The Impact of Singing and Painful Temporomandibular Disorders on Physical, Psychosocial Factors, Masticatory Muscles Activity and Jaw Movements During Maximum Clenching and Maximum Opening

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Dedication

This work is lovingly dedicated to my supportive parents, my lovely brother, and to everyone who has encouraged and guided me along this journey.

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List of Abbreviations

1.1. Jaw-related conditions

TMD: Temporomandibular Disorder

PTMD: Painful Temporomandibular Disorder

TMJ: Temporomandibular Joint

ROM: Range of Motion

1.2. Questionnaires

DC/ TMD: Diagnostic Criteria for Temporomandibular Disorders

GCPS: Graded Chronic Pain Scale (2.0)

JFLS: Jaw Functional Limitation Scale (2.0)

PHQ-9: Patient Health Questionnaire (9-item)

GAD-7: Generalized Anxiety Disorder (7-item)

PHQ-15: Patient Health Questionnaire (15-item)

OBC: Oral Behavior Checklist

1.3. Devices

sEMG: Surface electromyography

MOCAP: Motion Capture

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Abstract

Background: Painful temporomandibular disorder (pTMD) is a prevalent condition that affects jaw function and negatively affects quality of life. Singers develop precise jaw control through training but may also experience jaw trauma and overuse-related strain. This study aims to clarify the relationship between singing and pTMD by examining behavioral and physiological factors.

Objectives: The primary objective of this study was to compare the self-reported psychosocial factors (anxiety, depression, and somatic symptoms), parafunctional oral behaviors, TMD symptoms, and jaw functional limitations between singers and non-singers with pTMD versus those without. Additionally, this study investigates masticatory muscle activity and jaw movement during maximum clenching and opening in singers and non-singers with and without pTMD.

Methods: This study employed a cross-sectional design and used a convenience sample recruited between January 2024 to May 2024 from dental clinics and local community centers. Participants were categorized as singers or non-singers based on self-reported singing experience and as pTMD or no pTMD based on DC/TMD pain screener. Data collection combined self-reported questionnaires with objective measurements. Participants also completed the DC/TMD Axis II questionnaires to assess their pTMD symptoms and other self-reported measures of oral behaviors and psycho-social symptoms, parafunctional oral behavior, and psychosocial status. Data was collected at the Centre for Interdisciplinary Research in Music, Media and Technology, where we employed surface electromyography (sEMG) to measure masticatory muscle activity (i.e., masseter and temporalis) during maximum voluntary contraction (MVC) and maximum jaw opening, while also tracking jaw movements with motion capture (MOCAP) technology.

Results: The study recruited 44 total participants. Using the DC/TMD analysis, the non-singers with pTMD had higher anxiety ($p = 0.018$) and depression severity ($p = 0.022$) than the non-singers

without pTMD. The pTMD groups had greater somatic symptom severity ($p < 0.01$) and more parafunctional behaviors ($p < 0.01$) than non-pTMD groups. Furthermore, the score for the parafunctional behavior was significantly greater in singers without pTMD than non-singers without pTMD ($p = 0.02$).

In terms of muscle activity and jaw movement patterns, singers with pTMD exhibited a smaller maximum muscle activity in the left temporalis during maximum clenching than non-singers without pTMD ($p < 0.01$). Conversely, there were no differences in range of jaw motion; however, non-singers without pTMD demonstrated more consistency in range of motion (i.e., lower standard deviation) than the singers without pTMD ($p < 0.01$), suggesting possible compensatory mechanisms related to pTMD.

Conclusion: This research underscores the complex interplay between singing, pTMD, and related psychosocial factors (anxiety, depression, and somatic symptoms), parafunctional oral behaviors, TMD symptoms, and jaw functional limitations. The results suggest that singing may have both beneficial and detrimental effects on individuals with pTMD, emphasizing the need for tailored therapeutic approaches that consider an individual's vocal activities when managing pTMD symptoms.

Résumé

Contexte: Le trouble temporomandibulaire douloureux (pTMD) est une affection fréquente qui affecte la fonction mandibulaire et nuit à la qualité de vie. Les chanteurs développent un contrôle précis de la mâchoire grâce à leur entraînement, mais peuvent également subir des traumatismes mandibulaires et des tensions liées à une surutilisation. Cette étude vise à clarifier la relation entre le chant et le pTMD en examinant les facteurs comportementaux et physiologiques.

Objectifs : L'objectif principal de cette étude était de comparer les facteurs psychosociaux autodéclarés (anxiété, dépression et symptômes somatiques), les comportements oraux parafonctionnels, les symptômes du TMD et les limitations fonctionnelles de la mâchoire entre chanteurs et non-chanteurs atteints de pTMD, par rapport à ceux qui n'en sont pas atteints. De plus, cette étude examine l'activité des muscles masticateurs et les mouvements mandibulaires lors du serrage et de l'ouverture maximale chez les chanteurs et les non-chanteurs avec et sans pTMD.

Méthodes: Cette étude a adopté un plan transversal et utilisé un échantillon de convenance recruté entre janvier 2024 et mai 2024 dans des cliniques dentaires et des centres communautaires locaux. Les participants ont été classés comme chanteurs ou non-chanteurs selon leur expérience autodéclarée en chant, et comme ayant un pTMD ou non selon le questionnaire de dépistage de la douleur du DC/TMD. La collecte de données combinait des questionnaires autodéclarés et des mesures objectives. Les participants ont également complété les questionnaires de l'Axe II du DC/TMD pour évaluer leurs symptômes de pTMD, ainsi que d'autres mesures autodéclarées des comportements oraux et des symptômes psychosociaux, des comportements oraux parafonctionnels et de l'état psychosocial. Les données ont été recueillies au Centre de recherche interdisciplinaire en musique, médias et technologie, où nous avons utilisé l’électromyographie de surface (sEMG) pour mesurer l’activité des muscles masticateurs (masséter et temporal) lors de la contraction volontaire maximale (MVC) et de l’ouverture maximale de la mâchoire, tout en enregistrant les mouvements mandibulaires à l’aide de la capture de mouvement (MOCAP).

Résultats: L’étude a recruté un total de 44 participants. Selon l’analyse DC/TMD, les non-chanteurs atteints de pTMD présentaient des niveaux d’anxiété ($p = 0{,}018$) et de dépression ($p = 0{,}022$) plus élevés que les non-chanteurs sans pTMD. Les groupes atteints de pTMD présentaient une gravité plus importante des symptômes somatiques ($p < 0{,}01$) et davantage de comportements parafonctionnels ($p < 0{,}01$) que les groupes sans pTMD. De plus, le score des comportements parafonctionnels était significativement plus élevé chez les chanteurs sans pTMD que chez les non-chanteurs sans pTMD ($p = 0{,}02$).

Concernant l’activité musculaire et les schémas de mouvement mandibulaire, les chanteurs atteints de pTMD présentaient une activité musculaire maximale inférieure dans le temporal gauche lors du serrage maximal par rapport aux non-chanteurs sans pTMD ($p < 0{,}01$). En revanche, il n’y avait pas de différence dans l’amplitude des mouvements mandibulaires ; cependant, les non-chanteurs sans pTMD démontraient une plus grande constance dans l’amplitude des mouvements (c’est-à-dire un écart-type plus faible) que les chanteurs sans pTMD ($p < 0{,}01$), ce qui suggère des mécanismes compensatoires possibles liés au pTMD.

Conclusion: Cette recherche met en lumière l’interaction complexe entre le chant, le pTMD et les facteurs psychosociaux associés (anxiété, dépression, symptômes somatiques), les comportements oraux parafonctionnels, les symptômes du TMD et les limitations fonctionnelles de la mâchoire. Les résultats suggèrent que le chant peut avoir à la fois des effets bénéfiques et délétères chez les individus atteints de pTMD, soulignant l’importance d’approches

thérapeutiques personnalisées tenant compte des activités vocales dans la gestion des symptômes du pTMD.

Introduction and objectives

1.1. Introduction

Temporomandibular disorders (TMDs) refer to a group of musculoskeletal conditions characterized by pain and/or dysfunction affecting the masticatory muscles, temporomandibular joints (TMJ), and related structures (1, 2). Five to 12% of adults live with chronic disabling orofacial pain that affects the masticatory muscles (myalgia) and/or TMJs (arthralgia) (3). These are the most common types of painful TMDs (pTMDs), where biological, psychosocial, and other factors are believed to play an etiological role. pTMDs are linked to limited jaw function (4, 5) and could lead to changes in motor patterns as individuals avoid painful movements. While chronic pTMDs have no definitive cure, pain is typically managed with patient education, physical therapy (e.g., relaxation, stretching), pharmacological treatments, maybe occlusal appliances, and rarely, surgery (6).

Singers, as occupational users of the head and neck, train to precisely control jaw, lip, and tongue movements to shape vocal sounds. Singing is regarded as a putative trauma and/or jaw-overuse behavior due to the repetitive and wide jaw range of motion employed while singing (7, 8). On the other hand, physical exercise is known for its beneficial effects in the management of chronic pain, including pTMDs (9-12). Moreover, amateur singing benefits psychological and physiological well-being (13), and music-based therapies have been shown to be motivating for patients (14). Given the benefits of physical exercise in chronic pain management, amateur singing may contribute to masticatory muscle conditioning, potentially influencing pTMD symptoms.

Given the limited and conflicting evidence, this study aims to examine the role of self-reported pain intensity, somatic pain, psychosocial factors (anxiety, depression, and somatic symptoms), parafunctional oral behaviors, TMD symptoms, and jaw functional limitations. in pTMD. Additionally, it investigates whether singers and individuals with pTMD exhibit distinct masticatory muscle activity and jaw movement patterns during maximum opening and maximum clenching. By addressing these questions, the research seeks to contribute to a broader understanding of pTMD management and enhance the well-being and career longevity of Canadian singers.

1.2. Objectives

This study examines pain intensity, pain-related disability, psychosocial distress, jaw functional limitations, and parafunctional behaviors with DC/TMD Axis II questionnaire in singers and non-singers, both with pTMD and without pTMD. In these groups, masticatory muscle activity and jaw kinematics were measured during maximum clench and maximum mouth opening. We hypothesize that singers without pTMD develop motor patterns that support TMJ function, despite frequent jaw use.

2. Review of literature

2.1. Jaw anatomy

Jaw movements are involved in some of the head and neck's most essential functions, like communication, eating and breathing. Jaw movements are unique and complex, requiring both rotation and translation at the TMJ. Initially, the condyles rotate within the glenoid fossae, followed by translation towards the articular eminence (Fig. 1). Bilateral action of masticatory muscles (i.e., masseter, temporalis, medial and lateral pterygoid, suprahyoid) coordinates these movements, which are cushioned by a cartilaginous disc placed between the condyles and the fossae. As seen in Fig.1, the temporalis muscle is located within the temporal fossa on the side of the skull and primarily functions in closing the mandible. Similarly, the masseter muscle, positioned on the lateral side of the mandible, also plays a key role in closing the jaw, with the ability to generate both high and low forces during this movement. The medial pterygoid, situated within the infratemporal fossa, contributes not only to closing the mandible but also to facilitating lateral jaw movements. In contrast, the lateral pterygoid, which is also found in the infratemporal fossa, is responsible for opening the mandible, deviating the jaw, and moving it forward (15).

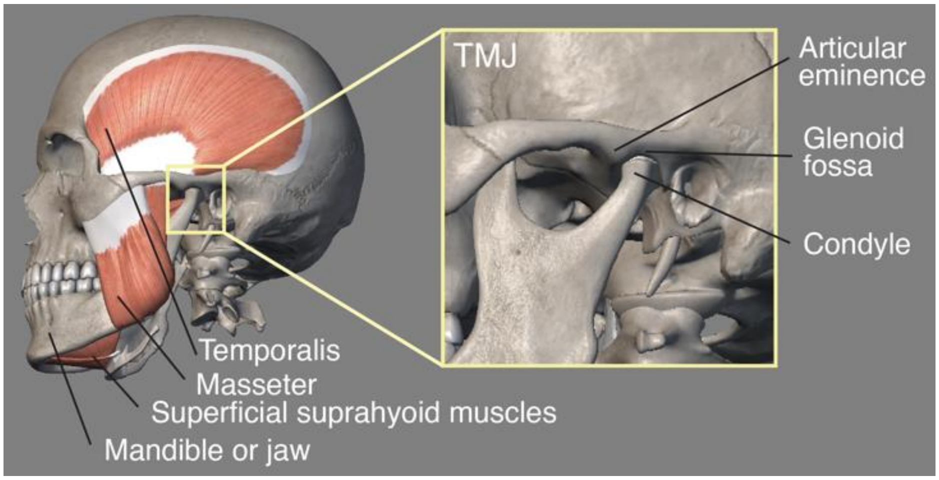


Figure 1 *Jaw anatomy.* The jaw articulates at the TMJs. The suprahyoid muscles (digastric, stylohyoid, mylohyoid, geniohyoid) and the lateral pterygoid (not shown) open the jaw resulting in rotation of the condyle at the glenoid fossa and translation along the articular eminence. The masseter, temporalis, and medial pterygoid (not shown) muscles close the jaw. Images created with Anatomy3DAtlas.

2.2. TMDs and pTMD

TMDs encompass a group of musculoskeletal and joint conditions affecting the masticatory muscles, TMJs, and associated structures. These disorders are recognized as one of the leading causes of orofacial pain, with an estimated 5–12% of adults experiencing chronic symptoms, significantly impacting their daily lives (3). As summarized by the National Academies of Sciences, Engineering, and Medicine (2020), TMDs affect 4.8% of adults in the United States, amounting to approximately 11.2 to 12.4 million people, which is comparable to conditions like fibromyalgia and migraines. Direct costs per patient average £2,280 in the UK and $1,800 CHF in Switzerland, alongside indirect costs such as lost productivity, estimated at £584 to $1,225 CHF every 6 months (15). Their treatment creates an annual economic burden of around $4 billion worldwide (16).

pTMD represents a subset of TMDs characterized by ongoing pain, which may originate from the masticatory muscles (myalgia) or the TMJs (arthralgia) (4, 5, 17). The physical impacts of TMD, particularly pTMD, can be profound. Altered muscle activity and restricted jaw mobility are commonly reported, significantly interfering with essential functions such as chewing, speaking, and facial expressions (4). These limitations can hinder social interactions and lead to dietary modifications, further reducing physical well-being. Additionally, research indicates that pain severity and mandibular function are closely associated with quality of life, highlighting the need for comprehensive management strategies (17).

2.3. Diagnosis of pTMD

Diagnosing pTMDs is challenging due to their varied causes and clinical presentation. The Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) was widely used for diagnosis and has since been updated to the Diagnostic Criteria for TMD (DC/TMD). The DC/TMD provides reliable diagnoses for common painful conditions such as myalgia, arthralgia, and headaches attributed to TMD. The DC/TMD is widely accepted for improving diagnostic accuracy in both clinical and research settings, demonstrating high validity and reliability across various populations (18).

While the DC/TMD provides a standardized framework, in-person clinical assessment is essential for accurate diagnosis. This involves combining patient history, physical examination, and imaging studies to evaluate symptoms, triggers, and movement issues. Hands-on examinations help identify tenderness and exclude other conditions. Imaging techniques, like X-rays or MRIs, provide structural insights, while reproducing familiar pain through palpation confirms the diagnosis. Imaging using MRI is required for a definitive diagnosis of TMJ disk displacement, and CT imaging is required for a definitive diagnosis of Degenerative Joint Disease. Together, these steps ensure a comprehensive evaluation (18).

2.4. DC/TMD Questionnaires

DC/TMD provides a comprehensive diagnostic tool with Axis I and Axis II evaluations. Axis I requires a clinical examination in addition to gathering the patient's history and its protocol includes a screener for TMD and diagnostic criteria for the most common TMD and one intra-articular disorder. Axis II primarily utilizes a series of self-report questionnaires to evaluate pain intensity, psychosocial factors (anxiety, depression, and somatic symptoms), parafunctional oral behaviors, TMD symptoms, and jaw functional limitations, and comorbid pain conditions. The tool’s dual evaluation approach helps identify both physical and psychosocial factors, enabling more personalized treatment (18, 19). Each of these questionnaires have specific items and scoring methods that help assess different aspects of TMD and its impact on individuals.

The **TMD Pain Screener** is used to screen for the presence of pTMD. Employing a recall period of 30 days, it includes one question assessing pain frequency (0 = no pain; 1 = pain comes and goes; 2 = pain is always present), one question on jaw pain or stiffness on wakening (0 = no; 1 = yes), and one question assessing if pain is modified (that is, made better or worse) by chewing hard or tough food, opening the mouth or moving the jaw forward or to the side, by jaw habits such as holding teeth together, clenching/grinding, or chewing gum, or by other jaw activities such as talking, kissing, or yawning (0 = no; 1 = yes). A sum score above 3 reliably indicates the presence of pTMD and is ideally recommended when a complete clinical examination cannot be performed (20).

