Viggo Pettersen

From Muscles to Singing

The activity of accessory breathing muscles and thorax movement in classical singing

Doctoral thesis
for the degree of dr. philos.

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Norwegian University of Science and Technology
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PREFACE

This thesis is submitted for the degree of dr. philos. at the Faculty of Medicine, Norwegian University of Science and Technology (NTNU). The research has been performed with Professor Rolf Harald Westgaard as supervisor. From my professional background as a singer and singing teacher he has gently guided me into the world of science.
The research project was financed by the University of Stavanger (UiS) and by the Stavanger University Fund.

From the long list of persons, to whom I am most grateful, I would like to extend especial thanks to Professor Rolf H. Westgaard for undertaking the task of cooperating with me on this research project, without having any formal responsibility for the project itself. Without him, no thesis would have seen the light of day. I would like to express my warm appreciation to Associate Professor Jan Terje Kvaløy for statistical guidance, and to my colleague, Professor Kåre Bjørkøy, for valuable discussions and cooperation in research. Warm thanks are also due to my employers and to my colleagues at the Department for Music and Dance, who have shown me a supportive attitude throughout the research period.

I am grateful to my daughter Kristin for the insight she has given me into the research field and many thanks to my son Håvard for most valuable discussions on human anatomy.

I dedicate this to my wife, Liv, who has been a constant source of encouragement and inspiration in all my work.

Viggo Pettersen

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ABBREVIATIONS and DEFINITIONS

ANOVA	analyses of variance
anterior	towards the front, away from the back
BF	biofeedback
body mass index	weight divided by height squared
caudal	towards the tail, away from the head
cranial	towards the scull
EMG	electromyographie
INT	intercostals
lateral	away from centre, towards the side
medial	towards the axis, near the midle
MVC	maximal voluntary contraction
OBL	abdominal muscles
PHY	physiometer
PN	muscles in posterior neck
POS	professional opera singers
posterior	towards the back, away from the front
RC	rectus abdominis
RMS	root-mean-square
rostral	towards the head
SC	scalenus muscles
SCP	student classical pianists
SCS	student classical singers
SP	splenius capitis

SPSS	statistical package for the social sciences
SSP	semispinalis capitis
STM	sternocleidomastoideus
TR	upper trapezius
TX	thorax
VC	vital capacity
VLP	vertical larynx position
µV	micro volt

ABSTRACT

The overall aim of the present studies was, in selected muscles, to investigate muscle activation levels and muscular patterns in classical singers. Further was these muscles' relation to thorax movement investigated.

Loading levels and respiratory phasing of TR, STM and SC was investigated in vocalization tasks with high and moderate expiration. Further, PN activity was investigated in inhalation and phonation and finally, TR, INT, OBL and RC muscle loading in student and professional singers was examined.

Muscle activity was recorded by use of an ambulatory four-channel monitoring system (Physiometer PHY 400, Premed, Norway). TX movement pattern was traced with two strain gauge sensors (RES-117) placed around the upper TX and lower TX .

A phasing of upper TR activity to INT and OBL activity was discovered, all muscles supporting the expiration phase. During phonation TR contributes in the compression of the upper TX, thus serving as an accessory muscle of expiration. TR activity is reduced with short breathing cycles and is mostly inactive in simplified speaking tasks During phonation professional opera singers activate the expiratory phased TR, INT, OBL and RC muscles to higher levels than student singers do.

STM and SC show correlated activity patterns during inhalation and phonation by classical singers. During demanding singing expiratory phased STM and SC activity peaks produce a counterforce to the compression of upper TX at high pitches. As breathing demands are lowered STM and SC activity are reduced and attain inspiratory phasing. Substantial muscle activity is observed in posterior neck muscles (PN) during inhalation and phonation. EMG biofeedback performed on TR and STM have a secondary effect of lowering EMG activity in PN.

PEDAGOGICAL FUNDAMENT FOR THESIS

During 30 years of experience both as a singer and teacher of young classical singers, an increasing need for more specific knowledge concerning muscle usage in classical singers is seen. Even if muscle usage varies considerably from singer to singer, teachers agree that the muscles in use when singing should be used as economical as possible. What is lacking, however, is a nuanced understanding of what we mean by economical. This thesis is an attempt to approach this issue.

Voice pedagogy heavily emphasize that relaxed neck and shoulders are favourable to good sound production. My assumption is, therefore, that the shoulder and neck region will be relaxed during singing by high skilled classical singers. Thus, individual differences in neck and shoulder activity levels will be related to vocal skills. Following this, professional singers will have less shoulder and neck activity than student singers. Therefore, the first aim of this thesis is to investigate activity levels and activity patterns in chosen neck and shoulder muscles in student and professional classical singers.

The term breathing support is frequently discussed among colleagues. Even so, consensus of term is missing. Lack of consensus regarding term in teaching breathing technique to students have for a long time been confusing to myself and many of my colleagues. When breathing support is instructed to students most of the attention is directed to the abdominal region. An observation is that the effect from these instructions on the students is highly individually conditioned. Inspired by a paper of Tom A. Sears (Some neutral and mechanical aspects of singing, 1977) I have for some years, additionally to abdominal activity, also directed my attention to thorax movement when practising breathing for singing and instructing it to others. The second aim of the thesis is, therefore, to investigate activity levels and activity patterns in chosen trunk muscles by classical singers.

The selection of muscles in the shoulder and neck is determined from different aspects. Many singers complain about tension and sometimes pain in the shoulder area. Often it is impossible to observe any misuse, and, therefore, difficult to guide posture improvement in the shoulder region. Through the work of Barlow (1973) I have for many years recognized the importance of proper posture. In the “Alexander Principle” (Barlow 1973) an economical use of the trapezius muscle is considered important to good posture. This, together with own experience in practising the “Alexander Principle” for more than twenty years, makes the trapezius muscle a natural choice. The specialist literature states that neck muscles not usually are included in breath management by classical singers (Miller 1986). On the other hand, activation of muscles in the neck is easily observed by some singers. It is, therefore, of interest to explore this activity. By observation of some colleges in singing and by student singers I have noticed that the sternocleidomastoideus muscle is activated during the phonation process. Some singers show an extensive use of this muscle, while others have a modest use. This divergence is easily observed and sternocleidomastoideus is, therefore, a natural second choice for investigation. The observed sternocleidomastoideus activity in singers leads to the assumption that this activity is involved in breathing. Pronounced use of upper thoracic and neck muscles during inhalation is called clavicular breathing (Zemlin 1998). If clavicular breathing is used by classical singers, the scalenes will probably be activated (Zemlin 1998, Miller 1986, Rørbeck 1988). The scalenes are, therefore, the third choice of muscles for investigation. The posterior part of the neck is often a concern when singers complain about neck pain. During phonation this area can be exposed to pain and stiffness by classical singers (and following this, also sometimes during rest). Therefore, the muscles in the posterior part of the neck are the fourth choice for investigation.

The final choices are in the trunk region. My interest in the intercostals and the movement of thorax was aroused, as mentioned above, by reading an article of Tom A. Sears (1977). The fifth choice is, therefore, the intercostal muscles. The sixth and seventh choice of muscles are in a region frequently discussed under the term “ breathing support” in voice pedagogy. The region discussed most is the abdominal region in general and the lateral and anterior parts in particular (Miller 1986). The sixth choice is, therefore, the lateral part of abdomen and the seventh is the anterior part of the abdomen.

INTRODUCTION

During second half of 20th centaury, the importance of posture to wellbeing became popularized through the works of Alexander (Barlow 1973) and others, but its importance to voice production have been recognized by singing teachers for centuries (Rubin et al., 2004).

Voice teachers are instructing posture to classical singers in order to improve vocal performance. Both breathing behaviour and correct posture in general are considered important in order to perform well (Proctor 1968, Sears 1977, Emmons 1988, Sundberg & Leanderson 1991, Ivarsson 2001). The individual differences in human anatomy that have to be considered when instructing posture to classical singers is not yet fully explored (Hixon et al. 1988). The precise pattern of activity in the individual singer is depending on many factors, including the basic shape of the singers' rib cage and the manner it is held when singing (Sears 1977).

Electromyographic recording of muscle activity (EMG) is a well-established technique to characterize muscle activity under a variety of conditions (Basmajian & De Luca 1985, Cram & Kasman 1998). Some work has been done in characterizing laryngeal muscle activity. Laryngeal electromyography on speakers and singers goes back to work by Katsuki in the 1950s, with other studies the following decades (Faaborg-Andersen 1957, Faaborg-Andersen & Soininen 1959, Zenker & Zenker 1960, Faaborg-Andersen & Vennard 1964, Hirano et al. 1967,1969,1970. Vennard et al. 1970-71, Lastkova et al. 1984, Hirano 1988. Redenbaugh et al. 1989). Studies investigating breathing function in the intercostals and the abdominal muscles have also been carried out (Floyd 1950, Taylor 1960, Elben 1963, Campbell 1968, Campbell et al. 1970, Newsom Davis & Sears 1970, Sears 1973,1977, Strohl et al 1981, Goldman et al. 1987, Watson et al. 1989, MacFarland 1989, De Troyer et al.1990, Sundberg et al 1991). Additionally, a few studies have investigated the breathing function in sternocleidomastoideus and the scalenes. (Raper et al. 1966, Campbell 1970, Vitti et al. 1973, Basmajian & De Luca 1985). However, it appears that little scientific research has been done to evaluate muscle usage in classical singers by use of surface EMG.

Far more research is needed to fully understand the complex relations between posture, muscle usage and breathing. The overall aim of the present studies is, therefore, to investigate muscle activation levels and muscular patterns in selected muscles by classical singers. Further will these muscles' relationship to thorax movement be investigated.

Selected muscles:

A pilot investigation of 12 actual muscles was performed at the NTNU EMG laboratory in Trondheim. An EMG response from most of the muscles was found, and motivated by these findings seven muscles were included in the study.

Upper trapezius (TR)

Motivation for research

"At the time when the student is willing to make sufficient efforts to learn breath control, a certain amount of time must be spent correcting posture and teach the singer to keep the shoulders relaxed and independent of the breathing mechanism". The statement by Emmons (1988) elucidates the thinking and language common among singing teachers and reflects their observations of the vocal benefits from the postural adjustments made. Shoulder muscles, such as TR, have received little attention in voice research, since these muscles have been perceived to have uncertain or no breathing function.

Westgaard et al. (1987) and later Wærsted et al. (1994) found that TR also was responsive to mental stress and may respond with quite high activation levels in situations that were mentally challenging even when no biomechanical effort was needed. Caspar (2001) stated that distress reduces behavioral efficiency and disturbs voicing, speaking and acting more or less seriously. In particular singing, which is sensory-motor phenomenon that requires particular balanced skills, is easily disturbed. Rubin (2003) describe tight TR to be one of the characteristics of tension fatigue among singers.

