIONING? _ NEVER _ AT MEALS
— FREQUENTLY
— CONSTANTLY
DOES PATIENT HAVE: _ GAG REFLEX? _ REFLEXIVE SWALLOW? _ VOLUNTARY SWALLOW?
— REFLEXIVE COUGH?
— CHOKING? _ ASPIRATION?
— REGURGITATION?

COMMUNICATIVE ABILITIES OF PATIENT: _ WNL _ IMPAIRED
— COMPREHENSION _ EXPRESSION

PATIENT/STAFF COMPLAINT: __________________________

PATIENT'S PREFERRED FOODS: __________________________

____________________________________________
DIRECT EXAMINATION OF PERIPHERAL SPEECH MECHANISM
AND ORAL MOTOR FUNCTION

(For all tasks examiner should note slowness, completeness of performance, and overall coordination.)

A. FACIAL MUSCULATURE AT REST (GENERAL):
   Masked expression? ___; Absence of forehead wrinkling? ___
   Eyelids partially closed? ___; Eyes unblinking? ___
   Does face appear symmetrical? ___; Angles of mouth droop? ___
   Lower on ___ (R/L) side
   Nose flattened? ___; pulled to one side? ___, (R/L) side
   Lips parted most of time? ___; complete ___ right ___ left
   Does patient drool? ___; occasionally ___ frequently

B. LIPS:
   1. PURSE LIPS:
      Left side: ___ WNL ___ Min. perf. ___ unable
      Right side: ___ WNL ___ Min. perf. ___ unable
      Strength: ___ WNL ___ Min. perf. ___ unable
      Coordination: ___ WNL ___ Min. perf. ___ unable
      Efficiency: ___ WNL ___ Min. perf. ___ unable
      Patient instructions: “Pucker your lips.
      Show me how you kiss someone.
      Say ‘Who?’”

   2. RETRACT LIPS:
      Left side: ___ WNL ___ Min. perf. ___ unable
      Right side: ___ WNL ___ Min. perf. ___ unable
      Strength: ___ WNL ___ Min. perf. ___ unable
      Coordination: ___ WNL ___ Min. perf. ___ unable
      Efficiency: ___ WNL ___ Min. perf. ___ unable
      Patient instructions: “Show me your smile.
      Show me your teeth.”
      (Demonstrate for patient, if necessary)
      “Say: ‘Whee! Why?’”

   3. ALTERNATELY SMILE AND PUCKER (PURSE/RETRACT LIPS):
      ___ slow ___ WNL ___ Min. perf. ___ unable

   4. LIP CLOSURE: ___ complete ___ partial ___ unable

Note: ____________________________________________
Patient instructions: "Close your lips and hum. 
Say: 'mmmmmmmmmm' 
Say: 'mama'"

5. LIP COMPRESSION:
   Left side: ___WNL ___Min. perf. ___unable
   Right side: ___WNL ___Min. perf. ___unable
   Center: ___WNL ___Min. perf. ___unable
Procedures: Have patient attempt to hold on to a piece of cardboard or straw using his lips only (no teeth) while 
   examiner tries to pull it away.
Patient instructions: Ask patient to pop his lips.
   "Say: 'puh, puh, puh; 
buh, buh, buh; 
papa, baby, pop, Bob'"

C. TEETH:
   Does patient have his own teeth? ___Yes ___No ___Some ___Dentures
   Do patient's dentures fit? ___Good ___Fair ___Poor
   Does patient use or need a denture fixative? ___Yes ___No
Other observations: ____________________________

D. TONGUE:
   1. AT REST:
      Size: ___average ___small ___large
      ___atrophied? ___furrowed? ___side only affected
      Fasciculations? ___observed ___reported
      Procedure: Look at edges of tongue while it is protruded over 
                 lower incisor teeth.
      Spontaneous gross movements? ___Yes ___No
      Deviation within the mouth? ___None ___Right ___Left
   2. DURING VOLUNTARY MOVEMENT:
      a. PROTRUSION:
      Deviation: ___None ___Right ___Left
      Range: ___Adequate ___Minimal ___None
      Strength: ___Adequate ___Minimal ___None
      Coordination & Efficiency: ___Good ___Fair ___Poor
      Procedures: Ask patient to stick out his tongue and hold it 
                 straight (give him model to imitate). 
                 Look for deviation to one side or the other. 
                 Ask patient to move tongue in and out of mouth 
                 three times.
                 Ask patient to push against a tongue depressor 
                 while you apply resistance.
b. LATERAL MOVEMENTS:

Outside of Mouth:
- to the left: __Yes __No
- to the right: __Yes __No

Inside of Mouth:
- to the left: __Yes __No
- to the right: __Yes __No

Procedures: Have patient imitate examiner moving his tongue from one corner of the mouth to the other.