The **DC/TMD Symptom Questionnaire** assesses jaw pain, as well as history of TMJ noise, jaw locking, and headache. It provides the necessary symptom history used in conjunction with the clinical examination from for the Axis I diagnostic criteria (21).

The **Graded Chronic Pain Scale (GCPS)** evaluates pain intensity and disability. The DC/TMD typically uses the 1-month (30-day) version, although 3-month and 6-month versions are also available. This questionnaire has eight items and provides three key scores: Chronic Pain Intensity (CPI), Limitation Days, and Interference. These items' scores are combined to determine the Chronic Pain Grade, ranging from Grade 0 (no pain) to Grade IV (severe disability) (22).

The **Jaw Functional Limitation Scale (JFLS)** is used to assess limitations in jaw function using 20 items. The scoring can be done in several ways, including a global score derived from all items or a subscale score based on mastication, mobility, and communication. While norms for the JFLS have not been fully established, observed scores for individuals with and without chronic TMD have been reported. For mastication limitation, individuals with no lifetime TMD scored an average of 0.28 (SE = 0.02), while those with chronic TMD had an average score of 2.22 (SE = 0.13). For mobility limitation, individuals with no lifetime TMD scored 0.18 (SE = 0.02), whereas individuals with chronic TMD had a score of 2.22 (SE = 0.13). Regarding verbal and emotional expression limitations, individuals without lifetime TMD had a score of 0.14 (SE = 0.02), while those with chronic TMD had a higher score of 0.72 (SE = 0.10). The global score, which combines these subscales, was 0.16 (SE = 0.02) for individuals with no lifetime TMD and 1.74 (SE = 0.11) for individuals with chronic TMD (23).

Psychological distress is also a significant factor in TMD, and several questionnaires assess this aspect. The **PHQ-9** (Patients Health Questionnaire) is used to measure depression severity, using nine items. It is scored by summing the responses, and interpretation categories range from mild depression (scores ≥ 5) to severe depression (scores ≥ 20) (24). The **GAD-7 (Generalized Anxiety Disorders)** assesses anxiety with seven items, summing the responses to determine levels of anxiety, from mild (scores ≥ 5) to severe (scores ≥ 15) (25). Additionally, the **PHQ-15 (Physical Symptoms questionnaire)** assesses non-specific physical symptoms, including functional or medically unexplained symptoms, with 15 items. Items are summed to produce a total score, with the following interpretations: a score of 5 or greater indicates low symptom severity, a score of 10 or greater indicates medium symptom severity, and a score of 15 or greater indicates high symptom severity (26).

The **Oral Behaviors Checklist (OBC)** assesses parafunctional behaviors with 21 items. Scoring can be done by counting the number of items with a non-zero response or by calculating a weighted sum of the endorsed frequencies for each item. Although norms have not yet been fully established, a score of 0-16 appears to represent normal behavior. Scores between 17 and 24 are observed twice as often in individuals with TMD, while scores between 25 and 62 occur 17 times more often in individuals with TMD. Only scores in the range of 25-62 are considered a risk factor for the onset of TMD (23, 27, 28).

2.5. Impact of pTMD on quality of life

The cause of TMD is considered multifactorial and complex, following the biopsychosocial model. This model suggests that precipitating, predisposing, and perpetuating factors are interconnected, contributing to the development, progression, and increased risk of the disorder (29). These factors, whether acting together or as a singular influence on various functions, disrupt the functional and orthopedic balance of the structures within the stomatognathic system. This imbalance plays a significant role in the persistence of pain and its impact on the patient's quality of life (30-32). Musculoskeletal disorders can affect both the physical and mental well-being of patients. Chronic conditions like fibromyalgia and TMDs negatively impact quality of life. These disorders often contribute to psychological distress, including anxiety, stress, and depression, which can lead to decreased work capacity, financial strain due to ongoing medical needs, social phobias, and sleep disturbances (33).

Ultimately, the combined physical, emotional, and social burdens of TMD highlight the need for comprehensive management strategies that address both the symptoms and their broader impacts on daily life (34).

2.6. Management strategies

Managing chronic pTMD requires a multidisciplinary approach. Moderate-certainty evidence or higher suggests that interventions promoting coping strategies and encouraging movement and activity are the most effective for reducing chronic pTMD. In contrast, several commonly used interventions are supported by only low or very low certainty evidence and need to be further studied (35). Treatment strategies typically include:

2.6.1. Occlusal appliances

Occlusal appliances, such as stabilization splints, are commonly used to manage pain in pTMDs. They aim to reduce muscle tension and stabilize the jaw, alleviating symptoms like muscle soreness, headaches, and joint pain (36-38). Systematic reviews indicate short-term benefits in pain reduction and improved jaw function; however, their long-term efficacy remains uncertain (39, 40). Some studies suggest comparable outcomes to physiotherapy, while others highlight no significant advantage over placebo in the long term (41). Success depends on factors like TMD type, patient compliance, and comorbidities such as widespread pain or psychological disorders (36).

2.6.2. Physical therapy

Exercises focusing on relaxation, stretching, and strengthening of the masticatory muscles. Physical therapy, including home exercises, manual therapy, and various modalities, is often recommended as a first-line treatment for pTMD. It is non-invasive, cost-effective, and allows for patient self-management (42, 43). Some clinicians suggest that tailored physiotherapy approaches can be promising (42). A recent meta-analysis showed that manual therapy and exercise interventions are effective in the reduction in pain intensity and improvement of maximum mouth opening in pTMD (44).

2.6.3. Pharmacological interventions

Pharmacological treatments for pTMD yield mixed results, with effectiveness varying by drug class, TMD type, and patient factors. A meta-analysis found no significant differences in pain reduction among therapies (45). NSAIDs (e.g., naproxen) show short-term efficacy for joint pain, while muscle relaxants (e.g., diazepam) target local spasms. Long-term use requires careful consideration of potential side effects and individual needs. Emphasizing the need to first identify each patient's multifactorial etiology and then apply a tailored, multifaceted treatment strategy (45).

2.6.4. Behavioral therapies

Behavioral therapy typically includes interventions like cognitive behavioral therapy (CBT), which has some evidence of effectiveness, though the overall evidence remains weak due to limited studies (46). Behavioral approaches focus on modifying actions that exacerbate pain, using techniques such as biofeedback, relaxation, and positive reinforcement. A study found that CBT significantly improved pain, activity interference, depression, and jaw function compared to a control group, with lasting benefits over 12 months (47). However, low-certainty evidence suggests CBT may reduce pain intensity and psychological distress more effectively than alternative treatments, but not necessarily improve pain-related disability outcomes (46).

2.6.5. Surgical options

Surgical treatments for pTMDs are considered for patients who do not respond to conservative treatments. Patients with defined intra-articular disorders who have not experienced improvement with time or conservative therapies may be candidates for surgical treatment (48). The current trend favors conservative approaches over surgery, as they are less aggressive and often yield satisfactory results in mild to moderate TMD cases (49).

In conclusion, a multi-modal approach combining various conservative treatments, including occlusal appliances, physical therapy, and behavioral therapies, appears to be the most successful strategy for managing pTMD due to its complicated nature (49). Despite advancements in pTMD management, further research is needed to tailor interventions that address both the physical and emotional dimensions of pTMD, considering the unique challenges faced by individuals in vocally demanding professions (50).

2.7. Sound Production and Singing Mechanics

Singing involves a complex interaction of the respiratory, phonatory, and articulatory systems. Sound is generated by airflow through the vocal folds, resonating within the vocal tract, which includes the pharynx, larynx, oral, and nasal cavities. Singers control tone, resonance, and vibrato by manipulating the vocal tract through jaw movement, tongue positioning, and coordinated contraction of head and neck muscles. Thus, as singers exert more control over their oral system, it is possible that singers have different kinematic patterns of jaw movement and muscle activity than non-singers. The question is whether this is beneficial for the jaw.

Some studies have investigated jaw kinematics in singers. Elite singers demonstrate distinct jaw kinematics, such as greater mouth opening and posterior jaw lowering, which may enhance sound quality by modifying the laryngeal space (51). Other studies found that variations in jaw movement impact pitch (52) and vibrato (53).

Muscle tension is central to discussions of vocal performance pedagogy. Controlled tension is necessary for precise manipulation of the vocal tract, but excessive tension—particularly in the facial, zygomaticus, and masseter muscles—is often associated with reduced sound quality (54, 55). For instance, lifting the zygomaticus muscle during singing has been shown to increase vocal intensity (56, 57).

2.8. pTMD in Singers

In the literature, it is unclear whether singing is associated with pTMD. In one of the earliest studies, if not the first study to look into this relationship, surveys were sent to members of the National Association of Teachers of Singing in the U.S. and Canada. In this descriptive study that does not include a thorough description of its methods, nearly 44% of the 158 respondents reported pain in the TMJ during talking, singing, and chewing and 24% to 40% indicated problems with muscle spasms, chronic pain in the head, neck, shoulder, or jaw, difficulty in opening or closing the mouth, migraine-like pain, sinusitus, or crepitus, although the specific proportions of each symptom were not reported (58).

In 1992, Taddey anecdotally reported a largely smaller pTMD prevalence among singing students (i.e., 1.2%), with pTMD being loosely defined by the self-report of a doctor's diagnosis of pTMD or by a history of jaw muscle or jaw joint pain (8).

In 2013, a study comparing the report of pain in 13 body sites between classic choral singers and non-singer controls recruited from the community in Sao Paulo, Brazil, found that controls had a greater number of painful body sites. There was no difference in the report of pain in the TMJ between groups and choral singers reported significantly less headaches, back, neck, arm, hand and ear pain (59).

In line with this, another study in 2017 comparing data from recreational choral singers and non-singer controls found that the former report significantly less pTMD symptoms using the validated Fonseca Anamnesis Questionnaire and significantly less anxiety symptoms. Anxiety is a well-known risk factor for pTMD, and this study found a positive correlation between pTMD and anxiety symptoms regardless of group assignment (60).

A study by van Selms et al. examined the prevalence of pTMD and TMJ sounds in vocalists versus instrumentalists. The results showed that 21.9% of vocalists reported pTMD, compared to 12.0% of the control group. Similarly, 20.0% of vocalists experienced TMJ sounds, compared to 15.1% of controls. However, multiple regression analysis found that being a singer was not a significant risk indicator for pTMD or TMJ sounds. Instead, the presence of pTMD was more strongly associated with female gender, frequent oral behaviors, and daily practice hours. (61).

A 2021 Singaporen study analyzing data from 159 musicians classified as either 'active jaw' instrumentalists (i.e., those playing an instrument that requires persistent oromandibular activities; n=70), 'non-active jaw' instrumentalists (n=25), or vocalists (n=64) found no difference in the prevalence of pTMD or in pain characteristics – such as pain intensity, duration, and pain-related disability – among groups (62).

A recently published German study enrolled 288 females using distinct recruitment strategies for each group and categorized them as professional (> 5 hours per week of singing), recreational (< 5 hours per week of singing), or non-singers (no singing) (n=96 each). They found a borderline significant difference in the prevalence of TMD among groups, with 42%, 31%, and 25% of professional singers, recreational singers, and non-singers reporting TMD symptoms, respectively. Importantly, TMD in this study was defined by the report of at least 3 of 6 signs and symptoms of which only 2 were related to pain. Hence, it is not possible to conclude that the prevalence of pTMD was greater among singers (63).

2.9. Tools for Analyzing Jaw Movements and Muscle Activity

Given the potential link between repetitive jaw movements in singers and pTMD, advanced tools such as MOCAP and sEMG have been used to analyze jaw function and muscle activity in these individuals.

2.9.1. Jaw kinematics

MOCAP provides a three-dimensional representation of jaw movements, enabling detailed observation of dynamic motion during singing. Optoelectronic markers are placed on specific anatomical locations on the head. A six-camera system tracks the 3D position of the markers in space by emitting infrared light, which is reflected back to the cameras by the markers. This enables the quantification of parameters like maximum opening, lateral excursions, and protrusion, aiding in diagnosing TMD, identifying abnormal jaw function, and guiding treatment strategies. While rigid markers attached to the mandible offer precise tracking, less invasive alternatives, such as skin-mounted markers on the chin, may be suitable for measuring lateral displacement and chewing rhythm.

The system employs specialized infrared cameras to detect retro-reflective markers. These markers reflect infrared light, allowing the system to track their movement and reconstruct jaw kinematics in 3D using algorithms like Direct Linear Transformation (DLT). A typical setup includes three strategically positioned cameras to ensure marker visibility and accurate data capture. High-frequency image capture (up to 100 fps) allows for detailed motion analysis, and the processed data outputs a 3D model with precise trajectories of jaw movements, offering valuable insights for clinical evaluation and treatment planning (64).

2.9.2. Muscle activity

sEMG is a non-invasive technique used to measure the electrical activity of muscles, offering insights into their function. By detecting electrical potentials generated during muscle contractions, sEMG provides quantifiable data on muscle activity (64, 65). Electrodes placed on the skin surface over the masseter and temporalis muscles—key muscles responsible for jaw movement—are commonly used to assess masticatory muscle activity for potential TMD diagnosis. To ensure accurate measurements, the skin is cleaned before electrode placement, and the signals are amplified, filtered, and processed.

While sEMG is a convenient and non-invasive tool for evaluating muscle function, its diagnostic value in TMD remains debated. Variability in findings and challenges such as sensitivity to skin impedance and technical artifacts limit its reliability. Despite these concerns, sEMG continues to be a valuable tool in understanding muscle activity and assisting in the evaluation of jaw-related disorders (66).

2.10. Methodological Challenges

Methodological challenges in sEMG & jaw kinematics research briefly consists of:

- **Inconsistent Findings:** Some studies show higher masseter activity at rest in pTMD patients, while others report no significant difference.
- **Variability in Study Design:** Differences in participant selection, equipment sensitivity, and data collection protocols impact comparability.
- **Pain-Related Alterations:** Pain may influence motor control and alter jaw kinematics, but the extent of this effect remains unclear.

These topics are explained in detail below.

2.10.1. sEMG in pTMD

Research has identified differences in sEMG outcomes between individuals with pTMD and those without pTMD, though findings remain inconsistent. Most studies report greater masseter and anterior temporalis (TA) muscle activity at rest in pTMD patients, suggesting increased tension or guarding (67), while others found no significant differences. During maximal voluntary contraction (MVC), individuals with pTMD generally exhibit lower masseter and TA activity, potentially due to pain avoidance or altered motor control, though some studies observed higher or no differences in activity. Limited research on chewing-related sEMG suggests variability, with some findings of greater balancing-side masseter recruitment in severe pTMD cases (65).

Inconsistencies in outcomes and methodological variability limit the reliability of sEMG as a standalone diagnostic tool for pTMD. While it may offer supplemental information, sEMG findings should be integrated with comprehensive clinical evaluations, including history, physical exams, and imaging. Standardized protocols and further research are needed to clarify its role in pTMD diagnosis and management, ensuring it is used as part of a multifaceted approach rather than in isolation.

2.10.2. MOCAP in pTMD

A recently published study examined individuals with myalgia, a subtype of pTMD, and compared their jaw movement patterns to those of healthy controls. Instead of focusing on absolute measures such as maximum mouth opening, the study employed a kinematic analysis approach using

MOCAP data, Fourier transformation, and unsupervised machine learning techniques. This analysis revealed two distinct clusters of mandibular movement patterns. One cluster predominantly included trials from individuals with pTMD, while the other was mainly composed of asymptomatic trials. This suggests that individuals with pTMD may exhibit characteristic alterations in jaw kinematics, possibly linked to the presence of muscle pain and its effect on movement coordination. The findings imply that pTMD, including myalgia, may lead to distinguishable movement signatures that reflect changes in motor control strategies during mandibular function (68). A limitation of the study is that it included only 5 participants with TMD and 3 healthy participants.

The study itself uses kinematic data to differentiate between symptomatic and asymptomatic states in individuals with myalgia, implying that jaw kinematics change with the presence of pain. While it doesn't directly involve muscle activity measurements, the findings and related research strongly suggest that both jaw kinematics and muscle activity are likely affected in individuals with pTMD compared to those without pTMD (68).

However, systematic reviews on jaw kinematics and muscle activity in pTMD patients (69, 70) found no significant difference regarding jaw kinematics or muscle activity in people with pTMD and healthy controls. However, these studies highlight key challenges in this field, such as methodological variability that stems from differences in participant selection, equipment sensitivity, and data collection protocols limit the comparability of studies and inconclusive findings due to inconsistent methodologies. These challenges underscore the need for standardized protocols to enhance the reliability and validity of findings in this area.

2.10.3. Integration of Tools for Comprehensive Analysis

The combination of MOCAP and sEMG provides a pathway for more comprehensive analysis:

- **MOCAP systems:** Enable detailed tracking of jaw movements in three dimensions, which is critical for evaluating the biomechanics of singing.
- **sEMG:** Offers insights into muscle tension and fatigue, which are key factors in understanding the functional limitations caused by pTMD.