Posture

The primary biomechanical effect of upper TR activation is elevation of the shoulders. The muscle further contributes in the stabilization of the scapula when performing arm movements (Basmijan & De Luca 1985).

Breathing

Some EMG activity was found during very deep inhalations (explored by Campbell 1968).

Sternocleidomastoideus (STM)

Motivation for research

Because of the relationship of STM to the supportive structure of the larynx and because of the relation of the skeletal frame to the sternum and to sternal posture, STM can, to some extent, be considered supportive of the phonatory mechanism. In some techniques of singing sternal elevation is relatively high while in other techniques a lowered sternum is considered desirable (Miller 1986). Tight sternomastoids is one of the characteristics of tension fatigue among singers (Rubin et al. 2003).

Jones (1972) showed that lowered activity in STM lead to lengthening of the muscle, which in turn gave increased richness of overtones in the singing voice.

Posture

STM fixes and elevates the head, flexes the caudal and extends the cranial cervical vertebrae and joints of the head. Unilateral innervation inclines the head and turns it to the opposite side (Sobotta, Atlas of Human Anatomy volume 1, 1994).

Breathing

Vitti et al. (1973) detected moderate STM EMG activity in 18 of 20 non-singers by deep breathing, and described STM as having auxiliary or accessory function to inhalation. Also Campbell (1970) described STM to be activated in breathing at very high levels of ventilation. Raper et al. (1966) investigated STM activity in seven young men, all nonsingers, and found that none used the STM muscles during quiet breathing. Onset of muscle activity was related to percentage of vital capacity during active inspiration. Campbell (1970), Raper (1966) and Basmjian/De Luca (1985) all classify STM as accessory muscles of inspiration by elevation of sternum, which increases the anterior-posterior diameter of thorax. Such, the activity found in STM is according to previous studies related to posture manoeuvres and to percentage of vital capacity by inhalation.

Scaleus muscles (SC)

Motivation for research

Sataloff et al. (2003) characterized healthy vocal technique to include relaxed shoulders and neck muscles even with deep inspiration. Further was economy mentioned as a basic principle of all art forms. Wasted energy and motion and accompanying muscle tension are incorrect and usually deleterious.

Two neck muscles are often mentioned as muscles of inspiration. STM lifts the sternum and SC lifts the two uppermost ribs when the head is kept in a fixed position by inhalation (Zemlin 1998). STM is already chosen and SC is, therefore, a natural second choice.

Posture

The anterior scalene, the middle scalene and the posterior scalene incline the cervical spine laterally (Sobotta, Atlas of Human Anatomy volume 1, 1994). Acting from below, the muscles on one side will bend the cervical column towards the contracting side, and when all scalene groups are active, they facilitate flexion of the cervical column (Zemlin 1998).

Breathing

Campbell (1970) reported that SC often was active during quiet breathing. Raper et al. (1966) investigated SC in seven young men, all nonsingers, and found that five of seven subjects showed scalene EMG activity during quiet breathing. Onset of muscle activity was related to percentage of vital capacity during active inspiration. Campbell (1970), Raper (1966) and Basmjian/De Luca (1985) all classify the scalenes as ordinary muscles of breathing. Their function is to elevate the two cranial ribs in forced inspiration.

Posterior neck muscles (PN)

Motivation for research

When pain discomfort was registered by 227 music students (Nordic Musculoskeletal Questionnaire, including nine body areas), Zetterberg et al (1998) found that musicians of all levels have a high incidence of musculoskeletal problems, especially from the neck and upper extremities. The group of musicians that included the singers had highest scores for pain experience in the neck region. From this, it can be hypothesized that there is a contradiction between the way voice -teachers advice shoulder and neck muscles to be used and the way some singers use these muscles when singing. Even if neck and shoulder activity during the phonation process is to be avoided according to voice experts (Carrol 2003), it is possible that the neck area is exposed to excess activity during the phonation process. In the study by Zetterberg and co-workers, it was not specified what part of the neck area the pain was related to. Therefore, in addition to anterior-lateral neck activity (STM, SC), also EMG activity from the posterior neck region (PN) is of interest to explore concerning activity levels during the phonation process.

Posture

The posterior cervical muscles can be divided into four layers. The first layer is formed by the upper trapezius muscle, the second and third layers are mainly formed by the splenius and semispinalis capitis muscles, respectively, and the fourth layer is formed by the small muscles between the occipital bone and the first two cervical vertebrae (Takebe et al. 1974). The function of upper trapezius is already described. The main function of the semispinalis capitis is the extension of the head and the main dual function of the splenius capitis is extension of the head and rotation to its own side (Takebe et al. 1974).

Breathing

The muscles in the posterior neck are not expected to have a breathing function.

Intercostal muscles (INT)

Motivation for research

A considerable body of evidence has shown that the neural regulation of intercostal muscles is similar to that of the limb muscles, especially with regard to their load-compensating function. By analogy with the small muscles of the hand, the muscles spindles of the intercostals are admirably well suited to the task of regulating sub glottal pressure during speech and singing (Sears 1977).

Posture and Breathing

Taylor (1960) suggested that the inner and outer layers of the muscle exert opposite rotational forces on individual ribs in posture manoeuvres.

In breathing, the external intercostals tighten the intercostal spaces in inspiration, and the internal intercostals tighten the intercostal spaces in expiration (Sobotta, Atlas of Human Anatomy volume 2, 1994). In quiet breathing Taylor (1960) found EMG activity was limited to the lower lateral part of the thoracic cage. No external intercostal activity was found in quiet breathing. In more vigorous breathing, activity was found throughout the external layer. There is evidence that activity spreads from upper spaces downwards with increasing size of inhalation. Expiratory activity during quiet breathing was discovered in the lower four spaces between the angel of the ribs and the anterior axillary line (Taylor 1960). With more vigorous breathing and forced expiration, activity occurs throughout the internal intercostals, spreading from the lower spaces upwards with increasing size of breath (Taylor 1960, Campbell & Newsom Davis 1970). Onset of activity between different recording sites in the intercostal region varies with lung volume. This is a notable feature during EMG sampling of the intercostal muscles (Newsom Davis & Sears 1970).

Abdominal muscles (OBL), Rectus abdominis (RC)

Motivation for research

Voice experts recognize the importance of these muscles as pressure generators for expiration. Modifying the habits of "breathing support" practice often solves a phonatory problem. However, a consensus understanding of the term "breathing support" in terms of muscle activation patterns is not properly established (Leanderson & Sundberg 1988). Furthermore, singers vary in their anthropometrics and posture and may therefore need individual adjustments in the use of the respiratory and postural muscles for the best singing result. Thomasson & Sundberg (1997) found that the contribution to lung volume changes from thorax and abdominal wall movement varied between professional singers, indicating that professional singing does not require a uniform breathing strategy. Therefore, a likely main reason why singing teachers teach breathing so differently is individual experiences from own career (Auserwald 1968, Sears 1977, Hixon et al. 1988).

Posture and breathing

Strohl et al. (1981) reported that the abdominal muscles acted independently during various respiratory and nonrespiratory activities. Goldman et al.(1987) found that the role of the individual abdominal muscle was to modulate trunk movement, but in breathing they acted together. De Troyer et al. (1990) found that transversus participated in breathing well before the rectus abdominis and the external oblique whenever contraction of the abdominal musculature was induced involuntarily. Voluntary respiratory manoeuvres did not reveal any clear-cut differences between the transversus and the rectus abdominis or external oblique. Cresswell et al.(1992) concluded that the coordinative patterns shown between the muscles of the ventolateral abdominal wall were task specific, based upon demands of movement, torque and stabilization. It appeared that transversus abdominis was the abdominal muscle whose activity most consistently related to changes in abdominal pressure.

MATERIAL and METHODS

Subjects

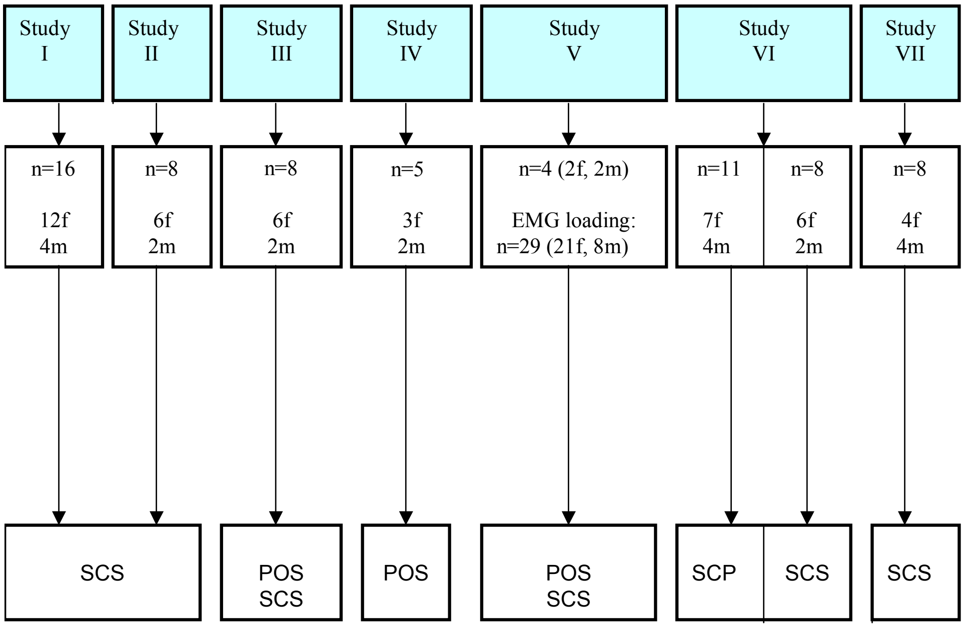


Figure 1. A schematic over-view of subjects participating in the experiments.

SCS: student classical singers, POS: professional opera singers, SCP: student classical pianists, n: number, f: female, m: male.

A schematic over-view of the subjects included in the different studies is seen in Figure 1. The students participating in study I, II, III, V and VI were students at the Department of Music and Dance, University of Stavanger (UiS). The professional singers in study III - V were under contract with the Norwegian Opera (DNO) and the student singers in study VII, and partly study V, were students at Trondheim Music Conservatory, Norwegian University of Science and Technology (NTNU). All subjects were normal, healthy singers. One of the opera singers was pregnant. Student singers and pianists were between 20 and 30 years old and the professional opera singers were between 30 and 40 years old.

Electromyographic recordings

Electrode placement and the location of the breathing sensors are illustrated in Figure 2. Muscle activity was recorded by an ambulatory monitoring system with surface EMG (Physiometer PHY 400, Premed, Norway), using silver/silver chloride bipolar electrodes with an active diameter of 6 mm. A center-to-center distance of 20 mm was used for all EMG recordings. The EMG activity was band-pass filtered at 20-800 Hz and sampled at 1600 Hz. The EMG signals were thereafter A/D converted, the root-mean-square (RMS) value calculated and transmitted at 10 Hz on a serial interface to a PC. The processed signals were further analyzed by use of the Physiometer software, using a time resolution of 0.2s.
The EMG sites corresponded to locations with stable, high EMG responses, verified by a 13-channel array electrode. The EMG responses were calibrated in percent of the EMG response in maximal voluntary contraction (%EMG_{max}), using static contractions in an attempted movement pattern that activated the muscle maximally. Electrode sites and attempted movements are described below.