Ask the patient to push the examiner's finger away as he pushes on tongue tip from outside of patient's cheek (left and right side).

Ask patient to put his tongue outside of his mouth and move it back and forth from one side to the other (give him model to imitate).

c. TONGUE-TIP ELEVATION:

Outside:
- WNL __Min. Perf. __Unable

Procedure: Ask patient to stick out his tongue and try to touch his nose.

Inside:

Procedure: Ask patient to say the following and note performance and any substitutions made by patient.

- "La, La, La" __Yes __No ________________
- "Tuh, Tuh, Tuh" __Yes __No ________________
- "Da, Da, Da" __Yes __No ________________

E. JAW (MASSETER AND TEMPORALIS MUSCLES):

1. MOVEMENT:

Opening:
- Full Excursion __Partial __Unable

Closing:
- Complete closure __Incomplete __Unable

Efficiency:
- Normal __Delayed __Severe delay

Deviation:
- None __To the left __To the right

Procedures: Ask the patient to open his mouth wide and then close it. Give patient model to imitate if necessary.

2. STRENGTH:

Opens mouth against resistance? __Yes __No

Closes mouth against resistance? __Yes __No

Procedures: Ask patient to open mouth while examiner strongly resists movement.

Ask patient to close mouth against resistance (this can be done using examiner's hand or by placing a padded tongue depressor over patient's lower incisors and applying firm resistance downward).

Ask patient to put his back teeth together and clench them tightly. Then examiner should feel the contrac-
ation at the back of the cheek just superior to the angle of the mandible. When there is good contraction, there is a palpable bulge.

F. PALATE:
1. UVULA AND SOFT PALATE:
   At Rest: _Midline; deviates to the _Left _Right
   During phonation: _Midline; Deviates _Left _Right
   _No movement observed
Procedure: Hold patient's tongue down with tongue depressor and look into mouth. A flashlight will help. During phonation or "Ah" or "Hah" observe to assess excursion of palate, which should be upward and backward. Also observe movement of posterior pharyngeal wall.

2. GAG REFLEX: _WNL _Present but weak _Absent
Procedure: Place tongue depressor or small cotton swab against soft palate at about a position midway back or gently touch posterior pharyngeal wall. A flashlight will make gag reflex easier to visualize.

3. ESTIMATE OF VELOPHARYNGEAL CLOSURE:
   Hypernasality: _None _Mild _Moderate _Severe
   Procedure: Tape-record conversation, reading passage or imitative speech sample.
   Plosive production: _WNL _Distorted _No performance
   _No nasal emission _Nasal emission
Comments: ____________________________________________________________________________
Can Patient Impound Air in Oral Cavity?
   _Yes _No _Seconds
   _Against resistance; _Nasal snort observed
Procedure: Ask patient to puff out his cheeks and hold air for ten seconds. If successful, push against patient's cheeks with short jabs of increasing force, and observe if seal is broken.
Does patient regurgitate fluids through the nose?
   _Yes _No _Observed _Reported
Can patient draw up liquids (drink) through straw?
   Thin liquids: _Yes _Min. Perf. _No
   Thick liquids: _Yes _Min. Perf. _No
   _Only by using a straw with a shortened vertical rise of approximately _cm (_inches).

G. LARYNGEAL MUSCULATURE:
1. EXCURSION (during swallow): _WNL _Min. Perf. _None
Procedure: Ask patient to swallow (volitional) or just his saliva.
If he has difficulty, try to have him suck on empty straw that is pinched off or on a lemon glycerin swab that has been squeezed dry. Look for movement of the larynx upward and forward with an excursion of about 1 inch.

2. GLOTTAL CLOSURE:
   Voluntary cough: ___WNL ___Weak ___Unable
   Reflexive cough: ___WNL ___Weak ___None observed
   Procedure: Ask patient to cough. If there is a good cough, glottal closure can be assumed.
   Voice Quality: ___WNL ___Harsh ___Breathy ___Other
   Vocal Volume: ___WNL ___Weak ___Inadequate
   Procedure: Listen to and tape record a speech sample including vowel production, extended phonation of “Ah,” and attempted volume increase. Note maximum phonation time and presence of inhalatory stridor.
   Patient response to Valsalva's Maneuver:
   Voice quality: ___No change ___Improved
   Vocal volume: ___No change ___Increased
   Procedure: Listen to and tape record the same or similar speech and voice sample as used above while the patient uses his arm or arms to push or pull with maximum force.