A recent study utilized EMG and mandibular motion analysis to compare muscle activity and jaw movements between healthy individuals and those with non-specific chronic neck pain without TMD symptoms. The study highlighted differences in myoelectric activity and mandibular biomechanics, demonstrating the value of integrating these tools to understand jaw function and dysfunction. This dual approach allows researchers to correlate kinematic data from MOCAP with muscle activation patterns from EMG, providing a holistic view of TMJ mechanics (71).

By integrating MOCAP and sEMG data, researchers and clinicians can develop targeted interventions for singers with pTMD. This dual approach could help identify movement patterns that contribute to pTMD symptoms and guide rehabilitation exercises aimed at optimizing jaw function while minimizing strain on vocal structures

3. Methods

3.1. Study Design and Participant Recruitment

The study protocol was approved by the McGill Institutional Review Board (ethical approval code: A05-B25-23B). This cross-sectional study examines jaw and masticatory muscle usage in singers and non-singers with and without pTMD. sEMG measures muscle activity, while MOCAP assesses jaw movement. The objectives are to determine whether singers and non-singers with and without pTMD have i) differences in physical or psychological factors related to pain measured through the DC/TMD, ii) differences in muscle activity during maximum voluntary contraction (MVC) of the temporalis and masseter muscles, and iii) differences in muscle activity or movement during maximum jaw opening.

We planned to recruit 48 total participants: n = 12 singers without pTMD, n = 12 singers with pTMD, n = 12 non-singers with pTMD, and n = 12 non-singers without pTMD. Sample size was estimated with a power analysis (F test: fixed effects ANOVA). The sample size calculation was performed for a larger study additionally investigating muscle activity during speaking and singing in singers and non-singers with and without pTMD. Fisher et al. observed 25-35% greater masseter muscle activity in instrumentalists than singers corresponding to an effect size of f = 0.88 - 1.4; Santana-Moraa et al. found 45% lower EMG masseter activity in individuals with TMD than without TMD corresponding to an effect size of f = 4.3 (54, 72). A priori power analysis was conducted for a one-way ANOVA with four groups. Assuming a more conservative effect size of f = 0.5, α = 0.05, and power (1-β) = 0.80, the required total sample size is 48 participants (n = 12 per group).

Participants were recruited through social media and email advertisements sent to members of various listservs at McGill University, Union des Artistes, and the National Association of Teachers of Singing. Electronic advertisements were also posted on the Quebec Pain Research Network's Recruitment Portal, and the Schulich School of Music undergraduate and graduate electronic newsletters.

3.2. Screening and Eligibility Criteria

Potential participants followed a link to the study's electronic interface, where they were asked a series of screening questions to determine their eligibility based on the inclusion and exclusion criteria. The inclusion criteria for singers: age $\geq$ 18 years, self-identified her/himself as a singer, and singing at least once a week. Inclusion criteria for non-singers: age $\geq$ 18 years and did not self-identify her/himself as a singer. Participants were classified as having pTMD or non-pTMD based on the Pain Screener Questionnaire. Individuals scoring 3 or more on the Pain Screener Questionnaire were classified as having pTMD.

Participants were excluded if they met any of the following criteria: having uncontrolled medical or psychiatric conditions, previously diagnosed with major psychiatric disorders such as excessive fear (phobia) or schizophrenia, recent injury or trauma to the face, known secondary pTMD caused by rheumatoid arthritis or fibromyalgia, ongoing orthodontic treatments, being a wind, brass, violin, or viola player due to the unique and consistent musculoskeletal demands placed on the orofacial and cranio-cervical regions during instrument performance, non-removable facial coverings (e.g., beard) due limitation in sensor placement, or pregnancy.

3.3. Screening, Consent and Data Collection

For the questionnaire portion of the study, LimeSurvey (hosted on McGill servers and maintained by McGill IT services) was used to screen participants for the inclusion and exclusion criteria, consent participants, and collect data in either French or English. Patients were first screened based on the inclusion and exclusion criteria by asking them a series of questions. If they met the criteria for the singers or non-singers group, then, they underwent an electronic consent process. During the electronic consent process, the study was explained, and consent was documented electronically. An electronic copy of the consent form was sent to each eligible participant.

3.4. Questionnaire

Participants filled out an online questionnaire on LimeSurvey, which collected the following information:

1. Sociodemographic data: date of birth, sex, gender, racial identity, marital status, highest education level, and family income. The DC/TMD sociodemographic questionnaire was used as a template. Sex and gender categories were based on recommendations from the Academies of Sciences, Engineering, and Medicine. Racial identity categories were based on recommendations from Canada (73). Additionally, highest education level was adjusted based on the situation in Québec. Data were categorical except for date of birth, which was used to calculate age.

2. Singing background (for singers' group): Singers filled out information on the singing history including the following: musical background, voice type, level of professionalism, hours per week of practice/performance, and number of years that singing was an important part of their life. These

questions were curated based on the findings of previous studies (62) and in consultation with collaborators who are singers. Data are categorical except for the number of years that music has been important in your life.

3. Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) questionnaires (10): TMD Pain Screener, Symptom Questionnaire, Graded Chronic Pain Scale (GCPS) 2.0, Jaw Functional Limitation Scale (JFLS) 2.0, Patient Health Questionnaire (PHQ)-9, Generalized Anxiety Disorder (GAD)-7, Patient Health Questionnaire (PHQ)-15, and Oral Behavior Checklist (OBC). Each questionnaire was scored according to the scoring manual for the DC/TMD.

3.5. In person experiments

Participants who completed the questionnaire and met the eligibility criteria were invited to the Centre for Interdisciplinary Research on Music, Media, and Technology (CIRMMT) for in-person experiments. After reviewing and signing the consent form, participants received a $40 Amazon gift card as compensation for their time.

3.6. Laboratory setup

A six-camera infrared MOCAP system (Oqus 300+, Qualisys, Sweden) was calibrated with the precision of <0.5 mm to track reflective markers placed on the head. Calibration was performed in tracking software (Qualisys Track Manager v2020.2, Qualisys, Sweden) by waving a calibration wand throughout the capture volume after positioning a reference object, ensuring adequate spatial coverage. The setup provides detailed insights into the dynamics of jaw and head movements to the tracking software during the study. The camera setup as shown in Fig. 2, consists of six strategically positioned cameras, ensuring comprehensive spatial coverage of the head. The upper cameras are mounted parallel to the ground, providing a stable, top-down perspective of the scene. These cameras capture an overhead view without any tilt, making them ideal for monitoring movements and changes across a broad area. In contrast, the lower cameras are positioned at lower elevations but are tilted upwards. This upward tilt allows them to capture details that would otherwise be obscured by objects or terrain, offering a clear perspective of subjects from below. The left-side cameras are positioned at (-232, 739, 1924) and (-171, 706, 1074), working together to cover the left region, while the front-facing cameras at (1539, -229, 1110) and (1493, -208, 1945) ensure full coverage of the front. Similarly, the right-side cameras at (-96, -1380, 2025) and (-145, -1404, 1135) monitor the right side with a mix of overhead and upward-tilted views. This careful placement and angling of cameras provide a multidimensional perspective, enhancing visibility and depth perception for analysis. The capture rate for all the cameras was set at 100 Hz and the exposure and flash time was set at 300 µs with a marker threshold percentage of 25.

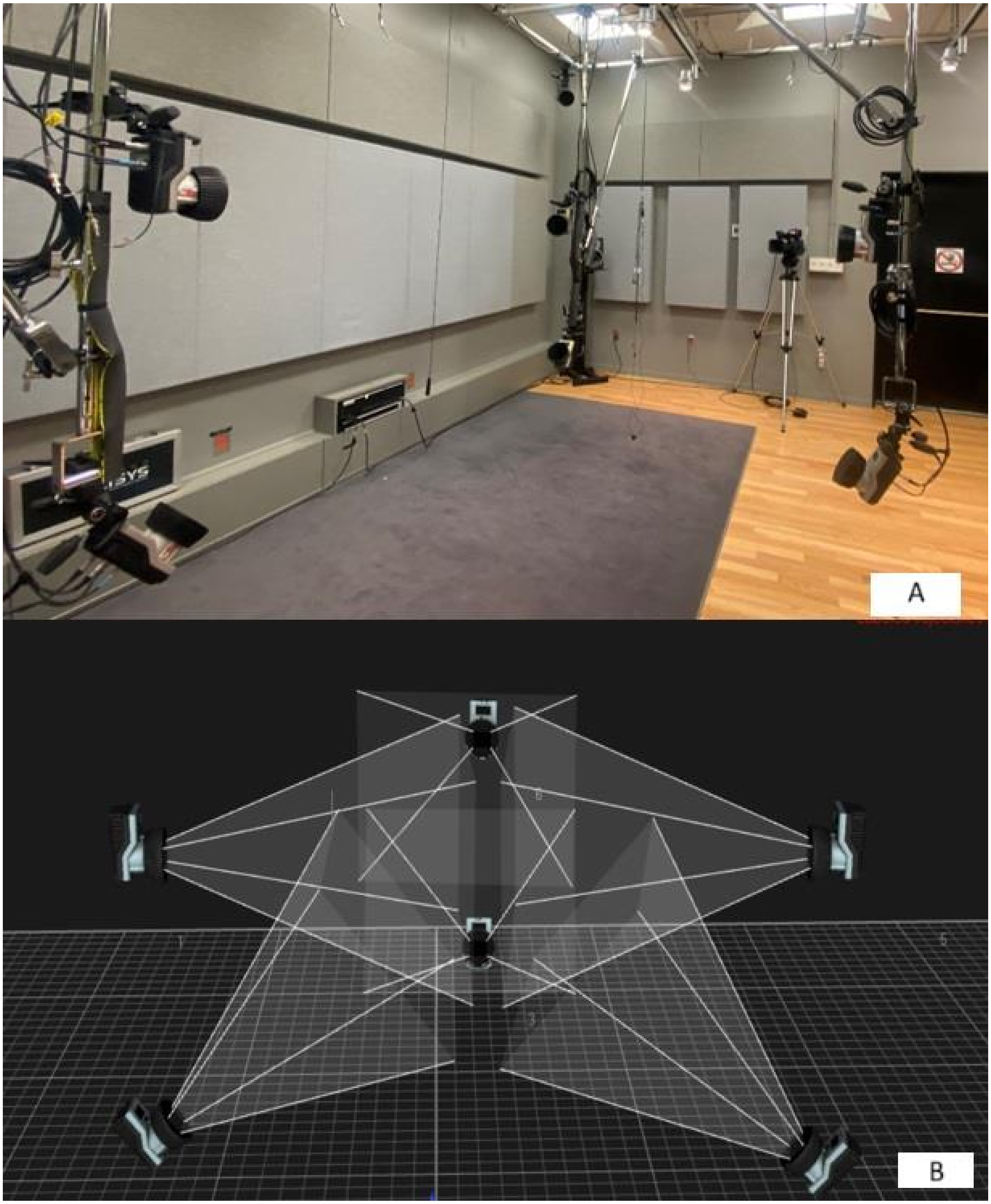


Figure 2 *Motion analysis setup at CIRMMT*. **A**: Image of the laboratory setup of the six cameras. **B**: Image of the field of view of each camera generated within the Qualisys software.

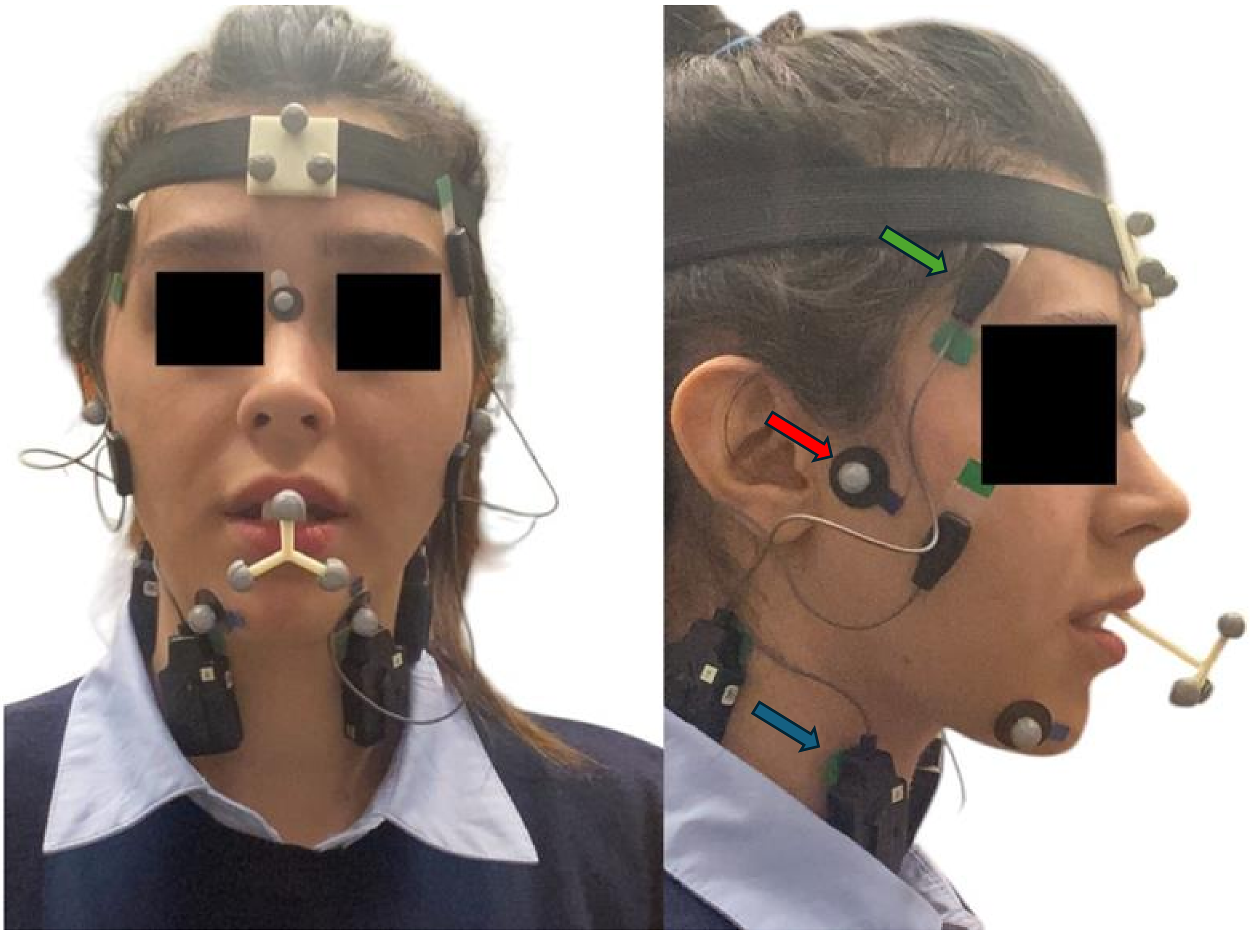


Figure 3 A full-face (left) and profile view (right) of the participant with attached sensors. The reflective markers (red arrow) were placed on the forehead (reference), at the TMJ (to define the hinge axis of the jaw) and at the chin (to define motion of the jaw). The intraoral device is attached to the mandibular incisors to validate the chin sensors. Muscle activity of the bilateral temporalis and masseter muscles was measured by placing the head of the sEMG sensor on the body of the muscle (green arrow) and the base of the sensor (blue arrow) on the neck.

3.7. Setup of sensors

To monitor muscle activity, four sEMG sensors (Trigno Mini, Delsys Inc., USA) were attached with double-sided tape (Trigno Mini Head Adhesive Interface, Delsys Inc., USA) to the bilateral masseter and temporalis muscles (Fig. 3). The masseter and temporal muscles, primarily involved in jaw closure, are often impacted by TMD. The sensors were placed parallel to muscle fibres, according to the literature (71). The bases of the sEMG sensors for the temporalis muscle were positioned inferior and posterior to the participant's ear to minimize signal interference (85). For the masseter muscle, the sensor bases were placed at least 2 cm anterior to the temporalis sensors to avoid signal overlap (85).

To capture precise jaw movements and 3D head rotation/translation, reflective markers (Qualisys, Goteborg, Sweden) were placed at key anatomical landmarks on the head, also secured with double-sided tape (Fig. 3). An intraoral device was designed to hold the sensor by 3D designer software (3Shape Unite 24.1, Denmark) and 3D printed (uPrint SE, Stratasys, USA) using a thermoplastic polymer (ABSplus-P430, Stratasys, USA). The intraoral device was aligned with the mid-line of the mandible and secured to the anterior mandibular teeth using dental putty (VP Mix HP Max Hydro, Henry Schein, China) (Fig. 4). The forehead sensor plate was also designed and 3D printed in the same manner and fixed on the forehead of the participant using wig straps (Fig. 3).

The reflective markers were placed on anatomical landmarks, similar to previous studies. The following anatomical landmarks were used:

- Forehead: The approximate center of the forehead was determined by the researcher vertically and horizontally. Three 9.5 mm diameter markers were placed on a plate fixed on this site by wig strap as stationary, non-muscular reference points.