TR site

The medial electrode was placed 2.5 cm lateral to the midpoint between C7 and acromion (Figure 2) (Jensen et al. 1993). For TR the attempted movement was arm elevation with the arms abducted 90° in the scapular plane.

STM site

The rostral electrode was placed 2 cm below processus mastoideus, towards the medial end of clavicula (Figure 2). The attempted movement was lateral flexion of the head.

SC site

First electrode was placed 2-3 cm caudal from Processus Mastoideus, and the second 2 cm further down the same line (Figure 2). For SC the attempted movement was lateral flexion of the head.

PN site

PN site had first electrode 3-4 cm cranial to C7 and second electrode 2 cm further up the same line, both electrodes 2 cm to the right of the midline (Figure 2). A backward (from bended forward) rising of the head (chin up) served as movement pattern.

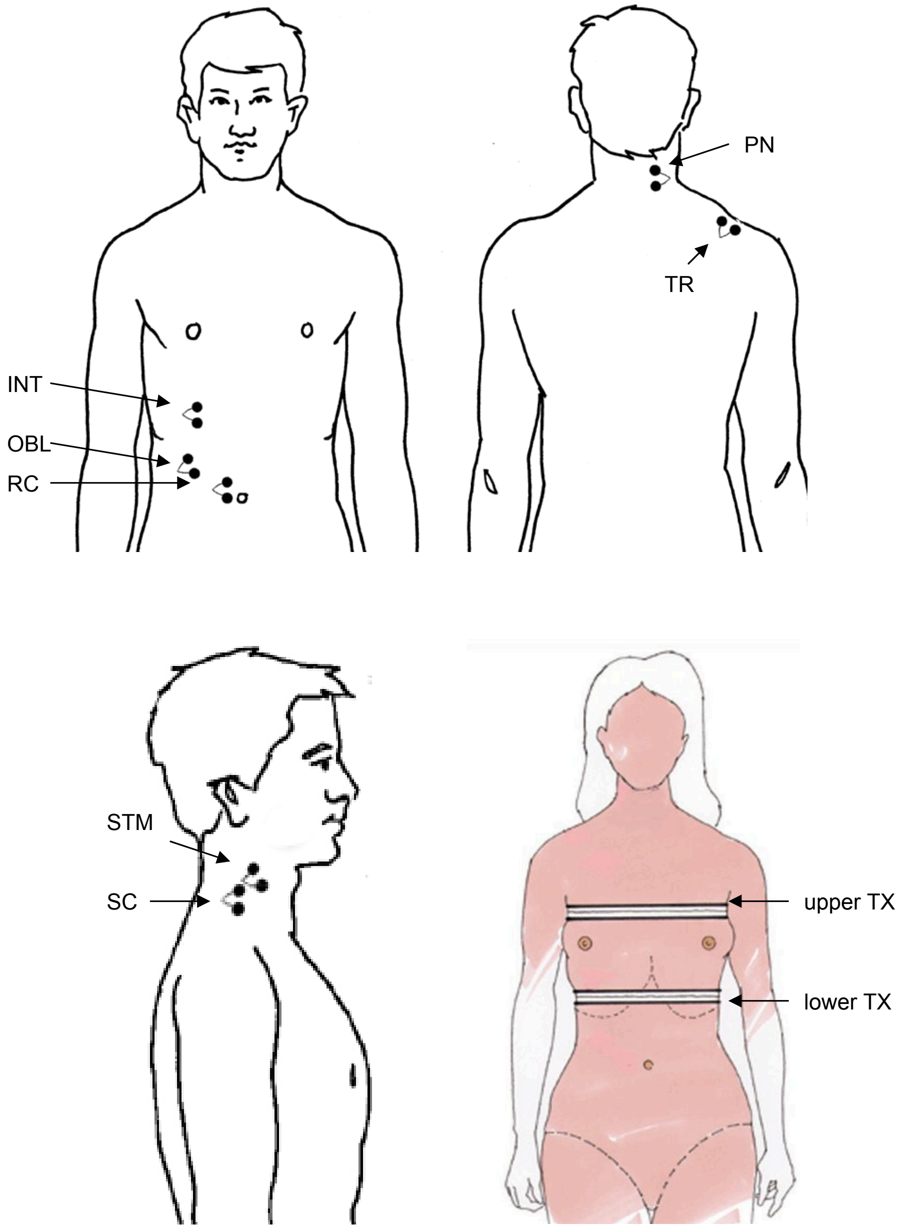
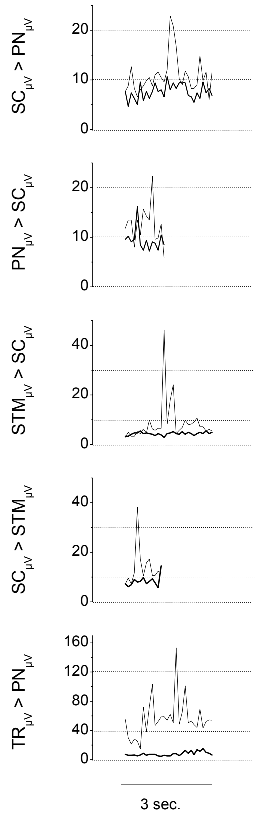


Figure 2. The anatomical position of electrode placement and the position of respiration sensors on TX (TR: upper trapezius, STM: sternocleidomastoideus, SC: scalenes, PN: muscles in posterior neck, INT: intercostals, OBL: abdominal muscles, RC: rectus).

Visual inspection of PN and TR recordings (Paper IV) excluded major TR contribution to the PN site EMG signal. Electronic crosstalk between STM, SC and PN electrode locations (Paper IV) was also excluded as a significant problem in the recordings. (c.f, Discussion: Methodological considerations; cross talk between signals). Figure 3 show examples of recorded segments considered in this analysis.



Figur 3. Selected segments of EMG recordings to illustrate the independence of signals between the recording positions.

The segments were selected to show a marked change in activity level at one position while the other recording at the same time had low EMG amplitude. The thick line is the EMG signal from the muscle with the lowest EMG activity.

INT site

The caudal electrode was placed between costae 9 and 10, perpendicular down from papilla mammaria, the rostral electrode between costae 8 and 9 on the same line (Figure 2). A maximal compressed and elevated rib cage served as movement pattern for INT.

OBL site

The rostral electrode was placed 2 cm below the lowest part of the rib and the lower electrode 2 cm further down towards the os pubis (Figure 2). For OBL the attempt to maximal compress the abdomen gave the best response.

RC site

For RC the caudal electrode was positioned 3 cm to the right of the midline at the height of umbilicus and the rostral electrode 2 cm higher at the same distance from the midline (Figure 2). The maximal contraction movement for RC had the subjects half lying in a chair with immobilized feet, lifting the upper part of the body halfway to sitting posture.

Two or three attempts of a maximal contraction were made for each muscle.
The ground electrode for the Physiometer with TR, STM, SC and PN recordings was placed on the spine of the C7 vertebra, and on Spina iliaca for the 2nd Physiometer with INT, OBL and RC.

TX movement

TX movement was traced with two strain gauge sensors (RES-117) placed around TX and sensing TX circumference. One sensor was located with the upper edge at the axilla level (upper TX) and the other around the lowest part of TX (lower TX), as illustrated in Figure 2.

Procedure

Table 1 describes the experimental procedure for studies with BF included. A schematic overview of all experimental procedures is shown in Figure 4. Four singing tasks were performed; 1) an aria, 2) sustained tones maintained to exhaustion, 3) extreme tones maintained to exhaustion (and performed in sequences: study VII) and 4) glissando. In studies I, II, III and VI the student singers chose the aria freely from their repertoire. The student singers in study IV all sang " Sommertime" from Porgy & Bess by Gershwin. In studies III - V the professional singers chose the aria freely from their professional repertoire. Pilot studies had shown that muscle activity varied with pitch and vocal loudness when performing. To trace possible variances due to changes in vocal loudness, the aria was performed three times in three different vocal loudness (normal, forte, piano). The singers were asked to envision the normal version as singing in a "normal" sized concert hall. The forte version was to be envisioned sung as if performed in the largest concert hall they had performed in, and the piano version in the smallest concert hall they had performed in. The intention was to create situations were the singers were allowed to sing closest to the way they were used to when performing. In all studies including sustained and extreme tones, these were instructed shortly before the recording concerning pitch, vowel, vocal loudness and duration. To trace possible variances due to pitch changes, the sustained tone was sung in three different pitches suited for the voice (normal, third up, third down). The three extreme tones was the comfort tone (used to test if the voice was functioning well, chosen freely by the singer), the highest tone used in professional singing and the lowest tone used likewise. To establish a normal good sound production the middle tone was first performed, then the highest version and finally the lowest version. All activities were repeated after the BF session in studies I - V. In study VII sequences of sustained vowels /a: e æ o:/ were performed in a glissando from low pitch to highest pitch back to low pitch, in extreme tones (comfortable, lowest and highest pitch) and spoken softly and loudly. The subjects inhaled between the vowels. The purpose of study VII was to explore neck and shoulder muscle activity and the movement of upper TX as pitch changed and as breathing demands changed. How to perform the singing and speaking tasks was instructed to the participants shortly before the recordings.

STUDIES	PROCEDURE	ACTIVITY
Calibration Studies I - VII	Each muscle was exposed to max effort; thereafter resting activity value was recorded.	All calibration is done in a sitting position. See text for details.
Studies I -VI	1st singing through the aria.	All singing was done in an upright position. Normal volume for singer.
	2nd singing through the aria.	Increased volume, forte (f) compared to the first singing.
	3rd singing through the aria.	Reduced volume, piano (p) compared to the first singing.
Studies I, II, IV, V.	1st sustained tone	The singer was asked to sing the tone in mezzo forte (mf), duration for as long as possible (vowel a:) (soprano:d2, mezzosoprano:c2, contraalto:a1, tenor: c#2, baritone: h1, base:a1)
	2nd sustained tone	A small third up from 4th reg. (vowel a:)
	3rd sustained tone	A small third down from 4th reg. (vowel a:)
Studies IV, V, VII	1st extreme tone	Comfortable tone (used to test if the voice sounded well) (Studies 4 & 5;vowel a:) (Study 7; sequences of tones on the vowels: /a: e æ o:/ sung in mezzo forte (mf))
	2nd extreme tone	Highest tone used in professional singing (Studies 4 & 5 ;vowel a:) (Study 7; sequences of tones on the vowels: /a: e æ o:/ sung in mezzo forte (mf))
	3rd extreme tone	Lowest tone used in professional singing (Studies 4 & 5 ;vowel a:) (Study 7; sequences of tones on the vowels: /a: e æ o:/ sung in mezzo forte (mf))
Study VII	Glissando	Sequences performed on the vowels /a: e æ o:/, from low to high to low pitch
	Speaking soft	Normal soft speaking voice /a: e æ o:/
	Speaking loud	Normal loud speaking voice /a: e æ o:/
Studies I- V	**Biofeedback**	10 min. session. EMG signals were observed and used to practice a reduction in muscle activity. No registration of activity was done.
Studies I - V	Procedures before BF are repeated	The singers were instructed to perform exactly as they did before BF. Additionally they were asked to keep a mental focus on keeping the activity level of TR and STM low.