H. TASTE RECEPTORS:
   1. SALT: ___Identifies substance ___No identification
      Taste strongest on ___Left ___Right; ___No difference
   2. SWEET: ___Identifies substance ___No identification
      Taste strongest on ___Left ___Right; ___No difference
   3. BITTER: ___Identifies substance ___No identification
      Taste strongest on ___Left ___Right; ___No difference

DIRECT EVALUATION OF SWALLOWING ABILITY THROUGH TRIAL FEEDING PROCEDURES

A. EVALUATION OF SWALLOWING FUNCTION WITHOUT FOOD:
   1. During evaluation of motor function, observe to see if patient demonstrates a reflexive swallow:
      ___present ___absent ___reported by others
   2. When assessment of laryngeal function is done, attempt to obtain volitional swallow from patient:
      ___swallows on command ___does not achieve swallow on demand
      _______________ cues needed to achieve swallow
   3. Compare differences, if any, between the reflexive and volitional
swallow demonstrated by the patient: ____________________________

__________________________________________________________

B. EVALUATION OF SWALLOWING FUNCTION USING FOOD:
This portion of the evaluation SHOULD NOT BE UNDERTAKEN UNLESS the patient has demonstrated that he has a reflexive swallow. Prepare patient for feeding and take all necessary safety precautions.

1. APPLESAUCE (Gerbers® strained):
   Have patient take a minute amount off tip of small spoon or from an eyedropper or straw. Instruct patient to: “close your lips, put your tongue tip up to roof of mouth, and then swallow.” Observe:
   — WNL if patient demonstrates a normal swallow
   — Minimal if patient tries to swallow but is not completely successful, if he chokes or drools, or if food leaks out through nose or is regurgitated.
   — No performance
   Specific comments or observations: ____________________________

2. WATER (room temperature):
   Using an eyedropper or a straw, give or have patient take 1 to 2 cc of water, and instruct patient to “close lips, put tongue tip up, and swallow.” (If patient can suck the water from the straw or eyedropper, he will have a better chance of success, as the tongue tip will already be elevated.) Observe:
   — WNL if patient swallows water without problems
   — Minimal if patient tries to swallow but encounters problems.
   (Note the problems: ____________________________________________)
   — No performance.

3. SOLID FOOD THAT REQUIRES CHEWING:
   A slice of ripe banana or soft bread may be used for this testing. Hard or crumbly items such as crackers can lead to extra problems and should be tried after it has been shown that the patient can effectively chew foods and control substances within his mouth. Observe:
   — WNL — Min. Perf. — No performance

4. OTHER ITEMS (Examiner’s choice):
   Name of item used: ____________________________
   Description of consistency of the item: __________________________
   Patient performance: ____________________________
   ________________________________________________
EVALUATION SUMMARY

A. ASSESSMENT: _____________________________________________

B. RECOMMENDATIONS:
Patient ______would/ ______would not be a good candidate for treatment under a dysphagia program.
Recommended patient diet levels:
Liquids: ___________________________________________________
Solids: ____________________________________________________
Patient participation in feeding:
Patient is/is not aware of problem and mentally able to participate in program.
Patient should be ______encouraged ______allowed ______discouraged from self-feeding.
Patient limitations and special needs:
____assistance with laryngeal excursion
____visual model (pantomime)
____verbal instructions (step by step/reminder to swallow)
____suctioning (occasionally/frequently/after each bite)
____patient needs food placed in (right/left) side of mouth
____patient takes liquids best through (straw/spoon/glass)
____patient should be fed from (left/right side)
____patient should have head turned to (right/left side for intake)
____patient needs (close/casual/none) supervision during intake of (liquids/solids)
____patient should be fed by (speech pathologist/nurse/family)

DATE: ____________

Speech Pathologist
APPENDICES

APPENDIX C: PROS AND CONS OF VARIOUS EVALUATION METHODS

CINE/VIDEOFLUOROSCOPY

The most widely accepted evaluation technique available today is the method of cine/videofluoroscopy, a technique where fluoroscopic images are acquired for later frame-by-frame, visual analysis (i.e., analysis of individual fluoroscopic image taken at a specific time) of the physiological events of the swallowing process (see Figure 2.9). Often referred to as the barium-swallow test, because of the radioopaque bolus that is swallowed in order to demarcate the structural borders (soft tissues) during the passage of the bolus, this technique is essential in monitoring pharyngeal peristaltic activity and airway protection mechanism, and in establishing the timing of swallowing events [55,78]. A new technique, the modified barium swallow test, has been devised by Logemann [9,48], which replaces the large bolus used in the regular barium swallow test with a "safe", small size bolus to reduce the possibility of harmful effects to the subject during the swallowing test.

Although cine/videofluoroscopy is recognized as the "gold" standard of evaluation techniques, it is still only a semi-quantitative, visual imaging technique that is predominantly useful in monitoring swallowing function. Except for the timing of swallowing events, this technique offers little in terms of measurable, quantitative
parameters. Because of its poor images of soft tissues and the obliteration of surrounding structures by the radioopaque bolus (see Figure 2.13), this technique has rarely been the optimal apparatus for oral phase visualization. It also requires a costly setup and the involvement of additional specialists to run the tests and analyze the results. Significant health risks due to radiation must be considered along with the discomfort of the barium swallow. Recently, controversy has surrounded the issue of using a "safe" bolus (i.e., modified barium swallow), as compared to using a larger bolus (stress test) in order to see the realistic representation of the swallowing mechanism.