- Nasion: A 0.5 mm diameter marker was placed on the deepest point at the bridge of the nose, located at the midline where the forehead meets the nasal bone.

- TMJ: This landmark was detected on the face by palpating just in front of the ear canal, where the jaw's condyle moves when opening and closing the mouth. Two 9.5 mm diameter markers were placed there. Together the two TMJ points denote the hinge axis.

- Sides of the chin: These two points were detected by palpating the lower jawbone, on either side of the chin, where the mandible curves upward toward the ear. Two 9.5 mm diameter markers were placed. These points were used to measure the opening angle of the mandible. The pogonion point was not used because facial expressions can change its position.

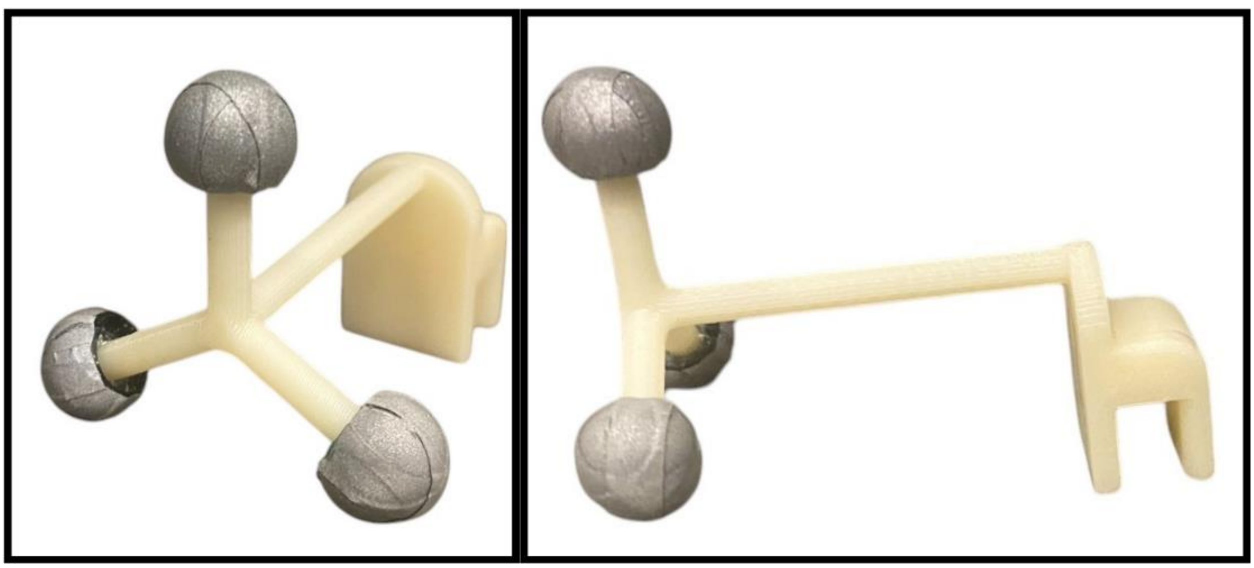


Figure 4 *Intraoral device* for validation of skin markers at chin. The intraoral device consisted of three reflective markers on one end, while the other end has a notch that fits over the mandibular incisors with dental putty to hold it in place. The movement of the intraoral device represents the true movement of the jaw, as it is attached to hard tissue.

3.8. Protocol for data collection

3.8.1. Experiment Design

To standardize data collection, an instructional video was presented to participants using headphones. The first video demonstrated a series of range-of-motion movements, including maximum mandibular opening, lateral movements, and maximum protrusion, each repeated three times.

After MOCAP recording, participants sat upright in a chair without head support. They were instructed to clench on a cotton roll for 10 seconds, rest for 50 seconds, and repeat this task two more times.

3.8.2. MOCAP data analysis

Motion capture and sEMG data was captured as .QTM files using Qualisys software. A single person labeled the landmarks in the software and checked manually that they were correctly labeled at each timepoint. The (x, y, z) location of each marker in space at each timepoint was then exported in .MAT format.

Samples were post-processed in MATLAB (Mathworks). First, the sampling frequency was lowered to 25 Hz. To simplify the geometry, the 3D locations of the markers were collapsed onto the sagittal plane by calculating projected points (PPs are projections or shadows of a point onto another surface or along a certain vector direction) or weighted points (WPs are averaged from other points on the sagittal plane between two real markers). The following points were calculated for each timepoint:

- WP_hinge: This is the weighted point at the center of the hinge axis, calculated as halfway between the markers on the left and right TMJ. This point defines where the jaw hinges.

- WP_forehead: Three markers were placed on the forehead centered around the midplane of the face. This point is at the center of the forehead markers and is assumed to not move during the tests (in translation).
- WP_chin: A marker was placed on the left and right sides of the chin in line with the corners of the lip. This point is at the center of the chin markers on the sagittal plane.
- WP_iod: The intraoral device (IOD) contained three markers arranged in a triangle. The fourth projected point is at the center of the triangle.
- PP_iod: This point is a projection from the WP_iod to approximate it to the tip of the chin bone. It is calculated from the vectorial or dot product of two vectors formed from the 3 points of the IOD.

Next, the following distances and angles were calculated for each timepoint:

- Jaw opening angle: the angle formed between two vectors, WP_hinge to WP_forehead and WP_hinge to WP_chin or PP_iod, calculated through the scalar product equation.
- Jaw opening distance: the magnitude of the vector formed from WP_forehead to WP_chin or PP_iod.
- Jaw translation distance: the magnitude of the vector formed from WP_hinge to WP_chin or PP_iod.

The resulting datafile contained the jaw opening angle, opening distance and translation distance as a function of time. These data were plotted showing the movement as a function of time, which consisted of three trials of maximum mouth opening.

The RMS was plotted as a function of time in a custom-made MATLAB interface. The investigator marked the beginning and end for each trial and the data within that range were extracted. The only difference was that the last three seconds of the file, where the participant was asked to keep their mouth at rest, were averaged, and this average was then subtracted from all the numbers in the maximum opening ranges to account for the resting interval.

3.8.1. Validation of chin markers

The intraoral device was considered to represent the true movement of the mandible. However, future studies will be on singers during speaking and singing exercise; therefore, it will not be possible to use an intraoral device during some functions. Thus, we assessed the validity of the chin markers to represent movement of the mandible. Data were acquired simultaneously for the chin and intraoral device for maximum mouth opening. We then calculated jaw opening angle, jaw opening distance, and jaw translation distance using the chin markers and using the intraoral device. Next, we constructed Bland Altman plots to represent agreement between movement of the jaw measured by sensors placed at the chin and intraoral device. The plots show the average value on the x-axis and the difference on the y-axis.

3.8.2. sEMG data analysis

The sEMG data was also extracted from Qualisys software as the signal as a function of time. The data was processed in MATLAB. First, a band pass filter (filter order was set to 8) was designed and applied to remove low frequencies (10 Hz) and high frequencies noise (200 Hz) (74). Next, the background was subtracted such that muscle activity was zero when no muscles were active.

Data was resampled or resized through the root mean square method to 25 Hz of frequency for several reasons: to avoide conversion from MATLAB to excel, to standardize the sampling rate for better comparison, reduce noise and data volume without losing essential information, and improve signal analysis by smoothing the data and removing high-frequency fluctuations.

3.9. Post processing of MOCAP and sEMG data

The MOCAP outcomes for maximum opening and the sEMG outcomes for MVC and maximum opening were plotted in MATLAB. The data were plotted as a function of time, which illuminated three trials, where the person moved their mouth to maximum opening or clenched their teeth. For each trial, the beginning and end of the trial was indicated manually by the researcher and the numbers within the respective ranges were extracted. Furthermore, for the sEMG data, the last three seconds of the file, where the participant was asked to keep their mouth at rest, were averaged, and this average was then subtracted from all the numbers in the maximum opening ranges to account for the resting interval.

Then, from the extracted ranges, the following were calculated:

- Max_max: Maximum value of muscle activity over the three trials.
- Mean_mean: First, the mean value of the muscle activity was measured for each trial. Then, the average value of the mean over the three trials was calculated.
- MeanDIVMax_max: Next, Mean_mean was normalized by Max_max.

- MeanOfStandardDeviations, The standard deviation of the muscle activity was calculated for each trial and the mean of the standard deviation was calculated for the three trials.

3.10. Statistics

The data were organized and tabulated using Microsoft Excel (Microsoft Corporation, USA) and analyzed using SPSS version 26 (IBM, Armonk, NY, USA). Descriptive statistics for continuous variables were reported as mean, standard deviation, minimum, and maximum values, while categorical variables were presented as counts and percentages. Data normality was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated with Levene's test.

For continuous variables, an independent t-test was used to compare two groups when comparing variables related to singers only (years of singing). For comparisons involving more than two groups, a one-way ANOVA was performed, followed by Tukey's post-hoc test to identify pairwise differences when the assumption of normality was satisfied across all groups. When data were not normally distributed, the Kruskal-Wallis test was applied, followed by the Post-Hoc Dunn's test or the Mann-Whitney U test with Bonferroni correction for post-hoc pairwise comparisons.

Categorical data were analyzed using the chi-square test or Fisher's exact test, as appropriate.

Statistical significance was set at $\mathbf{p} < 0.05$.

4. Results

4.1. Demographics

The demographic characteristics of participants, including non-singers and singers, stratified by pTMD status, are summarized in Table 1. The assessed variables included age, sex, gender, race, marital status, education level, and income level. A significant difference between groups (using Pearson Chi-Square test) was observed only for racial distribution but post-hoc tests were not significant.

Table 1: *Demographics of participants.* Significance between groups for age was tested with the Kruskal-Wallis test. Significant differences between groups for sex, gender, race, marital status, education level, and income was assessed using Pearson Chi-Square test (results shown in Table) and confirmed with the Fisher Exact test (results not shown). * P<0.05: statistically significant.

Variable	**Measure**	**Non-singers**		**Singers**		**P-value**
		without pTMD	**with pTMD**	**without pTMD**	**with pTMD**	
Age	Years, Mean ± SD	30 ± 5	28 ± 4	30 ± 12	27 ± 8	0.26
Sex	Male : Female	5 : 5	2 : 10	4 : 6	2 : 10	0.22
Gender	Male : Female	5 : 5	2 : 9	4 : 6	2 : 10	0.25
Race	White : Non-white	2 : 8	2 : 10	7 : 3	6 : 6	**0.03***
Marital Status	Living with a partner : Not living with a partner	3 : 7	3 : 9	1 : 9	2 : 10	0.69
Education Level	Professional or Postgraduate : Below Professional	7 : 3	9 : 3	5 : 5	4 : 8	0.16
Income Level	≥ $60K/year : < $60K/year	2 : 6	3 : 6	4 : 2	4 : 2	0.25

4.2. Singing Background

For singers, detailed characteristics such as the use of other instruments, weekly singing hours, professional stage, and average years of singing are summarized in Table 2. No significant differences were observed between singers with and without pTMD in terms of the use of other instruments, weekly singing hours, professional stage, or average years of singing. These findings suggest that the singing-related characteristics are generally comparable between the two singing groups.

Table 2: Musical Background of singers. Significant difference between groups was tested for number of years singing with the Independent T-test. Significant differences between groups were tested using the Fisher Exact test for categorical data: playing other instruments, singing hours per week and professional stage. Statistical significance was set at $p < 0.05$.

Variable	Measure	Singers Without PTMD	Singers With PTMD	P-value
Other instruments	Singing only : Instruments not using head and neck	4 : 6	9 : 3	0.19
Singing hours per week	≥ 3 hours : < 3 hours	6 : 4	9 : 3	0.65
Professional stage	Professional : Amateur	8 : 2	7 : 5	0.38
Number of years of singing	Mean ± SD	11.0 ± 4.8	11.0 ± 8.2	0.93

4.3. Symptoms

4.3.1. Pain Presence

The percentage of participants reporting pain presence varied across the groups: Non-singers without pTMD: 20%, Non-singers with pTMD: 75%, Singers without pTMD: 10%, and Singers with pTMD: 83.3%. The Pearson Chi-Square test indicated a significant association between pain presence and group membership (p<0.001). Fisher's exact test confirmed this result (p<0.001). Post-hoc Fisher's exact test (Bonferroni corrected) showed significant differences between singers with and without pTMD (p=0.01). These findings indicate that participants with pTMD, particularly singers, were more likely to report experiencing pain compared to those without pTMD. However, there is no significant difference between non-singers with and without pTMD regarding pain presence. It is surprising that some individuals with pTMD reported pain, even though they were classified to the non-pTMD group with the pain screener questionnaire.

Table 3: *DC/TMD symptom questionnaire.* Pain presence, temple headache, TMJ noises, closed locking, open locking, headache modified by function. Categorical data are presented as % of participants (percentage of participants). Years of temple headache is presented as mean ± SD. For categorical variables, the Pearson chi-square was used, and the result was double checked with the fisher's exact test and *Post-hoc comparisons were done using Fisher's exact test with Bonferroni correction*. For years of temple headache, Kruskal- Wallis test was used. Post-hoc tests revealed significant differences between: #Singers with and without pTMD; *Non-singers with and without pTMD

Variable	**Non-singer**		**Singer**		**P-value**
	Without pTMD N = 10	**With pTMD** N = 12	**Without pTMD** N = 10	**With pTMD** N = 12	
Pain Presence	2 (20%)	9 (75%)	1 (10%)	10 (83.3%) #	<0.001
Temple Headache	2 (20%)	6 (50%)	1 (10%)	7 (58.3%)	0.054
Years of Temple Headache	2.54 ± 3.48	6.29 ± 7.85	5 ± --	5.77 ± 9.91	0.82
TMJ Noises	1 (10%)	9 (75%) *	4 (40%)	11 (91.7%)	<0.001
Closed Locking	0 (0%)	0 (0%)	1 (10%)	1 (8.3%)	0.8
Open Locking	0 (0%)	0 (0%)	1 (10%)	2 (16.7%)	0.4
Headache Modified by Function	0 (0%)	5 (41.7%)	0 (0%)	6 (50%)	0.002
Disabling Pain: non disabling pain (Graded Chronic Pain Scale)	--	0:12	--	2:7	0.037

4.3.1. Presence and history of temple headache

The percentage of participants reporting temple headaches varied across the groups (see Table 3): Non-singers without pTMD: 20%, Non-singers with pTMD: 50%, Singers without pTMD: 10%, and Singers with pTMD: 58.3%. The Pearson Chi-Square test indicated a potential association between temple headache and group membership, with a p-value of 0.054. However, this result did not reach the threshold for statistical significance ($p<0.05$). These findings suggest that participants with pTMD, may be more likely to report temple headaches, though the evidence is not conclusive. Years of temple headache did not reveal significant differences among the groups ($p = 0.82$).

4.3.2. TMJ Noises

The percentage of participants reporting TMJ noises varied across the groups: Non-singers without pTMD: 10%, Non-singers with pTMD: 75%, Singers without pTMD: 40%, and Singers with pTMD: 91.7%. The Pearson Chi-Square test indicated a significant association between TMJ noises and group membership ($p<0.001$). Fisher's exact test confirmed this result ($p<0.001$). Post-hoc comparisons using Fisher's exact test with Bonferroni correction revealed significant differences between non singers with pTMD and non-Singers without pTMD (adjusted $p=0.03$). These findings suggest that non singers with pTMD have more TMJ noises than those without pTMD.

4.3.3. Closed Locking

Closed locking, a condition where the jaw cannot fully open due to displacement of the articular disc without reduction (18), was reported by the following percentages of participants: Non-singers without pTMD: 0%, Non-singers with pTMD: 0%, Singers without pTMD: 10%, and Singers with pTMD: 8.3%. Fisher's exact test co test indicated no significant association between closed locking and group membership (p=0.848). These findings suggest that closed locking is not significantly more prevalent in any of the groups, regardless of pTMD status or singing background.

4.3.4. Open Locking

Open locking refers to a condition in which the jaw becomes stuck in an open position, often due to anterior dislocation of the mandibular condyle, making it difficult or impossible to close the mouth (18). In this study, the percentage of participants reporting open locking was as follows: Non-singers without pTMD: 0%, non-singers with pTMD: 0%, Singers without pTMD: 10%, and Singers with pTMD: 16.7%. Fisher's exact test showed no significant association between open locking and group membership (p = 0.48). These findings suggest that open locking is not significantly more prevalent in any of the groups, regardless of pTMD status or singing background.

4.3.5. Headache Modified by Function

The percentage of participants reporting that headaches were modified by function was: Non-singers without pTMD: 0%, Non-singers with pTMD: 41.7%, Singers without pTMD: 0%, and Singers with pTMD: 50%. Fisher's exact test showed a significant association between headaches modified by function and group membership (p=0.002). Post-hoc Fisher's exact test (Bonferroni corrected) did not reveal any statistically significant pairwise differences.