Table 1. Table to show the experimental procedures for studies with BF included.

The BF procedure in studies I and II was carried out with a stationary PC display. The BF procedure in studies III, IV and V was carried out by use of a PC laptop display. In all studies the displays were also used to monitor the EMG signals. During the BF session the singer looked at the display and observed the recorded muscle activity from TR and STM. By looking at the display while varying the activity level, the singer experienced that he/she could influence the level of activity by varying the muscular effort. The singer was then instructed in maneuvers used to reduce the activity level in the two muscles to a minimum. The singer was not able to observe the display during the singing sessions before and after BF. Before singing tasks following BF, they were instructed to repeat exactly the procedures of the sessions before BF. In this, they should maintain a mental focus on keeping the activity level of TR (Study III), or TR and STM (Studies I, IV, and V) as low as possible, using their experience from the BF session.

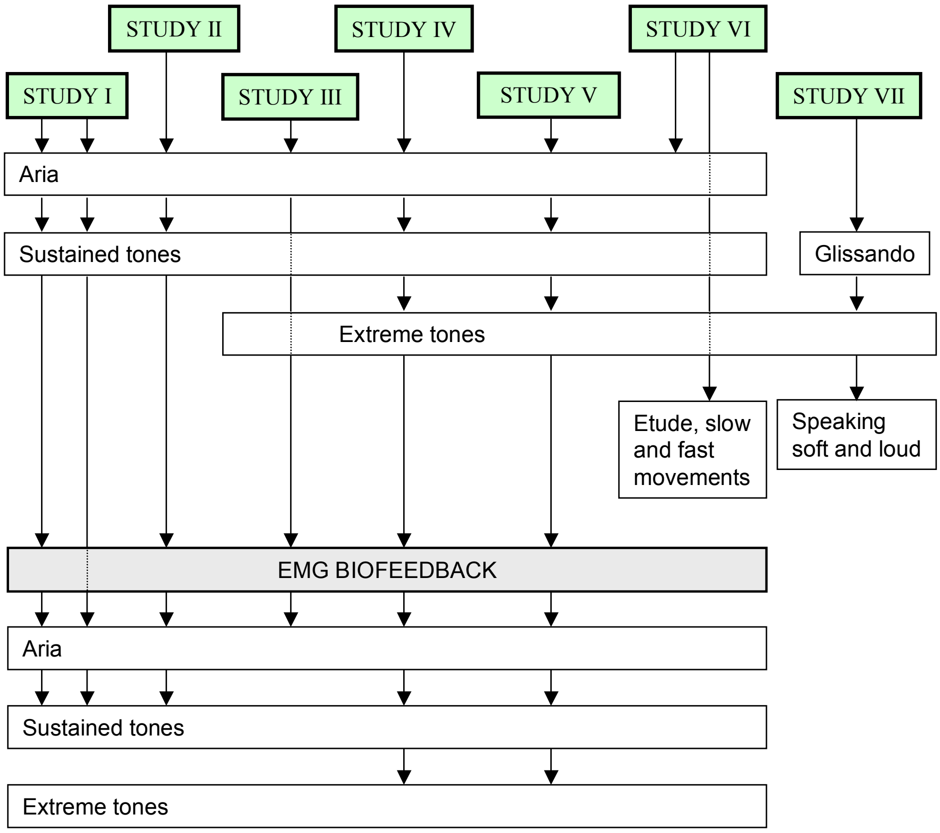


Figure 4. A schematic overview of the experimental procedures in all studies.

Procedures were carried out in fixed orders, as marked by arrows. Study I and VI consisted of two groups with different procedures. Difference in procedure is marked with solid and dotted line.

Analysis

All recordings were transferred as ASCII files to a PC for further analyses. The data were statistically tested by SPSS 11.0 (studies I, III, V) and SPSS 11.5.1 (II, IV,VI, VII) for Windows. Responses before and after BF were compared by a paired samples, two-tailed t-test (study I & V) and a non-parametric paired samples two-tailed Wilcoxon test (paper II, III and IV). The three conditions of the aria, the sustained tones, the extreme tones, and the between-subjects factor within each condition were tested by an ANOVA two-way analysis of variance. Ninety-five percent confidence interval (95% CI) of the difference in median activity level before and after BF was calculated based on the assumption of a normal distribution; however, normality was difficult to verify due to the low number of recordings (study I & V). For testing correlations, the Spearman's rho (ρ) nonparametric correlation test was used (studies III-VII). Responses from left and right side were tested by a non-parametric paired samples Wilcoxon test (study VI) and comparisons of median values between groups were tested by a non-parametric independent samples Wilcoxon test (study VI). A linear mixed-model was used for testing relationship between TX median% and EMG activity between tasks in vocalization of simplified singing and speaking (paper VII). A one-sample Kolmogorov-Smirnov test was used to test the normal distribution assumption, and correlations between muscle activity and upper TX circumference was tested by a one-sample t-test (paper VII).
For all analyses a p-value less than 0.05 (two – tailed) was considered to indicate statistical significance.

SUMMARY OF RESULTS

Paper I

Muscle activity in the classical singer's shoulder and neck region

The first objective of this study was to characterize the level of activation of TR and STM in singing students. BF was used to lower the activity of both muscles. Finally, it was examined whether the experiences from the biofeedback session could be transferred into regular singing by maintaining a mental focus on the experiences made in the BF session. This exploratory study indicated that BF was a useful method to lower the muscle activity level, particularly in TR but also in STM (Figure 5). The study indicated that singers, despite a daily awareness of posture, still may have an overuse of especially TR but also STM. Gross elevation of the shoulders or other clear misuse of muscles was generally not observed, however, excess activity still took place.

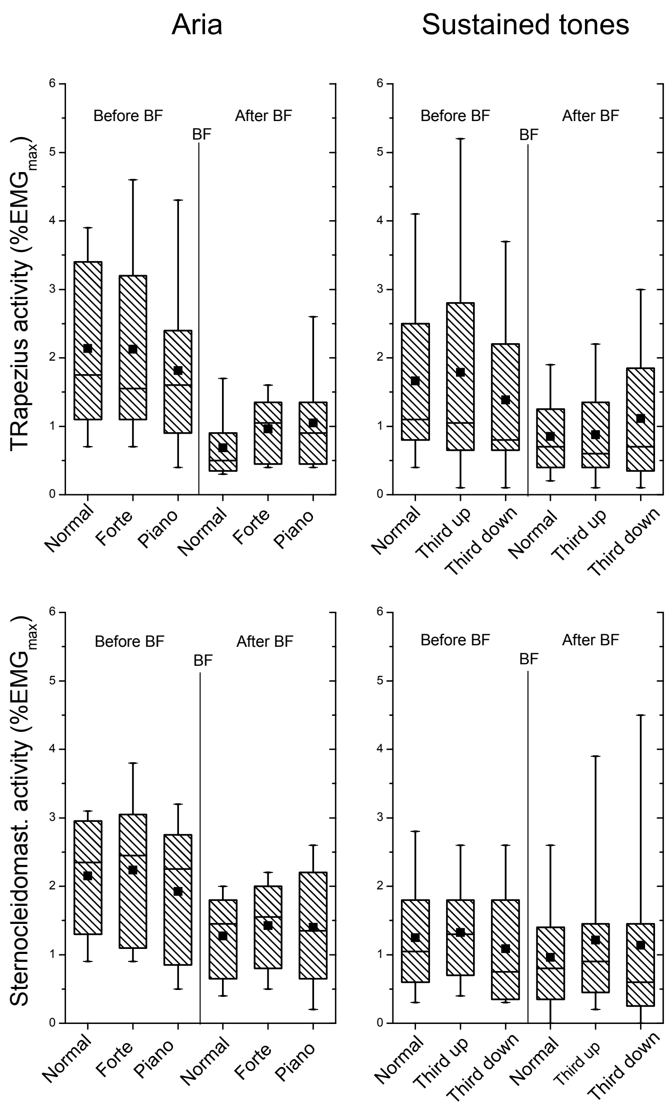


Figure 5. Box diagrams to show group results of medians before and after BF.

The reduction after BF is significant for TR and STM in all versions of the aria. In the sustained tones the corresponding result is significance for TR and STM reduction in the normal version. The horizontal lines in the boxes show the 25th, the 50th and the 75th percentile values (%EMG_{max}). The small squares within the boxes indicate the mean values, and vertical bars denote range values (%EMG_{max}).

Paper II

The opposition from the sternocleidomastoideus muscle to the influence from EMG biofeedback in classical singing.

This study aimed to investigate the pattern of EMG activity in STM and TR during inhalation and phonation. A BF session was used to lower the activity in both muscles, and activity pattern before and after BF was compared. Further were activity patterns related to changes in pitch compared before and after BF. The main finding was that EMG BF performed on STM and TR lowered the activity in both muscles but caused no pattern changes for STM activity during inhalation. TR activity was more influenced by EMG BF and pattern changes during phonation were observed (Figure 6).

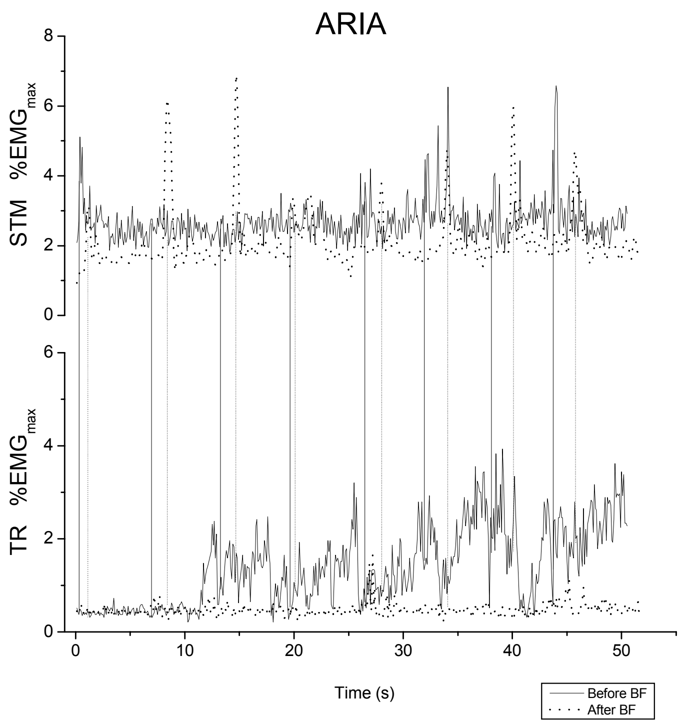


Figure 6. Individual time plots for one singer to show STM and TR EMG activity during eight breathing cycles (aria) before and after BF.