**INTRALUMINAL MANOMETRY**

Intraluminal manometry measures the fluid pressure generated in the pharyngeal and esophageal lumen during the swallowing process (see Figure 2.10). The technique employs a multi-tube catheter connected to multiple pressure transducers, usually three to five, that is placed into the pharynx/esophagus to simultaneously measure the pressure at various levels of the lumen. The resulting pressure pattern output defines the timing of swallowing events, as well as a measure of the propulsive activity (Figure 2.31-2.33). Intraluminal manometry is particularly suited for detecting esophageal and sphincter dysfunctions, often outperforming videofluoroscopy.
The ability of intraluminal manometry in accurately recording the oral and pharyngeal manometric pressures has often been questioned. To date, it has been exclusively utilized to assess the esophageal phase, where the complexities of the pressure measurement encountered in the oral and pharyngeal phases are non-existent (e.g., a much longer time frame for analysis). Often, the introduced catheter has shown to be quite invasive to the subject and pose technical problems, as its thickness and orientation affected the swallowing pressure pattern [46,174]. Recently, through the development of precision manometric setups (e.g., high fidelity strain gauge recording probes [46,56]), some of the aforementioned problems of using traditional fluid-filled catheters have been addressed. Investigations using these setups mostly continue to neglect oral phase manometry, and experimental variability and inconsistency continue to exist [174]. It has been documented that intraluminal manometry exhibits a generally lower sensitivity than cine/videofluoroscopy (e.g., inability to detail structures [46]), and that it also requires a specialist to perform the tests.

**ULTRASONOGRAPHY**

Ultrasonography has only come into prominence during the past decade as an optimal evaluation technique to monitor the oral phase of swallowing (see Figure 2.11). The technique utilizes a sound wave source/detector, attached below the
mandible and behind the chin, to send waves upwards into the oral cavity and receive the reflected waves. This technique, enhanced by frame-by-frame analysis capabilities, has been exclusively used to visualize the movement of the tongue and bolus transport during the oral phase. Its chief advantage lies in its minimal invasiveness to the subject and clinical safety (i.e., compared to cine/videofluoroscopy), where radiation is not an issue, allowing for a limitless testing protocol.

The restriction of ultrasound application to the oral phase stems from the inability of sound waves to pass through air and bony structures [177-179], thereby limiting the only possible placement of the transducer to just below the mandible. This flaw prevents the visualization of the interaction between the tongue and the hard palate, which may be the most critical aspect of the tongue function during the oral phase. It also creates problems when any type of bolus is introduced, which further diminishes the image quality. Repeatable transducer positioning is another problem, along with the limitation on monitoring other relevant swallowing events of interest (e.g., movement of the posterior segment of the tongue) [177,179,181]. Furthermore, although ultrasound is effectively utilized for monitoring the oral phase, it only applies to the propulsive and not the preparatory segment, where imaging difficulties arise with the involvement of dentition. Like cine/videofluoroscopy, ultrasonography requires a specialist to perform the tests, and it is another visual, imaging technique able to only observe function and timing of events.
ELECTROMYOGRAPHY

Electromyography measures the electrical activity of a contracting muscle. For swallowing, electromyography has been used to measure muscle activity regarding pharyngeal peristalsis and tongue movement, employing needle, surface, and suction electrodes (see Figure 2.12).

The problems with electromyography utilization in swallowing evaluation include the variability of electromyographic signals among subjects and even within subjects, and the subsequent interpretation of the data. This non-repeatability of the data makes electromyography a restrictive evaluation technique except for estimating the timing of swallowing events and for checking the existence of a given event (see Figure 2.12). Although the technique assists in providing a good neurophysiological understanding, it fails to accurately and repeatably quantify the swallowing mechanism. Isolation of a muscle of particular interest is especially difficult in terms of electrode placement and resulting data analysis for complex structures such as the tongue. Artifacts may be introduced in cases of imprecise electromyographic setups. The invasive placement of electrodes and clinical safety are further problems of this technique. As with other methods, electromyography requires a specialist, and its sensitivity in detecting dysphagia is not very high [47,57].
APPENDIX D: CONSENT FORMS AND QUESTIONNAIRES FOR TEST SUBJECTS