4.3.6. GCPS (Graded Chronic Pain Scale)

GCPS was only reported by non-singers with pTMD and classifies participants as have disabling pain vs non disabling pain. A majority of non-singers (0:12) and singers (2:7) with pTMD has non-disabling pain. Fisher's exact test showed a significant association between disabling pain and group membership (*p=0.037*). Post-hoc Fisher's exact test (Bonferroni corrected) showed that both singers and non-singers with pTMD experience more disabling pain than their peers with pTMD.

4.3. DC/ TMD questionnaires

Table 4 presents the results of the DC-TMD questionnaires assessing the behavioral and psychological aspects of pTMD. The questionnaire has been shown to be a reliable and repeatable tool in evaluating these factors.

The GAD-7 questionnaire measures generalized anxiety disorder. There was a significant effect of pTMD in mean GAD-7 scores. Non-singers with pTMD had a score that was double that of non-singers with pTMD indicating mild anxiety. Possible scores range from 0 to 21, with 21 being the highest level of anxiety. The score of 5 and above indicates mild anxiety. The averages for the pTMD groups were around 5, which is the cut-off for mild anxiety. The non-pTMD groups were below 5 indicating less than mild anxiety.

The OBC questionnaire evaluates oral behaviors. There was a significant effect of singing and pTMD in mean OBC scores. The pTMD groups of singers and non-singers had a score that was 10 points greater than the respective non-pTMD groups. Furthermore, singers with and without pTMD had scores that were 9 points higher than their respective non-singer groups. A score between 0-16 is considered normal; the average OBC score for non-singers without pTMD was lower than 16. The average values for the pTMD groups were within the ranges that occur more often in people with TMD. Interestingly, singers with pTMD had a score that was outside normal behavior and occurs twice as often in people with TMD; the average value was lower than the threshold for oral behaviors to contribute to the onset of TMD.

The PHQ-15 assesses somatic symptom severity. We found an effect of singing and pTMD on average PHQ-15 score. Here, the respective pTMD groups had significantly greater values than the non-pTMD groups. The average values for the non-pTMD groups were at or below the threshold for low physical symptoms, while the average values for the non-singer pTMD group indicates low physical symptoms and the singer pTMD group indicates medium physical symptoms. Significant differences were found between the pTMD and non-pTMD groups. Non-singers with pTMD had higher PHQ-15 scores compared to non-singers without pTMD. Singers with pTMD had higher PHQ-15 scores compared to singers without pTMD.

The PHQ-9 measures depression severity. There was an effect of pTMD on PHQ-9 score. Non-singers with pTMD had a significantly greater PHQ-9 score than non-singers without pTMD. The average values of the non-pTMD groups were below the cut-off for mild depression, while the average value of the pTMD groups were above the cut-off for mild depression.

The Jaw Functional Limitation Scale (JFLS Global) scores among individuals with pTMD exhibited higher scores than those without, with non-singers with pTMD showing slightly lower values compared to singers with pTMD, suggesting a potentially greater impact of pTMD on jaw function among singers.

Mastication function was more affected in individuals with pTMD. Non-singers with pTMD had the highest mean score, followed by singers with pTMD, while both non-singers and singers without pTMD had minimal limitations, with almost 10 times lower means than pTMD participants.This suggests that chewing difficulties were most pronounced in non-singers with pTMD. Values for people without pTMD were similar to those in the literature, while average values for people with pTMD were smaller in comparison to literature values for chronic pTMD (5, 75).

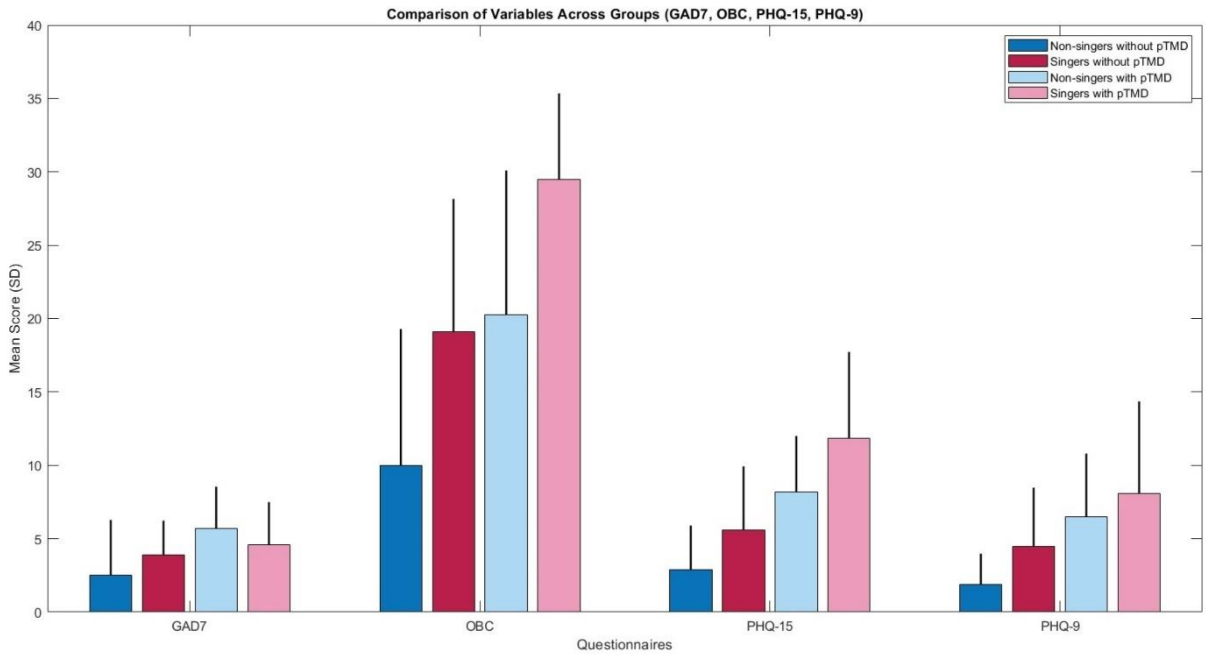
Mobility limitations was not observed in individuals without pTMD, but increased in those with pTMD, particularly among singers which was double of that in non-singers. This trend suggests that singers with pTMD may experience greater restrictions in the jaw movement.

Communication function remained largely unaffected in individuals without pTMD. However, those with pTMD exhibited increased scores, with singers reporting largely higher communication difficulties than non-singers, indicating that pTMD may have a greater impact on speech-related jaw function in singers.

CPI scores revealed substantial differences between groups, with individuals with pTMD experiencing significantly higher pain levels. Non-singers with pTMD had a mean CPI of 22.7 ± 14.7, whereas singers with pTMD exhibited the highest pain levels (33.3 ± 23.3). In contrast, pain levels were minimal in those without pTMD (2.3 ± 7.4 for non-singers and 3.0 ± 5.1 for singers). This suggests that pTMD is strongly associated with increased pain, with a potentially greater burden among singers.

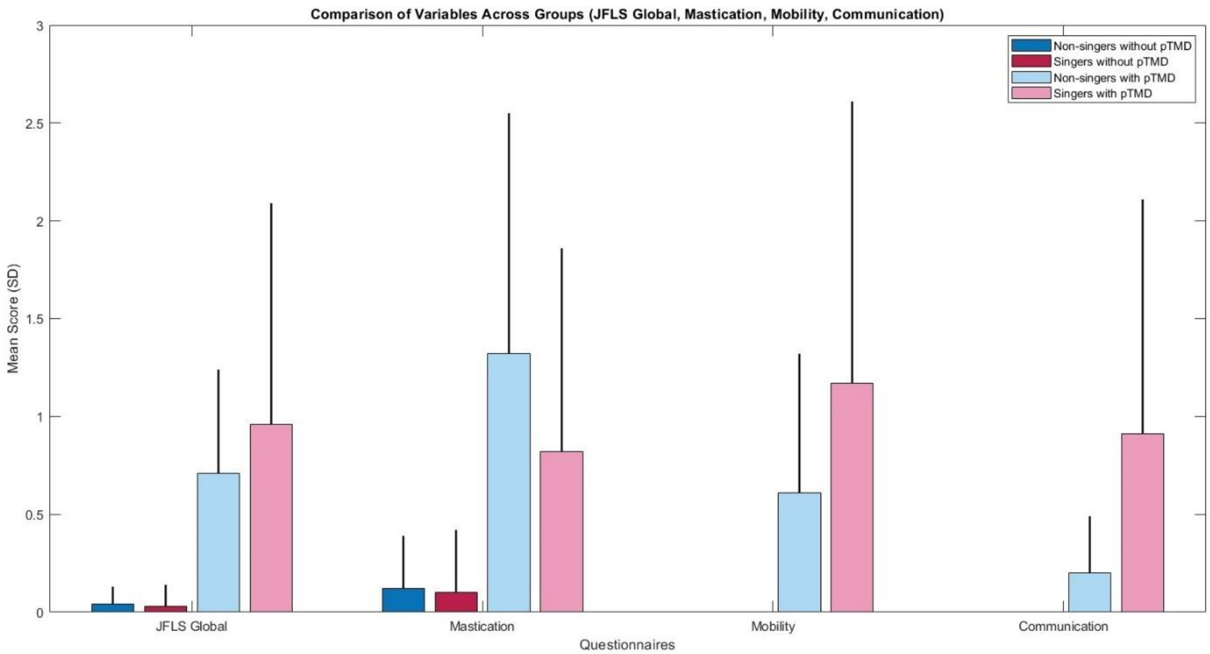
Table 4: DC-TMD results. Values are presented as mean ± SD of questionnaire scores. Group differences were assessed using the ANOVA test with Bonferroni correction for GAD-7, OBC, PHQ-15, and PHQ-9. No statistics were performed on the JFLS scores and the chronic pain index (CPI) because they were not normally distributed. P-value was considered significant at $p < 0.05$. An ANOVA was used to test for differences in a) singing group, b) pTMD group, c) interaction. Post-hoc Bonferroni tests were performed: *: Non-singers without pTMD and non-singers with pTMD. $: Singers with pTMD and singers without pTMD, #: Singer without pTMD vs non-singers without pTMD, §: Singers with pTMD vs non-singers with pTMD.

Variable	Non-singers		Singers	
	without pTMD	**with pTMD**	**without pTMD**	**with pTMD**
GAD7 [b]	2.5 ± 3.8	5.7 ± 2.9 *	3.9 ± 2.3	4.6 ± 2.9
OBC [a,b]	10.0 ± 9.3	20.3 ± 9.9*	19.1 ± 9.1 [#]	29.5 ± 5.9 [$, §]
PHQ-15 [a,b]	2.9 ± 3.0	8.2 ± 3.8*	5.6 ± 4.3	11.8 ± 5.9 [$]
PHQ-9 [b]	1.9 ± 2.1	6.5 ± 4.3*	4.5 ± 4.0	8.1 ± 6.3
JFLS Global	0.04 ± 0.09	0.71 ± 0.53	0.03 ± 0.11	0.96 ± 1.13
Mastication	0.1 ± 0.3	1.3 ± 1.2	0.1 ± 0.3	0.8 ± 1.0
Mobility	0.0 ± 0.0	0.6 ± 0.7	0.0 ± 0.0	1.2 ± 1.4
Communication	0.0 ± 0.0	0.2 ± 0.3	0.0 ± 0.0	0.9 ± 1.2
CPI	2.3 ± 7.4	22.7 ± 14.7	3.0 ± 5.1	33.3 ± 23.3



	Non-singers No pTMD	Non-singers With pTMD	Singers No pTMD	Singers With pTMD
GAD7	-	-	-	*
OBC	-	-	*	*
PHQ-15	*	-	*	*
PHQ-9	*	-	-	-

Figure 5 Mean Score and SD of GAD7, OBC, PHQ-9, and PHQ-15 across the groups.



	Non-singers No pTMD	Non-singers With pTMD	Singers No pTMD	Singers With pTMD
JFLS Global	-	*	-	*
Mastication	-	*	-	*
Mobility	-	*	-	*
Communication	-	-	-	*

Figure 6 Mean and SD scores of JFLS Global, Mastication, Mobility, and Communication across the groups.

4.4. Maximum Voluntary Contraction (MVC)

After the participants performed the maximum clench three times, the following parameters were compiled i) maximum muscle activity among the three trials (Max_max), ii) mean of the average muscle activity for the three trials (Mean_mean), iii) the mean muscle activity normalized by the maximum muscle activity (MeanDIVMax_max), and iv) the mean value of the standard deviation across the three trials (Mean_StDev). The data are presented in Table 5. In the right and left masseter as well as the right temporalis, muscle activity was not significantly different among the groups. However, in the left temporalis, there was an effect of pTMD in the maximum and mean muscle activity; the max was 53% lower and the mean was 50% lower in singers with pTMD than singers without pTMD. There was an effect of singing on the ratio of the mean to maximum muscle activity in the left temporalis; singers with pTMD had 30% lower muscle activity in the left temporalis than non-singers with pTMD.

Table 5: *Muscle activity during maximum clench. Three trials of maximum clench were performed by each participant. Muscle activity was measured with sEMG. For each trial, the maximum, mean, and standard deviation were calculated. Then, the following parameters were compiled: i) Max_max: the maximum of the three trials, ii) Mean_mean: the mean of the mean values of the three trials, iii) MeanDIVMax_max: the mean_mean normalized by the Max_max, iv) mean_StDev: the mean value of the standard deviation over the three trials. Data are reported as mean ± standard deviation. An ANOVA was used to test for differences in a) singing group, b) pTMD group, c) interaction. Post-hoc Bonferroni tests were performed: *difference between singers and non-singers with pTMD, # difference between singers with and without pTMD.*

Muscle Group	**non pTMD**						**pTMD**					
	Non singers			**Singers**			**Non singers**			**Singers**		
Right masseter												
Max_max	102.2	±	64.3	106.1	±	68	93.1	±	41.9	103.4	±	73.2
Mean_mean	42.3	±	23	38.4	±	19.1	38.5	±	22.5	40.5	±	24.3
MeanDIVMax_max	0.44	±	0.07	0.38	±	0.08	0.4	±	0.06	0.41	±	0.09
mean_StDev	16.5	±	7.6	14	±	5.4	15.2	±	7.1	15.3	±	10.3
Left masseter												
Max_max	84.4	±	42.1	91.3	±	62.6	92.7	±	43.1	88.3	±	54
Mean_mean	34.4	±	17.9	33.2	±	23.9	36.4	±	18.2	32	±	18.3
MeanDIVMax_max	0.41	±	0.06	0.37	±	0.07	0.39	±	0.05	0.38	±	0.08
mean_StDev	16.7	±	8.5	18.2	±	7.8	16.1	±	7.8	13	±	8.3
Right temporalis												
Max_max	156	±	61.7	151.5	±	55.2	123.2	±	65.1	130.1	±	78.3
Mean_mean	59.6	±	22.3	63.2	±	25.6	52.2	±	31.5	52.7	±	37.2
MeanDIVMax_max	0.39	±	0.06	0.41	±	0.06	0.41	±	0.05	0.39	±	0.1
mean_StDev	19.8	±	9.5	22.4	±	6.8	18.4	±	8.7	16.1	±	8.2
Left temporalis												
Max_max [b]	161.1	±	79.5	210.4	±	94	144.6	±	79.9	98.5	±	44.3[#]
Mean_mean [b]	65.4	±	31	79.4	±	27.1	64.2	±	34.1	39.6	±	20.9[#]
MeanDIVMax_max [a]	0.42	±	0.04	0.39	±	0.05	0.45	±	0.05	0.39	±	0.05 *
mean_StDev	19.2	±	7.9	21.9	±	9.8	18.1	±	8.8	15	±	8.1

4.5. Maximum opening

Participants were asked to open their jaw to maximum opening three times. Muscle activity and jaw movement were measured during maximum opening. The mean muscle activity normalized by the maximum clench is shown in Fig. 7 for the right and left masseter and the right and left temporalis. The masseters and temporalis use approximately 5% of the maximum muscle activity to open the jaw to its maximum opening.

For the muscle activity during maximum opening, there were no significant differences between the groups for the left and right masseter. In the left and right temporalis, there was an effect of pTMD in the normalized mean muscle activity. The normalized mean muscle activity in the left temporalis was significantly greater in the singers with pTMD vs singers without pTMD. Thus, singers with pTMD were using a greater percentage of their maximum muscle activity to open their jaw. This could be because the maximum muscle activity of the left temporalis was 50% lower in singers with pTMD than singers without pTMD (Table 5).

From the kinematic data, mean opening angle, mean opening distance and mean translational distance were measured. The standard deviation was also measured for each trial and then averaged across the three trials; standard deviation describes the variability or the consistency with which participants maintained their jaw open. These outcomes were measured using either the intraoral device or chin markers.

The kinematics data show that there is no difference between groups in the mean opening angle, mean opening distance or translation distance using the chin sensors or intraoral device (Fig. 8, 9). There were effects of singing and pTMD for the standard deviation measured by the intraoral device (Fig. 8). Singers without pTMD had a significantly greater standard deviation in the mean opening angle and mean opening distance than non-singers without pTMD. Furthermore, singers without pTMD had a significantly greater standard deviation in the mean opening angle and mean opening distance than singers with pTMD.