Peak size varies between breaths. Nevertheless, STM peaks are observed during inhalation both before and after BF. TR activity before BF increases during phonation. After BF, TR activity is low and even during most of the phonation time. Vertical solid lines mark inhalation before BF. Dotted vertical lines mark inhalation after BF.

Paper III

The association between upper trapezius activity and thorax movement in classical singing.

This study aimed to investigate a possible TR influence on TX movement in classical singing. Furthermore, EMG activity was recorded from INT and OBL sites in order to determine any phasing of TR activity to INT and OBL activity. Finally, a possible effect of different TR activation levels on the classical singer's use of TX was investigated. In this, TR activity was lowered by use of EMG BF and TX movement before and after BF was compared.

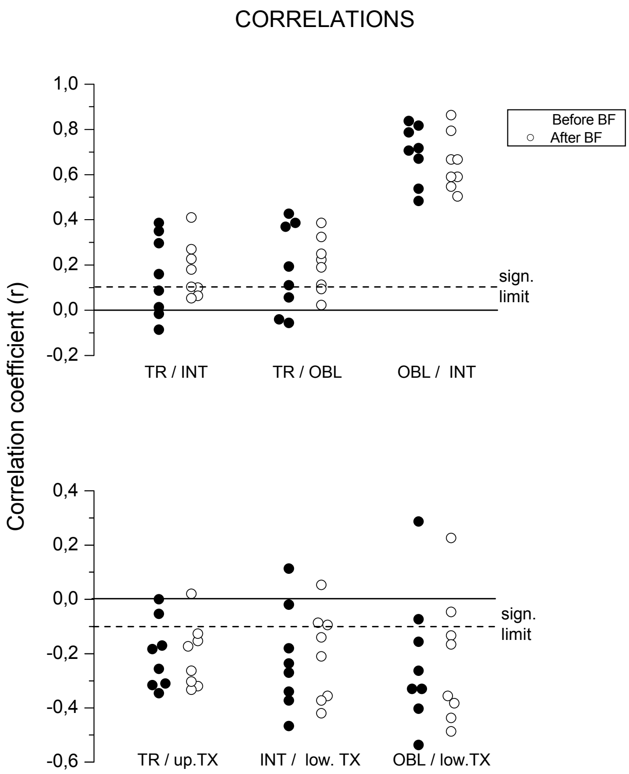


Figure 7. Results of correlation tests (Spearman ρ) between recordings.

TR was for most subjects positively correlated with the INT and OBL. All three muscles were negatively correlated with chest circumference. These associations were unchanged following BF. Thus, TR, together with INT and OBL, supports exhalation in classical singing. Each data point represents the mean correlation of the three versions of the aria by one singer. Results before (filled circles) and after (open circles) BF are shown.

The main new finding in this study was that TR supported exhalation by the classical singers that participated in this study. The duration of the singing sequence represented 10 or more respiratory cycles and revealed considerable individual variation in responses. The high data resolution made the number of data points entered in the correlation analyses high (600-1000), thereby reaching statistical significance for quite low correlations (Figure 7). However, visual inspection of the EMG recordings confirmed that TR, INT and OBL supported exhalation and had a consistent activity pattern for the individual breaths, ensuring that the results were trustworthy.

Paper IV

The activity patterns of neck muscles in professional classical singing.

The study aimed to characterize the activity patterns of neck muscles in classical singing. Muscle usage during inhalation and phonation and the relationship to changes in pitch and vocal loudness was of particular interest. Surface EMG was recorded from TR, STM and SC and the muscles in the posterior neck region (PN). EMG activity in TR and STM was lowered by EMG BF. Effect of lowered EMG activity in these muscles on the activity of SC and PN was analyzed. It was concluded that STM and SC showed correlated activity patterns during inhalation and phonation by classical singers (Figure 8).
Second, substantial muscle activity was observed in PN during inhalation and phonation. BF performed on TR and STM had a secondary effect of lowering EMG activity in SC and PN. The activity of all neck muscles was markedly elevated when singing in the highest pitch. There was no consistent task-based difference in EMG amplitude for the other singing tasks.

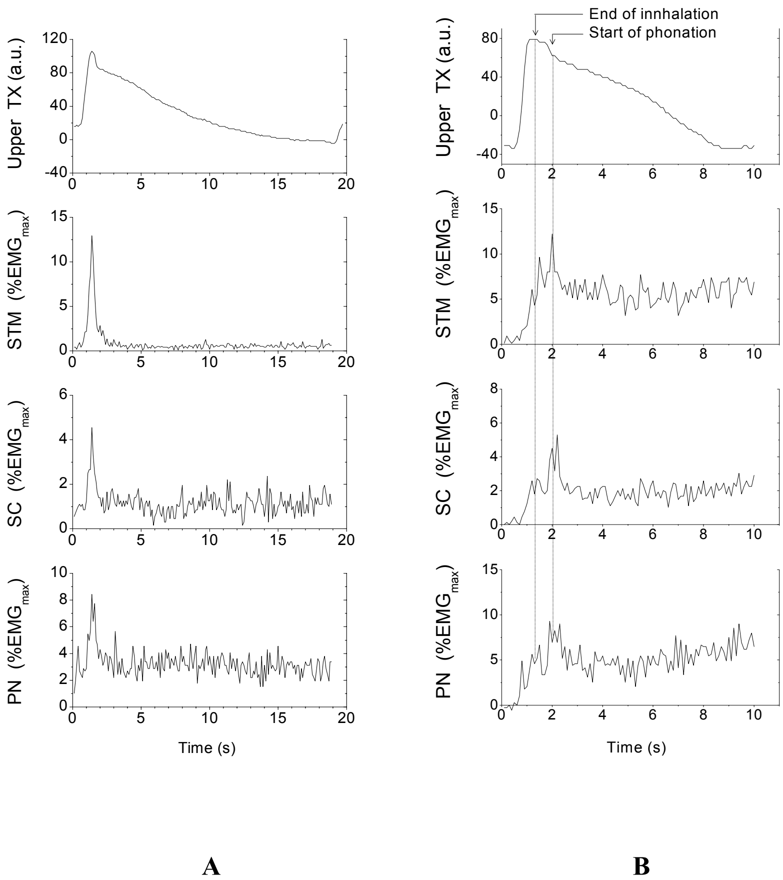


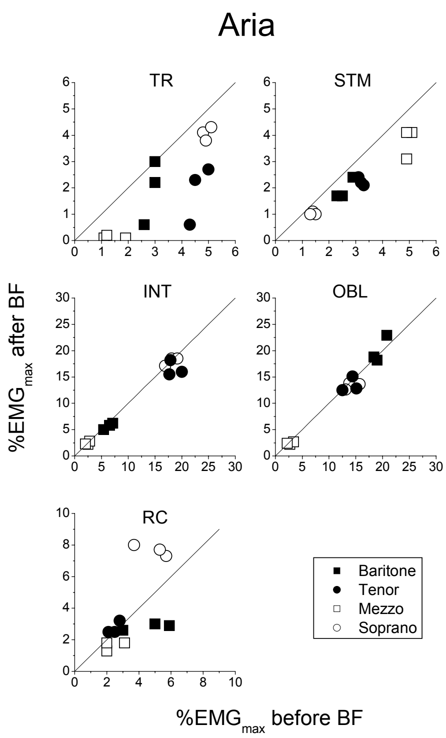
Figure 8. Time plots of chest movement and EMG activity for two singers singing the comfort version of extreme tones.

A. **This singer showed an activity pattern with marked modulation of muscle activity in inspiration and low activity levels during phonation.**
B. **The time plots of this singer are showing relatively low EMG activity levels in inhalation and considerably EMG activity at the start of phonation. a.u.: arbitrary units.**

Paper V

Muscle activity in professional classical singing:
A study on muscles in the shoulder, neck and trunk.

This study aimed to examine whether changes in the activity of shoulder and neck muscles have consequences for the activation of primary breathing muscles. It further aimed to compare muscle loading levels of professional singers and student singers. EMG recordings of TR, STM, INT, RC and OBL activity were performed. EMG BF was performed on TR and STM to lower the activity in these two muscles and the potential change in EMG activity of INT, RC and OBL were examined. No significant effect of reduced TR/STM activity on the activation of INT, RC and OBL was observed (Figure 9).



Figur 9 Scatter plots to show median EMG responses of four opera singers when singing the aria before and after BF.

Responses of the five recorded muscles at three volumes (piano, normal, forte) are shown (TR, STM, INT, OBL, RC). Values before BF are plotted horizontally and values after BF are plotted vertically. Line of identity is shown. Points below the line of identity show reduced activity level following BF.

Professional opera singers activated the TR, INT, RC and OBL muscles to higher levels than the student singers did (Figure 10). Another finding was large inter-subject variation in muscle usage, showing an idiosyncratic composition of the muscle contribution to subglottal pressure, also for the opera singers.

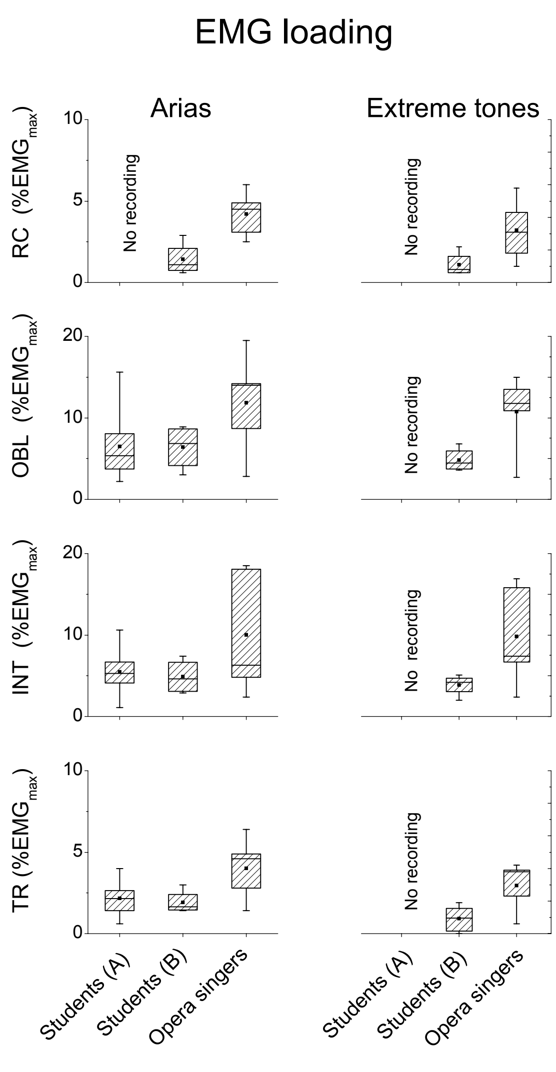


Figure 10. Box diagrams for comparisons of muscle responses between student singers and opera singers.