INVESTIGATORS: __________________________  __________________________

The purpose of this evaluation is to measure tongue strength (force) which is an integral parameter in the swallowing process. Measurements are taken in three directions (up, left, and right) under both, fatiguing and non-fatiguing conditions using a tongue depressor-like beam housed in an adjustable mouthblock. During the initial evaluation, the subject will be asked to bite lightly into a piece of plasterceme wrapped in a clear, plastic (sandwich bag) material, thereby leaving a bite size impression for the adjustment of the mouthblock. Then, the subject will be asked to bite into a set of dental tooth impression pieces that are placed on the mouthblock, thereby producing a customized set of tooth impressions to aid in the consistent, firm grip of the mouthblock. The actual evaluation involves the acquisition of a set of data consisting of trials, with each trial lasting 5 seconds (non-fatigue) or 30 seconds (fatigue). The subject is instructed about the protocol prior to the measurements. In all, a single evaluation session will last about 15-30 minutes. The subject may experience some discomfort in placing the mouthblock in the mouth or during the actual measurement of the tongue force as well as slight, muscular fatigue and soreness, especially during the initial session due to unfamiliarity. This will eventually diminish as more sessions are performed. Precautions (i.e., use of surgical gloves and cots) are taken such that the subject will be fully protected against any contact with unclean materials. The subject will be seated throughout the evaluation.

In signing this consent form, you state that you have read and understood the above statements. You enter the tongue strength/control evaluation willingly and you may withdraw AT ANY TIME without penalty or discrimination.

CONSENT

I have read the above comments and wish to proceed with the tongue strength/control evaluation. Any questions, that I have, have been answered to my satisfaction by the investigator(s).

Date_________________________  Name_________________________  (signature required)
Witness_________________________

I hereby consent to and authorize the use and reproduction of any and all tongue strength/control data taken of me during this evaluation for scientific or research purposes, with the understanding that my identity will be kept confidential.

Date_________________________  Name_________________________  (signature required)
Witness_________________________
PATIENT BACKGROUND INFORMATION
FOR CLINICAL ASSESSMENT OF SWALLOWING

1. Name?
2. Age?
3. Left or right-handed?
4. Occupation?
5. Disability? When and how?

6. Any orofacial or head/neck musculature weakness or imbalance?

7. Any problems with swallowing?
   - history?
     - what phase?
     - choking/aspiration or repeated swallows?
     - other anatomical structures affecting swallow (dentinion alignment, cleft palate, etc.)?
     - what type of bolus cause problems?
     - problems in bolus management or propulsion?
     - personal description of oral phase of swallowing.
       - movement of tongue, creation of seals.

8. Any previous swallowing assessments?
   - what methods used?
   - results?

9. Type of diet?
APPENDICES

APPENDIX E: FORCE SENSING RESISTOR SPECIFICATIONS

FSR™ Technical Specifications

These are typical parameters. FSRs are custom devices and can be made for use outside these specifications. Consult Applications Engineering with your specific requirements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size Range</td>
<td>Max = 20&quot; x 30&quot; (51 x 76 cm)</td>
<td>Any shape</td>
</tr>
<tr>
<td></td>
<td>Min = 0.2&quot; x 0.2&quot; (0.5 x 0.5 cm)</td>
<td></td>
</tr>
<tr>
<td>Device Thickness</td>
<td>0.008&quot; to 0.050&quot; (0.20 to 1.25 mm)</td>
<td></td>
</tr>
<tr>
<td>Force Sensitivity Range</td>
<td>30g to 20kg</td>
<td></td>
</tr>
<tr>
<td>Pressure Sensitivity Range</td>
<td>0.45 to 150 psi (0.03kg/cm² to 10kg/cm²)</td>
<td>30g to 10kg 1 cm² actuator</td>
</tr>
<tr>
<td>Part-to-Part Force Repeatability</td>
<td>± 15% full scale</td>
<td>For typical part with consistent actuation</td>
</tr>
<tr>
<td>Single Part Force Repeatability</td>
<td>± 2% full scale</td>
<td></td>
</tr>
<tr>
<td>Force Resolution</td>
<td>Better than 0.5% full scale</td>
<td></td>
</tr>
<tr>
<td>Break Force</td>
<td>30 to 100g (1 to 3.5 oz) typical</td>
<td>Dependent on probe size, shape</td>
</tr>
<tr>
<td>Stand-Off Resistance</td>
<td>&gt; 1 MΩ</td>
<td></td>
</tr>
<tr>
<td>Switch Characteristic</td>
<td>Essentially zero travel</td>
<td></td>
</tr>
<tr>
<td>Device Rise Time</td>
<td>1-2 msec (mechanical)</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt; 10 million actuations</td>
<td></td>
</tr>
<tr>
<td>Use Temperature</td>
<td>-30°C to +170°C</td>
<td>High temperature adhesives</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>1 mA/cm² of applied force</td>
<td></td>
</tr>
<tr>
<td>Sensitivity to Noise/Vibration</td>
<td>Not significantly affected</td>
<td></td>
</tr>
<tr>
<td>EMI/ESD</td>
<td>Passive device—not damaged by EMI or ESD</td>
<td></td>
</tr>
<tr>
<td>Lead Attachment</td>
<td>Standard flex circuit techniques</td>
<td>See TechNotes</td>
</tr>
</tbody>
</table>