There were effects of pTMD and interaction of pTMD and singing for the standard deviation measured by the chin sensors (Fig. 9). Using the chin sensors, there was an interaction effect. Singers with no pTMD had a greater standard deviation in the mean opening angle and mean opening distance than non-singers with no pTMD. However, the opposite was true for those with pTMD: non-singers with pTMD had a greater standard deviation in the mean opening angle and mean opening distance than singers with pTMD. Similarly, singers with pTMD had a lower standard deviation than singers with no pTMD; while non-singers with pTMD had a larger standard deviation than non-singers with no pTMD.

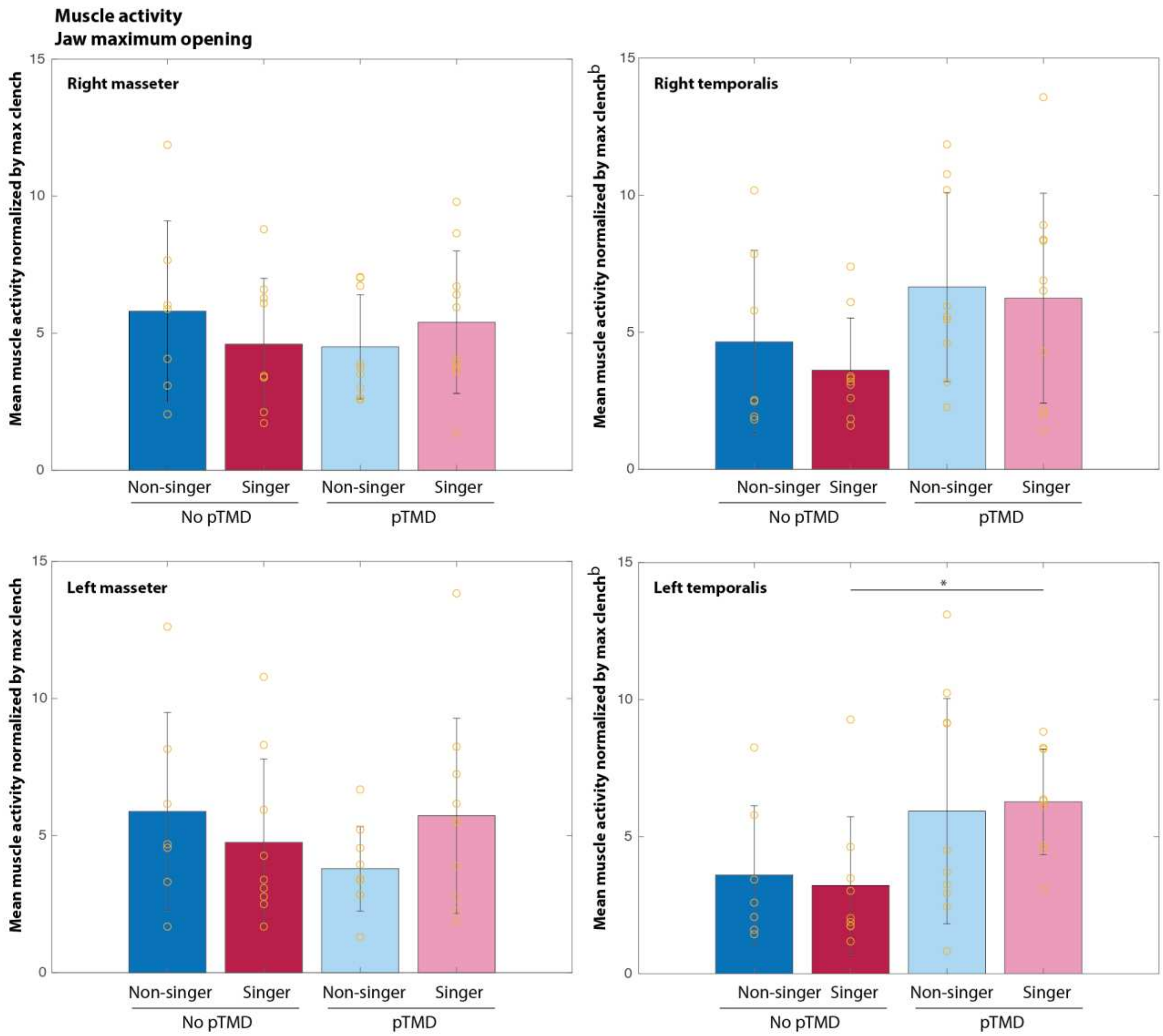


Figure 7 *Muscle activity during maximum opening*. Data are shown for mean muscle activity in the bilateral masseter and temporalis while participants opened their jaw to maximum opening. The mean muscle activity is normalized by the maximum muscle activity during MVC test. The values represent the percentage of the MVC used to open the jaw. Data are presented as bar graphs representing the mean value and errors bars representing the standard deviation. Individual data point shown. Statistical significance was defined as $p < 0.05$. ANOVA main effects: (a) singing, (b) pTMD, (c) interaction. * indicates significant Bonferroni post-hoc tests for pairwise comparisons.

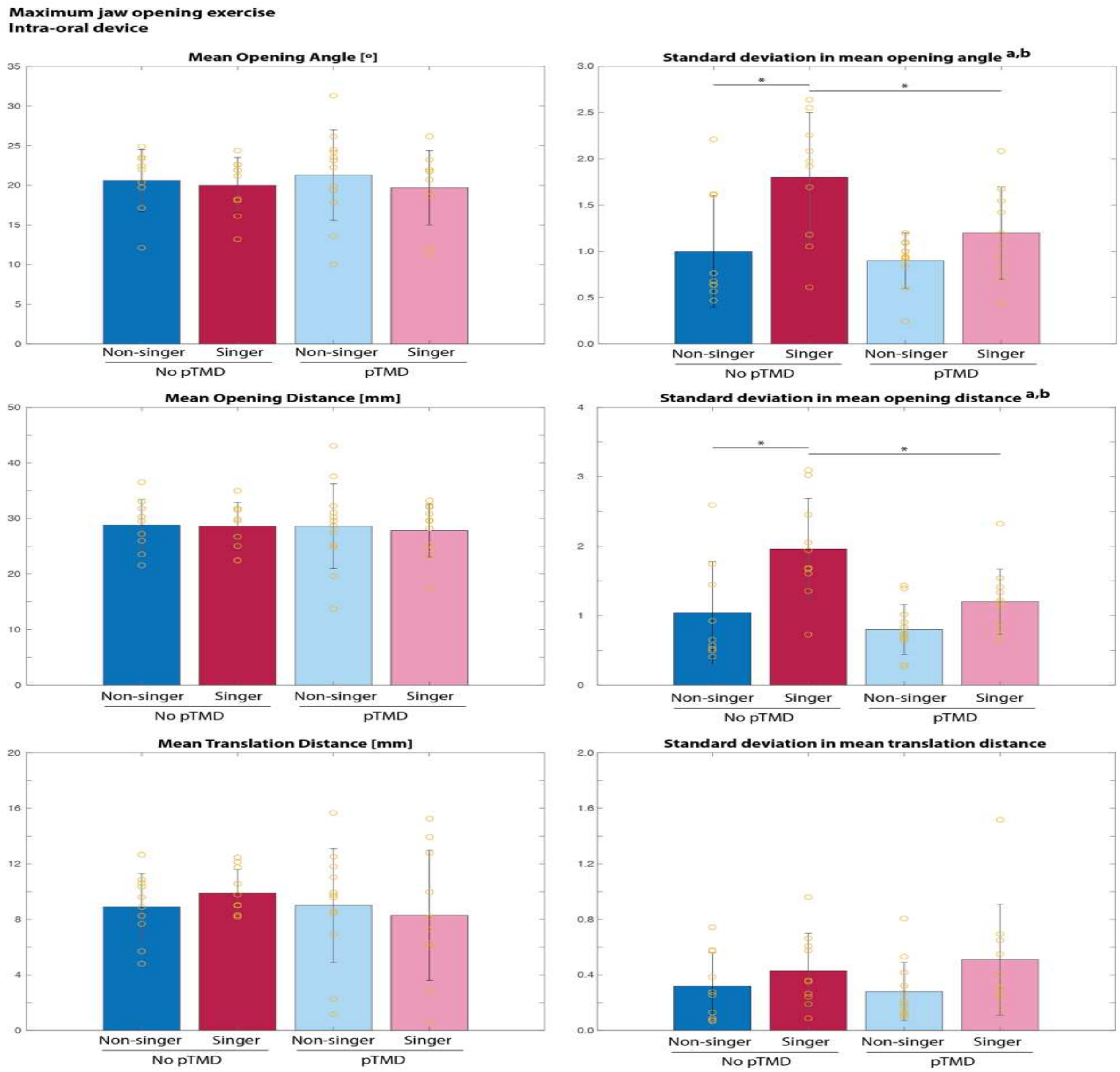


Figure 8 *Jaw kinematics during maximum opening measured with intraoral device.* Data are shown for mean opening angle of the jaw, mean opening distance, mean translation distance during maximum jaw opening measured with MOCAP data of the infrared sensors attached to either side of the chin. The mean values are the mean of three jaw opening trials. Also shown are the standard deviation (i.e., heterogeneity or consistence) in the opening angle, opening distance, and translation distance. Data are presented as bar graphs representing the mean value and errors bars representing the standard deviation. Individual data point shown. Statistical significance was defined as $p < 0.05$. ANOVA main effects: (a) singing, (b) pTMD, (c) interaction. * indicates significant Bonferroni post-hoc tests for pairwise comparisons.

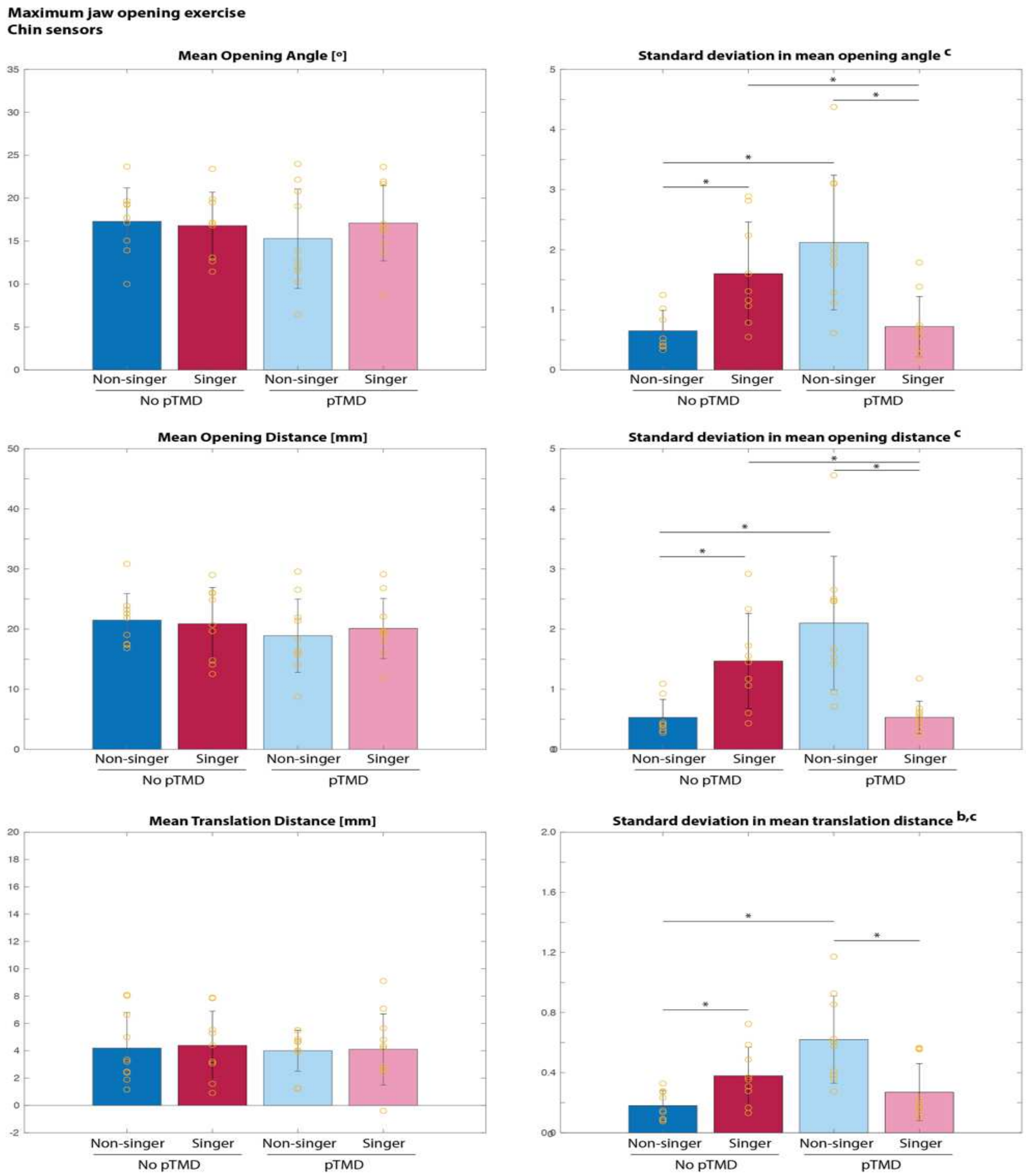


Figure 9 *Jaw kinematics during maximum opening measured with chin sensors.* Data are shown for mean opening angle of the jaw, mean opening distance, mean translation distance during maximum jaw opening measured with MOCAP data of the infrared sensors attached to either side of the chin. The mean values are the mean of three jaw opening trials. Also shown are the standard deviation (i.e., heterogeneity or consistence) in the opening angle, opening distance, and translation distance. Data are presented as bar graphs representing the mean value and errors bars representing the standard deviation. Individual data point shown. Statistical significance was defined as $p < 0.05$. ANOVA main effects: (a) singing, (b) pTMD, (c) interaction. * indicates significant Bonferroni post-hoc tests for pairwise comparisons.

4.6. Validation of Intraoral Device

Bland-Altman plots were constructed to investigate the relationship between the 'gold standard' intraoral device and the chin sensors. The intraoral device is the gold standard because its markers are attached to hard tissue that cannot deform during movement. On the other hand, the chin sensors are attached to skin, which lies on top of the moving bone. For future measurements during speaking or singing, it will not be possible to use the intraoral device. We aim to see the error between the chin sensors and IOD.

Bland-Altman plots for the opening angle, opening distance and translation distance are shown in Figures 10-12. In the Bland-Altman plots, the 'difference' (y-axis) is always greater than zero. Therefore, the chin sensors are systematically underestimating jaw movement, this is called a differential bias. The average ± standard deviation in the difference between the intraoral device and chin sensors is 3.86° ± 2.48 for the Opening Angle, 8.14 mm ± 3.6 for the Opening Distance and 4.56 ± 3.61 for the Translation Distance.

For the translation distance, there is a slight positive proportional bias in addition to the systematic bias. Fitting a regression line to the data shows that the slope is significantly different from zero. Thus, for larger values of translational movement, you have a greater difference.

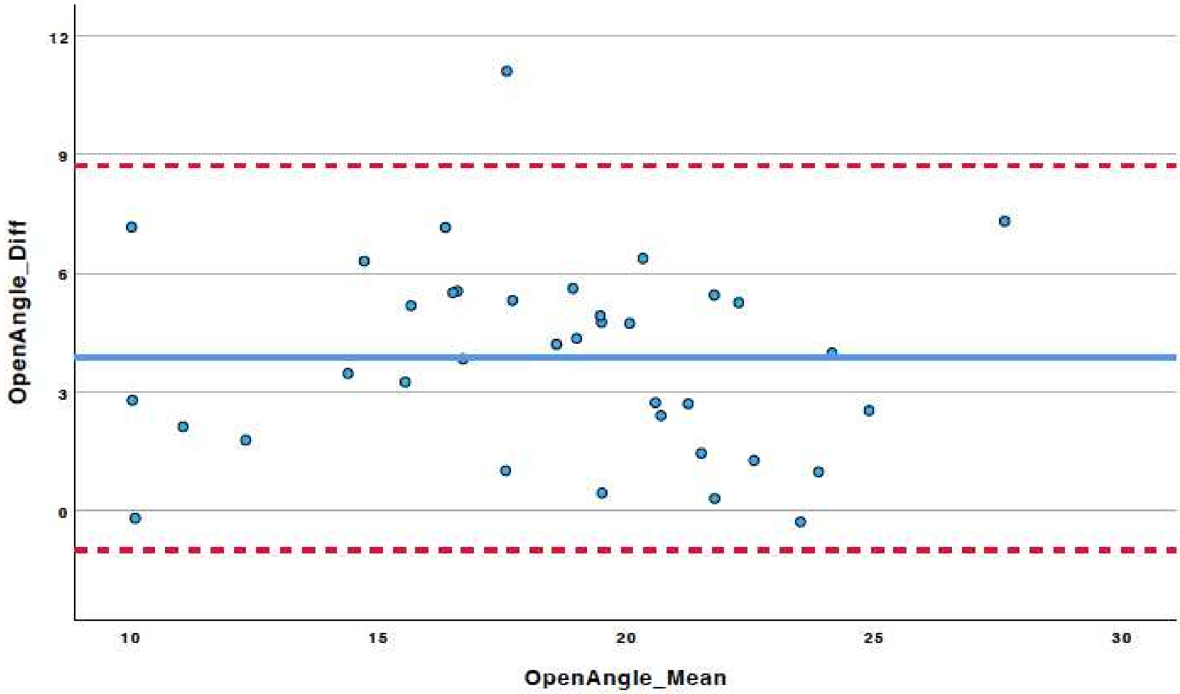


Figure 10 *Bland Altman plot for Opening Angle.* Here the difference (opening angle of IOD - opening angle of chin sensors) is plotted vs the mean of the opening angles for the IOD and chin sensors. The blue line shows the mean difference and the red dotted lines show the upper and lower 95% confidence intervals.