A clear increase in activity level of the opera singers v. student singers is observed. Each value used in the analyses is the mean of three median values for singing the aria (normal, forte, piano) and singing the extreme tones (comfortable, highest, lowest).

Paper VI

Some aspects of characterizing muscle activity levels in the neck and shoulder region by classical singers and classical pianists.

The objective of this study was to compare the level of use of TR and STM by classical singing students and classical pianist students. Surface EMG was performed on both muscles. The singers sang a song three times, with variation in vocal loudness. The pianists played an etude, a slow and a fast movement. Thereafter, muscle activity was compared between groups. The main finding was that TR and STM activity in classical singers and classical pianists was the same when tasks were of comparable effort considering required loudness and artistic challenge (Figure 11).

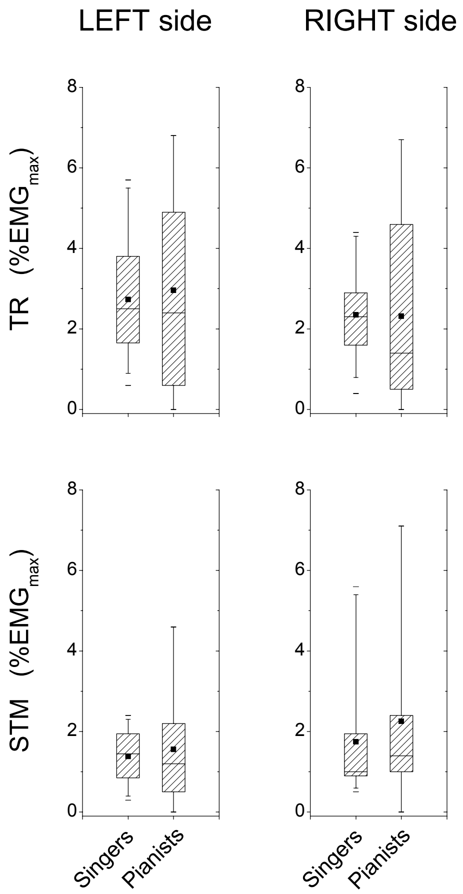


Figure 11. Median EMG responses of the singers' song (normal, forte and piano versions) and the pianists' etude.

Responses of left and right TR and STM are shown. The horizontal lines in the boxes show the 25th, the 50th and the 75th percentile values (%EMG$_{max}$). The small squares within the boxes indicate the mean values, and vertical bars denote range values (%EMG$_{max}$).

Paper VII

Neck and shoulder muscle activity and thorax movement in singing and speaking tasks with variation in vocal loudness and pitch.

The aim of this study was to examine respiratory phasing and load levels of STM, SC and TR in vocalization tasks with high and moderate exhalation. Surface EMG activity was recorded from STM, SC and TR. Thorax movement was detected by two strain gauge sensors placed around upper TX and lower TX. It was concluded that exspiratory phased STM and SC activity peaks produced a counterforce to the compression of upper TX at high pitches (Figure 12). As breathing demands were lowered in simplified singing and speaking tasks, STM and SC activity are reduced and attain inspiratory phasing. Second, TR contributes to expiration in singing with long breathing cycles (Figure 12), but TR activity is reduced with short breathing cycles and is mostly inactive in simplified speaking tasks.

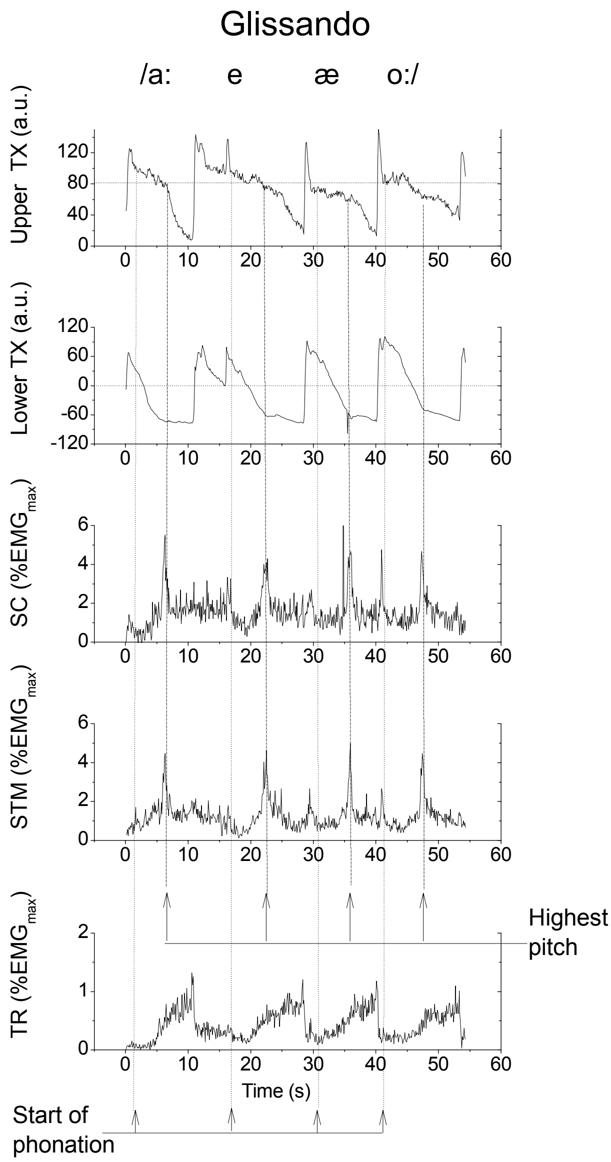


Figure 12. Time plots of TX movement and EMG activity of STM, SC and TR for one singer singing the glissando.

The glissando is repeated four times, sung at different vowels. Highest pitch and start of phonation is indicated by vertical lines. Note EMG peaks in STM and SC recordings at highest pitch and expiratory phasing of TR. a.u.: arbitrary units.

DISCUSSION

Methodological considerations

Calibration procedures

The large inter-individual variation in muscle activation levels for the different singing tasks, as well as for the calibration procedures, is a cause for concern. The EMG responses are quantified as a percentage of the EMG amplitude in maximal force exertion, which will make the EMG amplitudes during singing artificially high if the calibration responses are sub-maximal force exertions. This is less of a problem in the comparison of EMG responses before and after the BF procedure since the relative change in EMG level (increased, decreased or unchanged) is not affected by inaccurate calibration. However, this problem may significantly affect the findings in paper V, where EMG loading levels were compared between groups.

The EMG signal amplitude depends on many factors apart from the force exertion, including the amount of subcutaneous tissue of the different singers and the electrode location along the muscle fibers. It is a recognized phenomenon, observed in previous studies of TR (Jensen et al. 1993 &1996) and other muscles, and is a main reason why the calibration procedure is performed. For the other muscles an optimal electrode location near a local maximum in the EMG response was verified by the same method as used for TR by Jensen et al (1996). The calibration of STM, SC and PN has been discussed in paper IV and was judged to be reliable in consideration of consistent responses to repeated contractions and considerable force generated in the calibration movement. The calibration of RC was evaluated likewise, as the force generated by RC was resisted by movement restriction of trunk and lower legs and it was considered that considerable force was generated. The most uncertain calibrations concern INT and OBL, since no counter lever can be applied (discussed in paper V). Some singers produced higher response during singing than in the calibration exertions, and the reference values were adjusted to accept these new values as maximal responses. It is still reason to believe that the group differences in EMG activity levels, with higher responses of the opera vs. the student singers, are correct (paper V). The group means in the estimation of maximal EMG signals were lower for the students than the opera singers for all expiratory phased muscles (cf. paper V: Material and methods). If the calibration responses by the student singers had been on the same level as the opera singers, the difference in muscle responses between the groups would have been even larger. Another consideration is that the uncertainty in the calibration of maximal responses scales down proportionally to the EMG amplitude in the singing tasks, i.e., a 10% uncertainty in the determination of the maximal response becomes a 1% uncertainty if the signal amplitude is 10% EMG_{max} and 0.1% for a signal amplitude of 1% EMG_{max}. Since the group mean responses of the opera singers in some procedures were double the student responses, it is unlikely that the observed difference in responses is entirely caused by submaximal calibration efforts. However, the calibration uncertainty is additional to the general statistical uncertainty due to few subjects in the professional group. The higher EMG responses of the opera singers should therefore be confirmed by further studies. Finally, the large inter-group variation in responses is unlikely to be due to calibration error. In case of the opera singers, the singer with the highest activity levels during singing was also the one with the highest calibration responses. The inter-individual difference in EMG responses for the professional singers would be even larger if the calibration values had been similar for all subjects.

Cross- talk between signals

A cautionary remark is that the activity patterns of large muscles are monitored by one EMG electrode with limited pick-up area. We, therefore, do not know the extent the EMG recordings are representative for the activity pattern of the whole muscle. Cross talk of signals between muscles is another methodological concern. This error is difficult to estimate; however, TR is an extensive and fairly thick muscle at the recording site with a well-defined fascia underneath. Previous studies have shown that the electrode placement of TR records a representative activity pattern for upper trapezius (Jensen et al. 1993 &1996). The EMG signal from TR is, therefore, unlikely to be significantly contaminated by the underlying supraspinatus muscle. Likewise, the INT electrodes may record contributions from both the external and the internal intercostals. The INT recording was dominated by expiratory phased activity, indicating that the internal intercostals were the most active muscle at the INT site. It should also be kept in mind that the INT recording is not representative of activation of the full rib cage, which may show differential activity pattern, depending on lung volume (Hixon et al. 1995, Sears 1977). The OBL recording likely has contributions from both the internal and external oblique muscles and the traverses abdominis. It is difficult to assess the proportion of activity from the different muscles, which may change depending on the need for control of the subglottal pressure (De Troyer 1990, Floyd 1950). RC is an extensive, well-developed muscle and the RC recording is very likely from this muscle only.