For Linear Pots and XYZ Pads

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positional Resolution</td>
<td>0.003&quot; (0.075 mm) typical</td>
<td>1 cm wide actuator</td>
</tr>
<tr>
<td>Positional Accuracy</td>
<td>&lt;± 1% full scale</td>
<td></td>
</tr>
</tbody>
</table>

FSR terminology is defined in the Technical Overview's Glossary of Terms.
GLOSSARY

able-bodied: relating to healthy, "normal" individuals.

acute: of short and sharp course, not chronic; said of a disease.

alveolar ridge: the part of the upper or lower jawbone that holds the roots of the teeth.

amyotrophic lateral sclerosis (ALS): hardening of tissue, usually due to scarring after inflammation and affecting the lateral columns of the spinal cord and the medulla of the brain, causing progressive muscular paralysis.

anatomy: the study of the form and gross structure of the various parts of the human body.

anterior: describing or relating to the front portion of the body or organ.

articulation: distinct connected speech or enunciation.

aspiration: the entry of material into the airway below the vocal cords.

bolus: a chewed morsel of food ready to be swallowed.

buccal: pertaining to the cheeks.

carcinoma: any cancer that arises in the tissue that lines the skin and internal organs of the body.

catheter: a tubular instrument for the passage of fluid from or into a body cavity.

central nervous system (CNS): the brain and the spinal cord, responsible for the integration of all nervous activities.

chemotherapy: the prevention or treatment of disease by the use of chemical substances.

cleft palate: a fissure (groove) in the midline of the palate due to failure of the two sides to fuse in embryonic development.
cognition: a generic term embracing the quality of knowing, which includes perceiving, recognizing, conceiving, judging, sensing, reasoning, and imagining.

compensation: the act of making up for a functional or structural deficiency.

constrictor: any muscle that compresses an organ or causes a hollow organ or part to contract (e.g., pharyngeal constrictor muscles: inferior, middle, and superior).

cranial nerves: the 12 pairs of nerves that arise directly from the brain and leave the skull through small apertures; conventionally given Roman numbers.

cricoid cartilage: the cartilage, shaped like a signet ring, that forms part of the anterior and lateral walls and most of the posterior wall of the larynx.

cricopharyngeal: relating to the cricoid cartilage and the pharynx, a part of the inferior constrictor muscle of the pharynx.

deglutition: the act of swallowing.

dental arch: the curved composite structure of the natural dentition and the residual ridge, or the remains thereof after the loss of natural teeth.

dental impression material: a dental compound, biologically safe, which is available in various forms (i.e., powder, liquid, paste). It is initially molded into desired shape and left to solidify.

dentition: the number, type, and arrangement of the teeth as a whole in the mouth.

denture: artificial dentition.

diabetes: any disorder of metabolism causing excessive thirst and the production of large volumes of urine.

diagnosis: the process of determining the nature of a disorder by considering patients’ signs and symptoms, medical background, and test results.

distal: situated away from the origin or point of attachment or from the median line of the body.

dorsum: the upper or posterior surface of a part of the body.
dysarthria: disturbance of articulation due to emotional stress or to paralysis, incoordination, or spasticity of the muscles used for speaking.

dysphagia: difficulty in swallowing.

dystrophy: a disorder of an organ or tissue, usually muscle, due to impaired nourishment of the affected part.

electromyography: method of evaluation by recording the electrical activity of a muscle by means of electrodes inserted into the muscle fibers.

epiglottis: a thin leaf-shaped flap of cartilage, covered with mucous membrane, situated immediately behind the root of the tongue.

esophageal: pertaining to the esophagus.

esophagus: the gullet. A muscular tube, about 23 cm long, that extends from the pharynx to the stomach.

etiology: the cause of a specific disease.

expiration: the act of breathing out air from the lungs.

extrinsic muscle: a muscle that has its origin some distance from the part it acts on.

faucial isthmus: the narrowed or constricted opening from the mouth to the pharynx.

faucial pillars: folds of mucous membrane on either side of the opening from the mouth to the pharynx.

fluoroscope: an instrument on which X-ray images may be viewed directly, without taking and developing X-ray photographs. It basically consists of a fluorescent screen, which is coated with chemicals that exhibit the property of fluorescence when exposed to X-rays.

gastroenterology: the study of gastrointestinal disorders and diseases, which may involve any part of the digestive tract and also the liver, biliary tract, and pancreas.

gastroesophageal sphincter (GES): a sphincter at the junction between the stomach and the esophagus, controlling the flow of material between them.
gastrostomy: means of feeding through a tube, connected to the stomach to allow food and fluid to be poured directly, when swallowing is impossible.

glossectomy: surgical removal of the tongue, usually to remove cancer tumors.

hard palate: the anterior portion of the palate.

hemiparesis: paralysis of one side of the body.