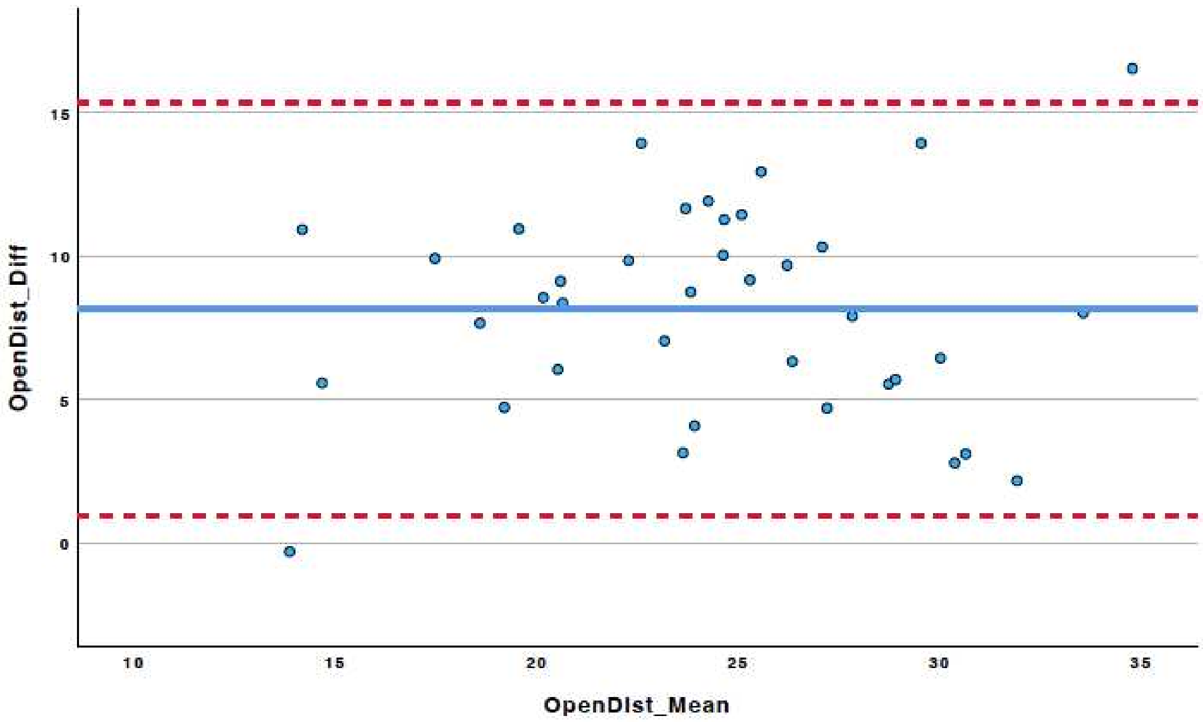


Figure 11 *Bland Altman plot for Opening Distance.* Here the difference (opening distance of IOD - opening distance of chin sensors) is plotted vs the mean of the opening distance for the IOD and chin sensors. The blue line shows the mean difference and the red dotted lines show the upper and lower 95% confidence intervals.

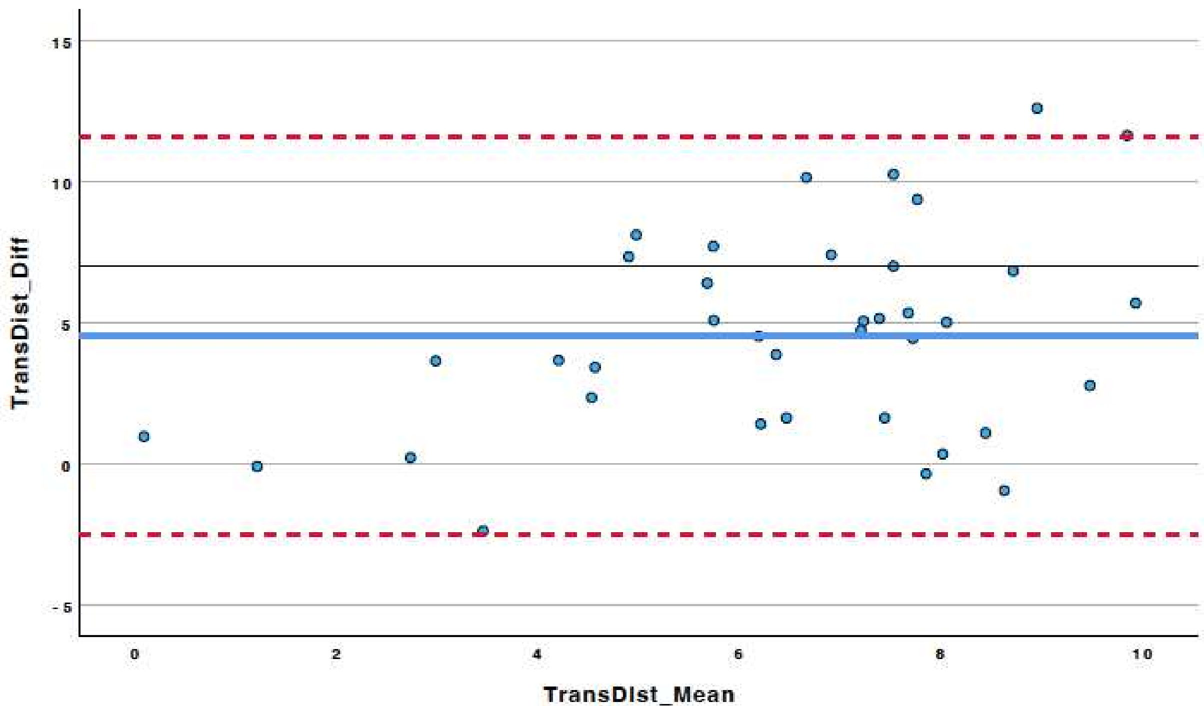


Figure 12 *Bland Altman plot for Translation Distance.* Here the difference (translation distance of IOD – translation distance of chin sensors) is plotted vs the mean of the translation distance for the IOD and chin sensors. The blue line shows the mean difference and the red dotted lines show the upper and lower 95% confidence intervals.

5. Discussion:

5.1. DC/TMD

We hypothesized that singers would display unique pain intensity, somatic pain, psychosocial distress, jaw functional limitations (anxiety, depression, and somatic symptoms), parafunctional oral behaviors, TMD symptoms, and jaw functional limitations compared to non- singers with pTMD. Additionally, this study investigates, and that they would have distinct masticatory muscle activities and jaw movements during maximum clenching and opening in singers and non-singers with and without pTMD..

The results confirm that participants with pTMD exhibit the expected characteristics outlined in the DC/TMD, aligning with anticipated scores for pTMD and non-pTMD groups on questionnaires and reported symptoms. This consistency strengthens the validity of the study's findings and their relevance to the broader understanding of pTMD. Our results provide valuable insights into the characteristics of pTMD as defined by the DC/TMD criteria. Consistent with existing literature (76), participants with pTMD, particularly singers, exhibited the expected symptoms and psychosocial characteristics associated with the disorder. As expected, individuals with pTMD reported elevated scores on questionnaires assessing pain severity, jaw functional limitations, and psychosocial impact. As the majority of cases involved in this study showed non-disabling pain, this sample appears skewed toward less severe presentations of pTMD

No significant differences in generalized anxiety levels were observed between groups, suggesting it may not vary substantially based on singing status or the presence of pTMD. While participants with pTMD tended to report slightly higher anxiety, this trend did not reach statistical significance ($p = 0.06$) and the group averages represented at most mild anxiety. These results contrasts with prior studies (77, 78), which have noted a consistent association between anxiety and TMDs. This discrepancy may be attributed to the fact that the majority of participants in the present study exhibited only mild forms of pTMD.

Interestingly, parafunctional oral behaviors among singers without pTMD was observed twice as often in individuals with pTMD. However, the level of these behaviors among singers without pTMD was not in the range that it is considered a risk factor for pTMD onset. This difference could stem from singers being more attuned to their oral behaviors, making them more likely to self-report such activities. Additionally, singing itself, even in the absence of pTMD, might contribute to increased oral behaviors, such as jaw clenching or teeth grinding, due to the physical demands of vocal performance. Singers are trained to maintain precise control over their jaw, lips, and tongue to produce specific sound characteristics, which may predispose them to these behaviors. Even though the singers without pTMD had a high level of oral behaviors, they were not classified as having pTMD. Thus, singing may have a protective effect on TMDs in some cases. Future studies should investigate whether singing is protective, as oral behaviors are strongly associated with pTMD but these singers did not have pTMD.

Depression severity shows almost the same pattern. Scores above 5 in the related questionnaire are associated with mild severity depression. Both singers and non-singers with pTMD had average scores between 5-10 which indicates mild depression conditions. These results contrast some studies believed that singing can reduce depression (79). This may be due to the pain associated with pTMD in this cohort, which could counteract the mood benefits of singing. Many of the participants in the singing group where students in the School of Music. Music has been investigated as a therapy and shows beneficial effects on wellbeing. However, the effects of music as a profession on well being may be different.

Somatic symptoms severity were significantly higher among both non-singers and singers with pTMD compared to their non-pTMD counterparts. Singers with pTMD showed the highest overall and the group average was associated with moderate stage of somatic pain, which could be due to physical demand and emotional pressures. A previous study found that somatic symptoms appeared to be positively associated with the frequency of singing, but they did not find a significant correlation between singing and somatic pain overall (80). Our findings suggest that singers with pTMD may need multidisciplinary approaches that address both the physical and psychological components of their condition for better treatment outcomes.

Similarly, jaw functional limitations was greater in pTMD groups than non-pTMD groups. This general domain can be broken down into the mobility, mastication, and communication subgroups. The pTMD groups had greater limitations in mobility, mastication and communication than the non-pTMD groups. These results are consistent with the expected differences between individuals with and without pTMD.

Chronic pain intensity (CPI) also followed this trend: the pTMD groups had greater CPI than the non-pTMD groups. with singers experiencing the most pronounced chronic pain levels. These findings are in line with the previous studies (81). It is important to note that the CPI scores for the pTMD groups indicate low pain intensity. Thus, the results should be interpreted in this context and future studies should investigate cohorts with disabling pain.

5.2. Maximal Voluntary Clenching (MVC)

Most research indicates **lower** masseter and temporalis muscle activity in people with pTMD during MVC compared to those without TMD (72, 82-88). This decrease in activity could be a protective mechanism to avoid pain. Some studies found **higher** masseter activity in individuals with pTMD during MVC Other studies showed **no significant difference** in muscle activity between the groups during MVC (89, 90). This again emphasizes the need for caution when interpreting sEMG results due to the lack of consistent findings.

Our results did not find significant differences between the masseter or the right temporalis. However, we found reduced peak and mean muscle activity of the left temporalis muscle in singers with pTMD compared to singers without pTMD. These results highlight the functional impact of pTMD on the left temporalis muscle, particularly in singers. One limitation of the study is that a clinical examination was not performed; thus, it is unknown which muscle groups are involved with pTMD for each participant. It could be that in this cohort, the left temporalis was consistently involved. This study found no significant overall difference in muscle activity between singers and non-singers, contrasting with prior research suggesting unique adaptations in singers' masticatory muscles (61). This discrepancy may result from methodological differences, and future studies should consider dynamic tasks like singing to uncover task-specific variations.

The lower relative utilization of their maximum potential in singers with pTMD compared to non-singers with pTMD highlights a potential difference in muscle utilization, but limited literature on this metric makes direct comparisons challenging. Further research is needed to explore its clinical significance.

While our focus on maximum clenching aligns with standard practices, incorporating dynamic and functional movements could provide a more comprehensive understanding of muscle function in pTMD and singing. Our findings emphasize the need for future studies to explore novel measures and functional tasks to better understand the relationship between pTMD, muscle activity, and singing.

5.3. Maximum Opening

5.3.1. The Activation of Muscles Upon Maximum Opening

The data focused on muscle activity during maximum jaw opening in singers with and without pTMD normalized by MVC values, highlighting the roles of the masseter and temporalis muscles during this non-habitual movement. The masseter muscles demonstrated relatively low activation, utilizing approximately 5% of their maximum muscle activity during jaw opening. However, the temporalis muscles, particularly the left temporalis, exhibited notable differences between groups. Singers with pTMD showed significantly greater activation, nearing 7% of their maximum muscle activity, compared to singers without pTMD. Indeed, the ratio of mean muscle activity during jaw opening was normalized to muscle activity during MVC. The left temporalis in singers with pTMD had a significantly lower MVC; thus, it appears that singers with pTMD are using a greater proportion of their maximum muscle activity. However, these findings may reveal distinct patterns of muscle activation in singers with pTMD, suggesting compensatory mechanisms or altered neuromuscular control.

5.3.2. Maximum Jaw Opening Measurements with Intraoral Device

The mean values for opening angle, opening distance, and translation distance did not show significant differences across the groups. Existing literature also did not find any difference between pTMD and controls in opening angle (91). The analysis revealed significant differences in the standard deviation (SD) of mean opening angle and SD of mean opening distance between singers with and without pTMD, as well as between singers and non-singers without pTMD. The standard deviation is a key measure of variability, reflecting the consistency with which individuals opened their jaws across the three trials. The observed larger standard deviations in some groups suggest a wide range of variability in jaw movement, particularly in the context of maximum opening. These findings are important because they highlight the inconsistency in jaw movements and indicate that the data could potentially serve as a reference for normalizing jaw movements during other functional activities such as chewing, speaking, and singing.

5.3.3. Maximum Jaw Opening Measurements with Chin Sensors

The mean values for opening angle, opening distance, and translation distance measured with the chin sensors did not show significant differences across the groups, which matches the trends for intraoral device. However, the standard deviation of the opening angle and opening distance measured with chin sensors were significant but showed an interaction effect of pTMD and singing; in contrast, the intraoral device showed an effect of pTMD and singing but no interaction. The interaction stems from a high standard deviation in the non-singing pTMD group, which differs in comparison to the data for intraoral device. The chin sensors could result in systematic error because they are attached to skin and not hard tissue.

5.3.4. Validation of the Chin Sensors using Intraoral Device Measurements as the Gold Standard

Most studies in literature use a device attached to the incisor to measure kinematic movements of the jaw. Here we compare movements measured with the gold standard intraoral device to sensors placed on the skin at the chin. In the future, it would be advantageous to use chin sensors when functional movements like speaking or singing are tested.

We used Bland-Altman plots to investigate the error in the outcomes due to the chin sensors. We found that the opening angle systematically underestimates the actual movement of the jaw (inferred from the intraoral device) by about 3.86 degrees, which is 23% of the mean opening angle measured with the chin sensors. Similarly for the opening and translation distances, the systematic error is 40% of the mean opening distance and 100% of the mean translation distance. The data stemming from chin sensors needs to be understood with these limitations.

5.4. Limitations

One of the limitations of this study stems from recruitment of participants. First, participants are self-reporting their pain status and singing history for the classification into study groups. As pTMD occurs in only 5-12% of the populations, it was difficult to access the population in a way that a random sample of the population was recruited. Thus, the study may be affected by selection bias limiting the generalizability of the findings.

Additionally, the diagnosis of pTMD was not confirmed through a physical examination, which is considered a critical component of a comprehensive diagnostic process. This reliance on alternative diagnostic methods (i.e., the DC/TMD symptom questionnaire) could affect the accuracy of pTMD classification, potentially impacting the study's outcomes and their interpretation (for instance, we do not know which muscle groups were affected). Furthermore, only two participants across the pTMD groups had disabling chronic pain indicating less severe pTMD in this cohort. Thus, the results are representative of a population of individuals with moderate pain intensity and non-disabling chronic pain.

5.5. Future Directions

To improve the study design, future studies should address these limitations by i) incorporating randomized sampling techniques, ii) ensuring physical examinations of the DC/TMD are performed for precise and standardized diagnoses, and iii) finding a more accurate measure of jaw movement without using an intraoral device.

Overall, singers without pTMD had more oral behaviors that are associated with pTMD. Future studies could explore whether singing has a protective effect.