The interpretation of the EMG signals from PN site (study IV) was a concern since the posterior cervical muscles consist of four layers. The first layer is formed by the trapezius muscle, the second and the third layers are mainly formed by the splenius capitis (SP) and semispinalis capitis (SSP) muscles respectively, and the fourth layer is formed by the small muscles located between the occipital bone and the first two cervical vertebrae. To determine TR contribution to the PN site EMG signal we have looked for co-variation in the EMG signal between TR and PN: if an electrotonic component from TR is present in the PN signal, this component should be observable throughout the recording. Thus, if instances of sharp changes in EMG amplitude are found in one (source) recording and the other muscle recording remains at an unchanged, low level, this is strong evidence to exclude electronic crosstalk as a significant problem in these recordings. Visual inspection of the recordings in paper IV showed this was the case for all electrode locations and subjects. Figure 3 shows examples of TR, STM, SC and PN segments considered in this analysis. Concerning the EMG signals from STM and SC sites, a cautionary note must be added: although electrotonic coupling between the recording sites in the neck region was minimal, surface EMG recordings are less discriminating than intramuscular recordings and co-activation by other muscles closer to SC and STM cannot be excluded. The main contributing muscles to the EMG signals would still be SC and STM, respectively.

Procedures

In studies I - VI both opera and student singers performed the arias three times with variation in vocal loudness (normal, forte, piano). The singers were asked to envision the normal version as singing in a “normal” sized concert hall. The forte version was to be envisioned sung as if performed in the largest concert hall they had performed in, and the piano version in the smallest concert hall they had performed in. This instruction was given to create as much performance environment as possible in the singing procedure. Thus, it was the choice of the individual singer to choose vocal loudness in accordance to what they were used to when performing. However, it is not possible to create an experimental procedure to be exactly like a performance. Therefore, the subjectivity in the judgment of what was required from each singer has to be acknowledged.

The execution of the phonation tasks in study VII was to a considerable extent decided by individual judgement. Duration of speaking and singing sequences, loudness in speaking and pitch in singing varied in accordance with the participants’ understanding of instructions (cf. material and methods, paper VII). Nevertheless, the authors of paper VII feel that the participants vocalized in ways that are fair representations of soft and loud speaking and singing in three different pitches, covering two octaves or more.

Interpretation of the TR results

Campbell (1968) classified the trapezius muscle as a muscle of inspiration and Zemlin (1998) described the trapezius muscle to be oriented in such a way (from a mechanical standpoint) as to function as supplemental (or compensatory) muscle of inhalation. It was stated by Basmajian/DeLuca (1985) that no one has found evidence in support of the belief that trapezius is a respiratory muscle, and that this idea should be dropped. The findings in this thesis are restricted to the upper part of the muscle (upper trapezius: TR) and will, therefore, not exclude that other results may be found in the lower parts of the muscle.

TX movement

The respiration sensors were tested and found to show a linear relationship between transducer output and chest circumference within the movement range defined by maximum expansion and maximum contraction of TX in regular singing. Transducer output is dependent on the relative movement range (i.e., the movement is registered larger for the same expansion of the chest wall, measured in cm, if the circumference is small). TX movement is therefore not easily compared between subjects, but within-subject changes in chest movement with the respiratory cycle and the effect of altered TR activity on chest movement can be assessed.

Interpretation of results

Muscles of expiration

TR

Study I and II showed that lowered activity in TR, due to BF, caused pattern changes in activity and study II hypothesized breathing purposes in TR. The main new finding in study III is that TR supports exhalation by classical singers. The duration of the singing sequence considered in the analyses represented 10 or more respiratory cycles and revealed a habitual way of body use, i.e., considerable inter-individual variation in activity pattern. Further, is TR activity, related to breathing purposes, dependent on sustained breathing cycles and high vocal loudness (and thereby, the need for high subglottal pressure: Leanderson & Sundberg 1988). Therefore, professional opera singers (singing with habitually high vocal loudness) were singing with higher EMG loading of TR activity than student singers did (singing with habitually less vocal loudness than opera singers) (Figure 10) (study V). TR activity is reduced with short breathing cycles and is mostly inactive in simplified speaking tasks (study VII). This divergence in TR activity is presumably due to differences in breathing demands between tasks. Leanderson & Sundberg (1988) pointed out that in normal speech lung volumes just above functional residual capacity are used. This means that the passive expiratory recoil forces are utilized to generate the required subglottal pressure. In speaking the expiratory recoil forces of the breathing apparatus habitually play a predominant role in establishing the needed subglottal pressure. In singing, on the other hand, a greater portion of the vital capacity is used for phonation, so expiratory breathing muscle force is more important.

All singing procedures were carried out in an upright posture, with arms hanging down. Postural demands would, therefore, be slight and TR activity should predominantly be used to generate subglottal pressure. With the reduction in TR activity after BF, other exhalation mechanics must replace the TR contribution. The dynamic levels of singing were unchanged after BF and a certain pitch and dynamic level normally requires the same sub-glottal pressure. A possible contributor in maintaining subglottal pressure is a more active lower chest wall; however, INT and OBL activity did not change significantly with TR activated at two different levels (study V). Conceivably, a higher and freer upper TX may allow more movement in lower TX, without significantly changing the activity level of muscles in the lower chest and abdomen.

Alternatively, a more expanded upper chest may lead to a lowered larynx, thus changing the settings for the needed sub-glottal pressure. Iwarsson (2001) found in a study of untrained singers that an elevated rib cage was associated with a lower laryngeal position than was the case with a decreased rib cage volume.

INT, OBL, RC

The main findings were, first, a reduction in the activity level of TR and STM following BF did not cause a compensatory change in activity level of the monitored trunk muscles. This result was consistent for all subjects and singing tasks with respect to INT and OBL. RC showed unchanged activity level following BF as a group response, but with inter-subject variation in responses (Figure 9). Second, professional opera singers activated the expiratory phased muscles (TR, INT, OBL and RC) to higher levels than student singers did, as a mean group response. Third, the singers activated the expiratory phased muscles in different patterns, with individually composed EMG loading levels between muscles. For each singer, the composition of muscular patterns and EMG loading levels also varied between tasks but were consistent when tasks were repeated (study V*)*. The latter result is consistent with earlier findings in singers: Seidner and Wendler (1997) pointed out that the type of breathing is decided by the shape of the thorax and abdominal region. Thomasson & Sundberg (1999) explored a variety of breathing habits among classical singers and showed consistency in breathing habits when tasks were repeated.

The higher activity levels of expiratory phased muscles for professional opera singers compared to student singers is a conclusion based on the group results. Individual differences were seen in singing both the arias and the extreme tones, for both student and opera singers. An inspection of the results in Figure 10, with range values marked by horizontal bars, shows there was no difference between opera and student singers for singers with the lowest responses. The difference between the two groups is, however, more marked than is evident from Figure 10. In the comparisons of EMG loading levels for student singers and opera singers each value is the mean value of three median values; for the aria the mean value of the piano, normal and forte versions, and for the extreme tones, the mean value of lowest, comfortable and highest tone. Therefore, the very high EMG activity levels generated by the four opera singers in the INT, OBL and RC muscles for the highest of the extreme tones are reduced by this averaging procedure. For the extreme tones, differences between opera singers and student singers are even more marked than indicated by the results shown in Figure 5. The reason for different activity levels in the extreme tones (same task for opera and student singers) is probably the higher vocal loudness by the opera singers. This was a subjective observation by ear during the recording sessions, but the highest of the extreme tones was also performed in a higher pitch by the opera singers. The differences in EMG loading levels between the two groups should, therefore, come from the need of higher subglottal pressures by the opera singers. A contribution from expiratory muscles is needed when singers require high subglottal pressures (Leanderson & Sundberg 1988).

Muscles of inhalation

STM / SC

Study I and II showed that lowered activity in STM caused no changes in activity pattern and it was hypothesized in study II that STM was involved in breathing also during phonation. Study IV showed that STM and SC support inhalation by classical singers, although in individual patterns and to various degrees between subjects (Figure 8 A). This result supports earlier studies (McFarland et al. 1989, Vitti et al. 1973, Campbell 1970, Raper et al. 1966) that have reported some EMG activity in these two muscles during voluntary forced inspiration by non-singers, and extend these results by quantifying the EMG activity during the inhalation and the phonation phase in professional classical singing. Second, STM and SC are also active during the phonation phase, especially at the start of phonation (Figure 8 B). Study VII showed that the inspiratory phased STM and SC muscles was activated to higher levels during phonation than in inhalation, thereby producing a counterforce to the compression of upper TX, such as at highest pitch in study VII (Figure 12). As breathing demands were reduced (in vocalization of simplified singing and speaking tasks with short breathing cycles: study VII) STM/SC activity was reduced and peak activity was observed mainly during inhalation.

Visual inspection of recordings of the extreme tones, in study IV, shows that the inward movement of air (i.e., expansion of TX) and onset of SC and STM activity occurred simultaneously (Figure 8 A). This confirms the findings of Raper et al. (1966), who reported this activity pattern with speakers when the inhalation was performed very quickly. This was the dominant pattern for one of the female singers in study IV and one female singer in study VII. However, the remaining singers in both studies (11 subjects) showed a more complex pattern with activity related to different parts of the inhalation phase. Furthermore, these two muscles were also activated at individual levels during phonation, most marked at the start of phonation (study IV) and at high pitches (study VII). The condition of high activity during phonation was often combined with relatively low activity during inhalation. This was the case of the majority of the singers in studies IV and VII. Raper (1966) and coworkers reported that STM and SC activity in inhalation was dependent on lung volume, as the EMG activity increased sharply for both muscles when approaching 100% VC. Classical singers often begin long and powerful phrases with close to 100% VC. Furthermore, the range below functional residual capacity is also utilized, and VC by classical singers is therefore ~20% greater than for non-singers (Leanderson & Sundberg 1988). This would require even more expansion of the rib cage by singers than by speakers. The high EMG peaks in both STM and SC during inhalation, seen by a female singer (Figures 3 & 4, study IV), can therefore be explained by the need of maximum loading of air. On the other hand, the other four singers in study IV had the same need for air by inhalation, but showed more complex activity patterns when inhaling. Even if the need for air by inhalation should differ between singers due to the performance of different arias, the sustained and extreme tones would start at close to 100% VC for all singers since they were told to maintain all tones for as long as possible in mezzo forte. Durations of more than 12 s for all tones, except for the highest of the extreme tones, indicate high loading levels of air by inhalation (Thomasson & Sundberg 1997). Even so, individual variations in activity patterns were observed during the inhalation phase. One singer (study IV) maintained the comfortable version of the extreme tones for 24 s virtually without involving STM and SC by inhalation. Professional classical singers may therefore inhale to high VC without much involvement of neck muscles. The majority of the singers who did so, activated these muscles most markedly at the start of phonation (Figure 8 B) and in individual patterns during phonation (Figure 12).

Muscles in posterior neck

PN

EMG activity was relatively high in PN (study IV). Takabe et al. (1974) reported either inactive or negligible activity in SP and SSP during deep breathing, flexion of the head, free lateral bending and lateral bending against resistance. SP showed activity in movements with rotation of head, which was not the case for SSP. The main function of SSP was thus extension of the head, while SP performs extension of the head and rotation of the head to its own side. The pattern and level of use of the muscles providing EMG activity at the PN site must be explained by other biomechanical action than those primarily related to breathing since the posterior neck muscles have no breathing muscle function. High correlations were found between the EMG activity of PN and SC, but it should not be assumed that the muscles at both sites perform breathing contractions. Campbell (1968) pointed out that a muscle contracting in a particular phase of breathing is not necessarily a prime mover of that phase. It can be a synergist or an antagonist, or its contraction may even be coincidental, due to, e.g., postural or random activity often found during concentrated efforts. Inspections of individual recordings showed that the EMG activity at PN often was phased to STM in inhalation and to TR towards the end of phonation. The action of the posterior neck muscles is thus, more likely to counteract the forces exerted by STM and TR, thereby stabilizing the head.