Huntington’s chorea: a jerky involuntary movement particularly affecting the shoulder, hips, and face. A chronic, hereditary disorder with gradual loss of mental faculties.

hyoid bone: a small isolated U-shaped bone in the neck, below and supporting the tongue, and also connected to the larynx.

hypopharynx: laryngopharynx.

hyposalivation: a decrease in saliva production.

incisor: any of the four front teeth in each jaw.

inferior: situated below or directed downward.

inflammation: the immediate defensive reaction of tissue to any injury which may be caused by infection, chemicals, or physical agents. It involves pain, heat, redness, swelling and loss of function of the affected part.

ingesta: solid or liquid nutrients taken into the body.

innervation: the nerve supply to an area or organ of the body.

intraluminal: within a tube.

intravenous: into the vein.

intrinsic muscle: a muscle that is contained entirely within the organ or part it acts on.

irradiation: the therapeutic application of electromagnetic radiation to a particular structure.
jejunostomy: means of feeding by direct connection to the jejunum (part of small intestine) through an opening in the abdominal wall.

labial: pertaining to the lips.

laryngeal: pertaining to the larynx.

laryngectomy: surgical removal of the larynx, usually to remove cancer tumors.

laryngopharynx (hypopharynx): the part of pharynx that lies below the hyoid bone (epiglottic level).

larynx: the organ responsible for the production of vocal sounds, also serving as an air passage conveying air from the pharynx to the lungs.

lateral: situated at or relating to the side of an organ.

lesion: a zone of tissue with impaired function as a result of damage by disease or wounding.

leukemia: any of a group of malignant diseases in which the bone marrow and other blood-forming organs produce increased numbers of certain types of white blood cells, suppressing the production of red blood cells.

lingual: pertaining to the tongue.

linguopalatal: pertaining to the tongue and the palate.

lumen: the space within a tubular or saclike part.

malocclusion: inability to properly bring the upper and lower jaws together due to misaligned dentition.

mandible: the lower jaw.

mandibular: pertaining to the mandible.

mandibulectomy: surgical removal of the mandible.

manofluorography: new, advanced technique of swallowing mechanism evaluation, employing simultaneous manometry and videofluoroscopy.
manometry: method of evaluation, measuring fluid pressure, using a catheter pressure transducer (manometer) (e.g., swallowing pressure (profile) in the pharynx and esophagus).

mastication: the process of chewing food.

maxilla: the upper jaw.

maxillary: pertaining to the maxilla.

maxillectomy: surgical removal of the maxilla.

molar: any one of the three posterior teeth on each side of each jaw.

motoneuron: one of the units that goes to make up the nerve pathway between the brain and an effector organ.

motor: relating to the output division of the nervous system, which carries information from the CNS to bring about activity in a muscle or gland.

multiple sclerosis (MS): a chronic disease of the nervous system affecting young and middle-aged adults, affecting different parts of the brain and spinal cord, resulting in scattered symptoms. These include unsteady gait, dysarthria, spastic weakness.

myotonia: a disorder of the muscle fibers that results in abnormally prolonged contractions.

myasthenia gravis: a chronic disease marked by abnormal fatiguability and weakness of selected muscles.

nasal: pertaining to the nose.

nasal cavity: the space inside the nose that lies between the floor of the cranium and the roof of the mouth.

nasogastric tube: a stomach tube passed through the nose.

nasopharynx: the part of pharynx that lies above the soft palate.

neurology: the study of the structure, functioning, and diseases of the nervous system.
neuromuscular: referring to the relationship between nerve and muscle, in particular to the motor innervation of skeletal muscles.

neuropathy: any disease of the peripheral nerves, usually causing weakness and numbness.

neurophysiology: the study of the complex chemical and physical changes that are associated with the activity of the nervous system.

oral: pertaining to the oral cavity.

oral cavity: the mouth.

orofacial: pertaining to mouth and face.

oropharyngeal: pertaining to the oropharynx.

oral-pharyngeal junction: the anatomical border between the oral cavity and the oropharynx.

oropharynx: the part of the pharynx that lies between the soft palate and the hyoid bone (epiglottic level).

orthodontics: the art and science of correcting malocclusion of the teeth.

palatal: pertaining to palate.

palatal vault: the arched "roof" of the mouth.

palate: the roof of the mouth, which separates the mouth from the nasal cavity and consists of two portions, the hard and soft palate.

palpation: the process of examining part of the body by careful feeling with the hands and fingertips.

parkinsonism: a disorder of middle-aged and elderly people characterized by tremor, rigidity, and a poverty of spontaneous movements.