In the arias that should reveal a habitual way of singing, PN activity was lowered much more than STM activity after BF (study IV). A plausible explanation is that PN is activated to provide a counterforce to TR: with less TR activity after BF, the need for counteraction from the PN muscles is lower. The occipital fibres of TR rotate the head to the opposite side (Putz et al 1994), a movement that is counteracted by SSP (as well as the contralateral TR). A reduction in TR activity would reduce the head rotation force and generally reduce the activity level of all muscles potentially participating in the postural movement of the head. This speculation is phrased in general terms due to the complex biomechanics of the shoulder and neck muscles.

Pedagogical applicability

TR

A discrepancy between the way professional opera singers think they are breathing and how they actually breathe has been reported (Watson & Hixon 1987). This is consistent with the finding of TR as an accessory muscle of expiration: none of the recorded singers were aware of using TR in this capacity, but the majority of singers lowered their activity by keeping a mental focus on doing so. That professional opera singers activated TR to higher levels than student singers was contrary to the hypotheses described in the section on pedagogical fundament for theses. Even so, one of the singers with lowest TR activity during singing was a professional opera singer (study III). This, despite singing an aria with high artistic challenge in high vocal loudness. Study I and study III demonstrated that the singing task is executed without problems with markedly reduced TR activity following BF. With unchanged head posture, a reduction in the TR activity lower the upward pull on the clavicle and reduce the rotational movement of scapula, presumably accounting for a more expanded upper TX. The reduction in movement range of upper TX after BF, (study III) implies that the reduction in TR activity leads to less separation of maximum inhalation and exhalation positions. This change in breathing pattern should be favorable to singers, according to Hixon's statement (1988); "Trained singers would avoid the extremes on the relative-volume chart. They would stay more centralized on their chart. They would not go into extreme positions in controlling any of the chest wall parts. That would be the most economical biomechanical strategy".

The statement of Shirlee Emmons (1988) and other voice experts on keeping the shoulders relaxed and independent of the breathing mechanism in order to improve breath control in classical singing, may well be referring to the TR role as a pressure generator, as found in study III. It is assumed that the TR contribution in creating a subglottal pressure is not a conscious act of the singer in composing the breathing support. It still is thought provoking that a majority of the singers analyzed in this thesis use TR this way. Individual results before BF and most of the results after BF show that singing can be performed with TR activated to a low level. This fact, and the consequences of high TR activation on TX movement, should be communicated to singers in teaching correct posture and breathing behavior.

STM /SC

Study I & II showed that STM is used very consistently in classical singing. STM activity, which was a primary target of the BF procedure in study IV, was not lowered more than SC activity after BF. The posture role of TR (Zemlin 1998) and the function of STM and SC in breathing (Raper et al. 1966) should point to TR activity as synergetic to STM/SC activity in breathing. Study III has shown that TR contributes to compress upper TX in singing with high breathing demands. Therefore, TR could be considered an antagonist to STM/SC in breathing. Following this, lowered TR activity would cause lowered STM/SC activity. It may, therefore, be hypothesized that lowered STM values after BF are mostly due to lowered TR activity after BF. With lowered TR activity following BF upper TX is more expanded and both STM and SC have to work less to expand upper TX in inhalation and phonation. Such, the effect of BF on STM may be determined both by a direct effect and indirect effects pertaining to the overall distribution of forces in the shoulder and neck, with TR as the prime determinant of the muscle activity levels.

Hoit (1995) stated that an expanded rib cage is advantageous for classical singing, in which the demands for rapid and precise pressure control are greater than for speaking. In fact, classical singers have been shown to employ very large displacements of the abdomen to elevate the rib cage to a high position during performance. This thesis shows that also neck muscles are employed to elevate the rib cage during phonation. Nevertheless, neck muscle activity in inhalation and phonation varies between tasks: When breathing demands are low, as in speaking soft and loud (study VII), the passive chest wall recoil forces are used to generate the required subglottal pressure without muscle contribution from expiratory muscles. In these vocalization tasks upper and lower TX movement is highly correlated. With increased breathing demands in singing the correlation between upper and lower TX movement is reduced, showing independent control of upper and lower TX in the more demanding singing tasks. Simultaneously, STM and SC activity showed increased correlation to upper TX movement with pitch and loudness, indicating an increased involvement of the neck muscles in the positioning of upper TX.

A characterization of TR and STM EMG loading for breathing purposes

In study I it was concluded that especially TR, but probably also STM was overused by classical singers. This was concluded on the basis of the EMG activity recorded in these two muscles in spite of slight posture demands in the experimental procedures. But how much is actually much? To quantify neck and shoulder EMG activity in singers, study VI aimed to compare neck and shoulder activity in singers to neck and shoulder activity in classical pianists. The mental stress factor, due to the physical and mental arousal should be the same in both groups (TR is responsive to stress; Wærsted 1994), but posture demands would vary between groups. One difference is that classical singers sing with arms hanging down during the recordings. Classical pianists, on the other hand, use both arms continuously. The main finding in study VI was that TR and STM activity is on the same level for classical singers and classical pianists when tasks are comparable considering required loudness and artistic challenge.

Due to postural demands required when pianists perform demanding music, relatively high EMG loading in both TR and STM was expected in pianists. That singers with their low postural demands required EMG loading levels corresponding to those found in classical pianists, characterize the level of EMG loading for breathing purposes in the STM and TR muscles by classical singers.

Muscles in posterior neck

Singers often complain about stiffness and pain in the posterior neck. The reason for this, among others, may well be that these muscles have to provide a counterforce to the force exerted by the TR muscle during phonation. In paper IV we found that EMG BF performed on TR and STM lowered PN activity more than STM activity. We hypothesized that reduced TR activity after BF caused less counteraction from the muscles in posterior neck, thereby lowering PN activity after BF. On the hypothesis that TR is the prime determinant of neck muscle activity, the shoulders free of unnecessary tension should be a first aim to achieve economical muscle usage in the posterior neck.

INT, OBL, RC

The idiosyncratic patterns of EMG activity in expiratory phased muscles are most easily observed for the extreme tones, which were phonated in pitches wide apart. Figure 6 in study V show individual time plots of the four opera singers producing different INT activity patterns between muscles in the extreme tones: In the lowest version the soprano and the mezzo produce more INT activity than the two other singers. In the comfortable version the tenor and the soprano predominantly use INT, while in the highest version the tenor and the baritone generate the most powerful EMG signals. In other words, the singers with highest values in the lowest version have the lowest values in the highest version and *vice versa*. The mezzo is most consistent in the use of INT throughout the three versions of the extreme tones.

The soprano has her highest values in the comfortable pitch while the male singers have increasing activity with pitch. These individual patterns of muscle usage are fair illustrations of the individual use of expiratory muscles by the professional singers in study V. It may be hypothesized that the muscle action in primary expiratory muscles is composed in accordance to body shape. It is obvious that the support from exhalatory muscles in moving the rib cage has to vary with the trunk shape as pointed out by Seidner and Wendler (1997). The idiosyncrasy in muscle contribution to breathing support by classical singers must therefore be acknowledged.

Muscles' co-activity patterns and TX movement

It is acknowledged that the anatomy of the breathing apparatus in the upper trunk region is not fully explored (Zemlin 1998). However, it seems fair to conclude that the inhalatory STM/SC and upper external intercostals have a similar interplay with the exhalatory TR and upper internal intercostals in controlling movement of upper TX to the interplay between lower external intercostals and diaphragm vs. lower internal intercostals and abdominal muscles in controlling lower TX.

Studies with EMG biofeedback have shown that TR activity can be lowered and TR expiratory phasing reduced without consequences for sound production (study III). Lowered STM (study I, II, IV) and SC activity (study IV) did not change the respiratory phasing of these muscles. It, therefore, seems that STM and SC activity in classical singing is of greater functional significance in balancing the subglottal pressure than the role of TR as a pressure generator.

CONCLUSIONS

A phasing of TR activity to INT and OBL activity was discovered, all muscles supporting the expiration phase. During phonation TR contributes in the compression of the upper TX, thus serving as an accessory muscle of expiration. TR EMG activity was significantly lowered by EMG BF and resulted in an expanded upper TX circumference and less upper TX respiratory movement after BF. TR contributes to exhalation in singing with long breathing cycles, but TR activity is reduced with short breathing cycles and is mostly inactive in simplified speaking tasks.

During phonation professional opera singers activate the expiratory phased TR, INT, OBL and RC muscles to higher levels than student singers do; however, the idiosyncratic composition of muscle contribution to subglottal pressure must be acknowledged.

STM and SC show correlated activity patterns during inhalation and phonation by classical singers. During demanding singing expiratory phased STM and SC activity peaks produce a counterforce to the compression of upper TX at high pitches. As breathing demands are lowered, STM and SC activity are reduced and attain inspiratory phasing.

Substantial muscle activity is observed in posterior neck muscles (PN) during inhalation and phonation. EMG BF performed on TR and STM have a secondary effect of lowering EMG activity in PN. We hypothesize that PN activity is a secondary effect caused by the need to stabilize the head.

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159. CLINICAL AND EXPERIMENTAL STUDIES
160. Christina Vogt Isaksen: PRENATAL ULTRASOUND AND POSTMORTEM FINDINGS – A TEN YEAR CORRELATIVE STUDY OF FETUSES AND INFANTS WITH DEVELOPMENTAL ANOMALIES.
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162. Stein Hallan: IMPLEMENTATION OF MODERN MEDICAL DECISION ANALYSIS INTO CLINICAL DIAGNOSIS AND TREATMENT.
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177. Carina Seidel: PROGNOSTIC VALUE AND BIOLOGICAL EFFECTS OF HEPATOCYTE GROWTH FACTOR AND SYNDECAN-1 IN MULTIPLE MYELOMA.

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178. Alexander Wahba: THE INFLUENCE OF CARDIOPULMONARY BYPASS ON PLATELET FUNCTION AND BLOOD COAGULATION – DETERMINANTS AND CLINICAL CONSEQUENSES
179. Marcus Schmitt-Egenolf: THE RELEVANCE OF THE MAJOR hISTOCOMPATIBILITY COMPLEX FOR THE GENETICS OF PSORIASIS
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254 Viggo Pettersen: FROM MUSCLES TO SINGING: THE ACTIVITY OF ACCESSORY BREATHING MUSCLES AND THORAX MOVEMENT IN CLASSICAL SINGING