peripheral nervous system: all parts of the nervous system outside the CNS (the brain and the spinal cord). It includes cranial nerves and spinal nerves and their branches.
peristalsis: a wavelike movement that progresses along some of the hollow tubes of the body, induced by the distension of the tube walls, thus pushing the contents of the tube forward.

pharyngeal: pertaining to the pharynx.

pharyngoesophageal sphincter (PES): a sphincter at the junction between the pharynx and the esophagus, controlling the flow of material between them.

pharynx: the throat. A muscular tube that extends from the esophagus to the base of the skull, divided into three regions: nasopharynx, oropharynx, and laryngopharynx.

physiology: the science of the functioning of living organisms and of their component parts.

physiotherapy: the branch of treatment that employs physical methods to promote healing (e.g., massage, exercises).

poliomyelitis (polio, infantile paralysis): an infectious virus disease affecting the central nervous system.

posterior: situated at or near the back of the body or an organ.

postpolio sequelae: the condition in which a second or late progression of weakness and atrophy is observed after the initial attack of poliomyelitis much earlier in life.

preparatory segment (oral): the initial segment of the oral phase, where the bolus is formed and held between the tongue and the palate prior to its transport to the pharynx.

propulsive segment (oral): the concluding segment of the oral phase, where the bolus is transported from the oral cavity to the pharynx.

prosthesis: any artificial device that is attached to the body as an aid, to replace a missing or nonfunctional part.

prosthodontics: prosthetic dentistry.

proximal: situated close to the origin or point of attachment.
pyriform sinus: a recess in the pharynx on each side of the opening of the larynx.

radiography: the technique of examining the body by directing X-rays through it to produce images on photographic plates or fluorescent screens.

radiology: the branch of medicine concerned with the use of radiation, including X-rays, and radioactive substances in the diagnosis and treatment of disease.

radioopaque: having the property of absorbing, and therefore being opaque to X rays (e.g., barium).

receptor: a cell or group of cells specialized to detect changes in the environment and trigger impulses in the sensory nervous system.

reflex: an automatic or involuntary activity brought about by nerve stimulus.

regurgitation: the flowing back of material in a direction opposite to the normal one (e.g., nasal regurgitation).

respiration: the process of gaseous exchange between an organism and its environment. This includes external respiration (breathing) and internal respiration (oxygen - carbon dioxide exchange).

retainer: any type of clasp, attachment, or device used for the fixation or stabilization of a prosthesis.

scintigraphy: the process of obtaining a photographic recording of the distribution of an internally administered radioactive tracer with the use of a scintillation detector device, a gamma camera.

sensation: a feeling - the result of messages from the body's sensory receptors registering in the brain as information about the environment.

sensitivity: a measure of the reliability of a screening test based on the proportion of people with a specific disease who react positively to the test.

sensitization: alteration of the responsiveness of the body to the presence of a foreign substance.

sensory: relating to the input division of the nervous system, which carries information from receptors throughout the body to the CNS.
soft palate: the posterior segment of the palate.

spasticity: resistance to the passive movement of a limb that is maximal at the beginning of the movement and gives way as more pressure is applied.

sphincter: a specialized ring of muscles surrounding an orifice, controlling its opening and closure (e.g., PES, GES).

stimulus: any agent that provokes a response, or particular form of activity, in a cell, tissue, or other structure, which is said to be sensitive to that stimulus.

stroke: a sudden attack of weakness or paralysis, usually affecting one side of the body. It is the consequence of an interruption to the flow of blood to the brain.

suction: the mechanism by which material is transported by means of negative fluid pressure (gradient).

sulcus (anterior/lateral): the narrow groove between the teeth and the cheeks.

superior: situated above or directed upwards.

swab: a pad of absorbent material (cotton), attached to a stick, used for cleaning out or applying medication to wounds, operation sites, or body cavities.

tongue thrust swallow: the infantile pattern of suckle-swallow movement in which the tongue is placed between the incisor teeth during the oral phase of swallowing, often resulting in malocclusion.

tonic: relating to normal muscle tone.

trachea: the windpipe.

trauma: a physical wound or injury, such as a fracture or blow.

ultrasonography: method of evaluation, using sound waves of extremely high frequency, to produce pictures of structures within the body.

valleculae: a depression located just above the epiglottis.

velolingual: pertaining to the soft palate and the tongue.
velopharynx: the part of pharynx lying posterior to the soft palate, at the junction between nasopharynx and oropharynx.

videofluoroscopy: radiographic method of evaluation, using videotapes to record fluoroscopic images for frame-by-frame analysis of the physiological events.

wall: an investing part enclosing a cavity, or covering any anatomical unit (e.g., posterior pharyngeal wall).

X-ray pellet tracking: method of evaluating movements of a structure by tracking pellets, positioned to demarcate the structure, with transmitted X-rays.