6. Conclusion

This study provides valuable insights into the complex relationship between singing and pTMD, revealing significant differences in psychosocial factors and parafunctional oral behaviors among singers and non-singers. Overall, the pTMD groups in this study exhibited low intensiy pain that was not disabling. Post-hoc tests did not reveal any significant differences between the groups in terms of anxiety, oral behaviors, and depression severity. However, notably, the singers without pTMD had oral behavior score more likely in those with pTMD. Significant differences in somatic symptom severity and jaw functional limitations were found between the pTMD groups.

The findings indicate that pTMD may play a dual role, potentially reducing masticatory muscle activity during maximum clench while also influencing jaw movement patterns during maximum opening. Furthermore, non-singers displayed more consistency in jaw movements during maximum opening. These patterns highlight the need for a nuanced understanding of how vocal activities can affect individuals with pTMD.

Moreover, the study questions the psychological benefits of singing for individuals with pTMD. Singers reported on average greater pain intensity, anxiety, oral behavior, physical symptoms, and depression severity than non-singers (however, many of these trends were not significant). This finding challenges the notion that engaging in singing may contribute positively to overall well-being, potentially serving as a therapeutic avenue for managing pTMD symptoms. However, it is important to acknowledge that this was not an aim of the study.

The limitations of this study include its cross-sectional design and potential selection bias in participant recruitment, which may affect the generalizability of the findings. The absence of a standardized physical examination for pTMD diagnosis further limits diagnostic accuracy and may introduce misclassification bias. Additionally, as the majority of participants presented with mild to moderate symptoms, the findings may not be fully applicable to individuals with more severe forms of pTMD. Future research should prioritize longitudinal studies to better understand the progression of pTMD symptoms and to assess the potential role of singing in influencing or altering that trajectory. Examining the physiological mechanisms through which singing influences muscle activity and jaw function may inform the development of targeted therapeutic interventions. Additionally, expanding the focus beyond clenching and opening to include functional movements—such as vocal exercises and chewing patterns—could provide further insights into comprehensive management strategies for pTMD. This thesis underscores the potential of vocalization as a therapeutic approach in pTMD management. By recognizing the positive impacts of singing on physical and psycho-social factors, clinicians may develop more personalized treatment plans that incorporate vocal training as part of comprehensive care for individuals suffering from pTMD.

References

[1] Leeuw R, Klasser K. American Academy of Orofacial Pain-guidelines for Assessment, Diagnosis and Management. Chicago: Quintessence Publishing; 1996.

[2] List T, Jensen RH. Temporomandibular disorders: Old ideas and new concepts. Cephalalgia. 2017;37(7):692-704.

[3] Research NIoDaC. Prevalence of TMJD and its signs and symptoms 2018 [Available from: https://www.nidcr.nih.gov/research/data-statistics/facial-pain/prevalence.

[4] Ohrbach R, Bair E, Fillingim RB, Gonzalez Y, Gordon SM, Lim P-F, et al. Clinical orofacial characteristics associated with risk of first-onset TMD: the OPPERA prospective cohort study. The Journal of Pain. 2013;14(12):T33-T50.

[5] Ohrbach R, Fillingim RB, Mulkey F, Gonzalez Y, Gordon S, Gremillion H, et al. Clinical findings and pain symptoms as potential risk factors for chronic TMD: descriptive data and empirically identified domains from the OPPERA case-control study. The Journal of Pain. 2011;12(11):T27-T45.

[6] List T, Axelsson S. Management of TMD: evidence from systematic reviews and meta-analyses. Journal of oral rehabilitation. 2010;37(6):430-51.

[7] Rodríguez-Lozano FJ, Saez-Yuguero MR, Bermejo-Fenoll A. Orofacial problems in musicians: A review of the literature. Med Probl Perform Art. 2011;26(3):150-6.

[8] Taddey JJ. Musicians and temporomandibular disorders: Prevalence and occupational etiologic considerations. CRANIO®. 1992;10(3):241-4. https://doi.org/10.1080/08869634.1992.11677916

[9] Zhang S-K, Yang Y, Gu M-L, Mao S-J, Zhou W-S. Effects of low back pain exercises on pain symptoms and activities of daily living: A systematic review and meta-analysis. Percept Mot Skills. 2021:003151252110594. https://dx.doi.org/10.1177/00315125211059407

[10] Moleirinho-Alves PMM, Almeida AMCSd, Exposto FG, Oliveira RANdS, Pezarat-Correia PLCd. Effects of therapeutic exercise and aerobic exercise programmes on pain, anxiety and oral health-related quality of life in patients with temporomandibular disorders. J Oral Rehab. 2021;48(11):1201-9. https://doi.org/10.1111/joor.13239

[11] Zhang L, Xu L, Wu D, Yu C, Fan S, Cai B. Effectiveness of exercise therapy versus occlusal splint therapy for the treatment of painful temporomandibular disorders: a systematic review and meta-analysis. Ann Palliat Med. 2021;10(6):6122-32. https://dx.doi.org/10.21037/apm-21-451

[12] Shimada A, Ishigaki S, Matsuka Y, Komiyama O, Torisu T, Oono Y, et al. Effects of exercise therapy on painful temporomandibular disorders. J Oral Rehab. 2019;46(5):475-81. https://doi.org/10.1111/joor.12770

[13] Fancourt D, Finn S. What is the evidence on the role of the arts in improving health and well-being? A scoping review. . Copenhagen: WHO Regional Office for Europe; 2019. Report No.: Health Evidence Network (HEN) synthesis report 67.

[14] Ross S, Cidambi I, Dermatis H, Weinstein J, Ziedonis D, Roth S, et al. Music Therapy. J Addict Dis. 2008;27(1):41-53. https://doi.org/10.1300/j069v27n01_05

[15] National Academies of Sciences E, Medicine. Temporomandibular Disorders: Priorities for Research and Care. Bond EC, Mackey S, English R, Liverman CT, Yost O, editors. Washington, DC: The National Academies Press; 2020. 426 p. https://doi.org/10.17226/25652

[16] Stowell AW, Gatchel RJ, Wildenstein L. Cost-effectiveness of treatments for temporomandibular disorders: biopsychosocial intervention versus treatment as usual. The Journal of the American Dental Association. 2007;138(2):202-8.
[17] Li Yj, Han SLR, Xu Za, Cheng Qy, Fan Pd, Zheng Yh, et al. Pain, Function and Quality of Life in Temporomandibular Disorder Patients With Different Disc Positions. Journal of Oral Rehabilitation. 2024;51(12):2622-33.
[18] Schiffman E, Ohrbach R, Truelove E, Look J, Anderson G, Goulet J-P, et al. Diagnostic criteria for temporomandibular disorders (DC/TMD) for clinical and research applications: recommendations of the International RDC/TMD Consortium Network and Orofacial Pain Special Interest Group. Journal of oral & facial pain and headache. 2014;28(1):6.
[19] Minervini G, Marrapodi MM, Siurkel Y, Cicciù M, Ronsivalle V. Accuracy of temporomandibular disorders diagnosis evaluated through the diagnostic criteria for temporomandibular disorder (DC/TDM) Axis II compared to the Axis I evaluations: a systematic review and meta-analysis. BMC Oral Health. 2024;24(1):299.
[20] Gonzalez YM, Schiffman E, Gordon SM, Seago B, Truelove EL, Slade G, et al. Development of a brief and effective temporomandibular disorder pain screening questionnaire: reliability and validity. Journal of the American Dental Association (1939). 2011;142(10):1183-91. 10.14219/jada.archive.2011.0088
[21] rdc-tmd-international. DC/TMD Symptom Question-naire 2013 [Available from: https://ubwp.buffalo.edu/rdc-tmdinternational/wp-content/uploads/sites/58/2017/01/DC-TMD_SQ_shortform_2013-05-12.pdf.
[22] Von Korff M, Ormel J, Keefe FJ, Dworkin SF. Grading the severity of chronic pain. Pain. 1992;50(2):133-49. 10.1016/0304-3959(92)90154-4
[23] Ohrbach R, Knibbe W. Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) Scoring Manual for Self-Report Instruments. 6 VJ, editor. University at Buffalo2016.
[24] Kroenke K, Spitzer RL, Williams JB. The PHQ-9: validity of a brief depression severity measure. Journal of general internal medicine. 2001;16(9):606-13. 10.1046/j.1525-1497.2001.016009606.x
[25] Löwe B, Decker O, Müller S, Brähler E, Schellberg D, Herzog W, et al. Validation and standardization of the Generalized Anxiety Disorder Screener (GAD-7) in the general population. Medical care. 2008;46(3):266-74. 10.1097/MLR.0b013e318160d093
[26] Kroenke K, Spitzer RL, Williams JB. The PHQ-15: validity of a new measure for evaluating the severity of somatic symptoms. Psychosomatic medicine. 2002;64(2):258-66. 10.1097/00006842-200203000-00008
[27] Markiewicz MR, Ohrbach R, McCall WD, Jr. Oral behaviors checklist: reliability of performance in targeted waking-state behaviors. J Orofac Pain. 2006;20(4):306-16.
[28] Ohrbach R, Markiewicz M-R, Jr W-DM. Waking-state oral parafunctional behaviors: specificity and validity as assessed by electromyography. European Journal of Oral Sciences. 2008;116(5):438-44. https://doi.org/10.1111/j.1600-0722.2008.00560.x
[29] Ohrbach R, Dworkin S. The evolution of TMD diagnosis: past, present, future. Journal of Dental Research. 2016;95:1093–101.
[30] Alhowimel A, Alotaibi M, Alenazi A, Alqahtani B, Alshehri M, Alamam D, et al. Psychosocial predictors of pain and disability outcomes in people with chronic low back pain treated conservatively by guideline-based intervention: a systematic review. Journal of Multidisciplinary Healthcare. 2021;14:3549–59.

[31] Lee K, Jha N, Kim Y. Risk factor assessments of temporomandibular disorders via machine learning. Scientific Reports. 2021;11:19802.
[32] Karkazi F, Özdemir F. Temporomandibular disorders: fundamental questions and answers. Turkish Journal of Orthodontics. 2020;33:246–52.
[33] Gilheaney Ó, Chadwick A. The prevalence and nature of eating and swallowing problems in adults with fibromyalgia: a systematic review. Dysphagia. 2024;39:92–108.
[34] Research NIoDaC. TMD (Temporomandibular Disorders) 2024 [Available from: https://www.nidcr.nih.gov/health-info/tmd#:~:text=Limited%20movement%20or%20locking%20of,and%20lower%20teeth%20fit%20together.
[35] Yao L, Sadeghirad B, Li M, Li J, Wang Q, Crandon HN, et al. Management of chronic pain secondary to temporomandibular disorders: a systematic review and network meta-analysis of randomised trials. BMJ. 2023;383:e076226. 10.1136/bmj-2023-076226
[36] Albagieh H, Alomran I, Binakresh A, Alhatarisha N, Almeteb M, Khalaf Y, et al. Occlusal splints-types and effectiveness in temporomandibular disorder management. The Saudi Dental Journal. 2023;35(1):70-9.
[37] Bhargava D, Chávez Farías C, Ardizone García I, Mercuri LG, Bergman S, Anthony Pogrel M, et al. Recommendations on the use of oral orthotic occlusal appliance therapy for temporomandibular joint disorders: current evidence and clinical practice. Journal of maxillofacial and oral surgery. 2023;22(3):579-89.
[38] Yadav S, Karani JT. The essentials of occlusal splint therapy. Int J Prosthet Dent. 2011;2(1):12-21.
[39] Fouda AAH. No evidence on the effectiveness of oral splints for the management of temporomandibular joint dysfunction pain in both short and long-term follow-up systematic reviews and meta-analysis studies. Journal of the Korean Association of Oral and Maxillofacial Surgeons. 2020;46(2):87.
[40] Kuzmanovic Pficer J, Dodic S, Lazic V, Trajkovic G, Milic N, Milicic B. Occlusal stabilization splint for patients with temporomandibular disorders: Meta-analysis of short and long term effects. PloS one. 2017;12(2):e0171296.
[41] Zhang L, Xu L, Wu D, Yu C, Fan S, Cai B. Effectiveness of exercise therapy versus occlusal splint therapy for the treatment of painful temporomandibular disorders: A systematic review and meta-analysis. Annals of palliative medicine. 2021;10(6):6122132-6132.
[42] Michelotti A, de Wijer A, Steenks M, Farella M. Home-exercise regimes for the management of non-specific temporomandibular disorders. Journal of oral rehabilitation. 2005;32(11):779-85.
[43] Shaffer SM, Brismée J-M, Sizer PS, Courtney CA. Temporomandibular disorders. Part 2: conservative management. Journal of Manual & Manipulative Therapy. 2014;22(1):13-23.
[44] Arribas-Pascual M, Hernández-Hernández S, Jiménez-Arranz C, Grande-Alonso M, Angulo-Díaz-Parreño S, La Touche R, et al. Effects of physiotherapy on pain and mouth opening in temporomandibular disorders: an umbrella and mapping systematic review with meta-meta-analysis. Journal of clinical medicine. 2023;12(3):788.
[45] Christidis N, Al-Moraissi EA, Barjandi G, Svedenlöf J, Jasim H, Christidis M, et al. Pharmacological treatments of temporomandibular disorders: a systematic review including a network meta-analysis. Drugs. 2024;84(1):59-81.

[46] Penlington C, Bowes C, Taylor G, Otemade AA, Waterhouse P, Durham J, et al. Psychological therapies for temporomandibular disorders (TMDs). Cochrane Database of Systematic Reviews. 2022(8).
[47] Turner JA, Mancl L, Aaron L-A. Short- and long-term efficacy of brief cognitive-behavioral therapy for patients with chronic temporomandibular disorder pain: A randomized, controlled trial, Pain.121(3):181-94. https://doi.org/10.1016/j.pain.2005.11.017
[48] Reston JT, Turkelson CM. Meta-analysis of surgical treatments for temporomandibular articular disorders. Journal of oral and maxillofacial surgery. 2003;61(1):3-10.
[49] Gil-Martínez A, Paris-Alemany A, López-de-Uralde-Villanueva I, La Touche R. Management of pain in patients with temporomandibular disorder (TMD): challenges and solutions. Journal of pain research. 2018:571-87.
[50] Wadia R. TMD in vocalists. British Dental Journal. 2019;227(6):475-. https://doi.org/10.1038/s41415-019-0799-0
[51] Nair A, Nair G, Reishofer G. The low mandible maneuver and its resonential implications for elite singers. Journal of Voice. 2016;30(1):128. e13-. e32.
[52] Sundberg J, Skoog J. Dependence of jaw opening on pitch and vowel in singers. Journal of Voice. 1997;11(3):301-6.
[53] Patinka PM, Nix J. Changes in Vibrato Rate, Vibrato Extent, and Vibrato Jitter in Soprano Voices in Response to Changes in Mouth Opening: A Pilot Study. Journal of Singing. 2020;77(2):213-9.
[54] Fisher RA, Hoult AR, Tucker WS. A comparison of facial muscle activation for vocalists and instrumentalists. Journal of Music Teacher Education. 2020;30(1):53-64.
[55] Miller R. On the art of singing: Oxford University Press, USA; 1996.
[56] McQuade JH. The effect of the position of the zygomatic musculature of the experienced baritone singer on the voice spectra. Journal of Singing-The Official Journal of the National Association of Teachers of Singing. 2016;72(4):441-9.
[57] Schiffman E, Ohrbach R. Executive summary of the Diagnostic Criteria for Temporomandibular Disorders for clinical and research applications. The Journal of the American Dental Association. 2016;147(6):438-45.
[58] Frey LE. Temporomandibular joint dysfunction in singers: A survey. J Singing. 1988;44(3):15-40.
[59] Vaiano T, Guerrieri AC, Behlau M. Body pain in classical choral singers. CoDAS. 2013;25(4):303-9. 10.1590/s2317-17822013000400002
[60] Caetano KAdS, Ferreira IMF, Mariotto LGS, Vidal CL, Neufeld CB, dos Reis AC. Choir singing as an activity to manage anxiety and temporomandibular disorders: Reports from a Brazilian sample. Psychology of Music. 2019;47(1):96-108. 10.1177/0305735617739967
[61] van Selms MK, Wiegers JW, Lobbezoo F, Visscher CM. Are vocalists prone to temporomandibular disorders? Journal of Oral Rehabilitation. 2019;46(12):1127-32.
[62] Nair R, Tanikawa C, Ferreira JN. Orofacial Pain, Musical Performance and Associated Coping Behaviors, Psychological Distress and Disability among Asian Young Adults. Journal of Clinical Medicine. 2023;12(4):1271.
[63] Wollenburg M, Wolowski A. Impact of professional, recreational and nonsinging on temporomandibular disorders - a comparative study based on a self-assessment questionnaire. Head & Face Medicine. 2024;20(1):19. 10.1186/s13005-024-00419-z
[64] Kulesa-Mrowiecka M, Barański R, Kłaczyński M. sEMG and vibration system monitoring for differential diagnosis in temporomandibular joint disorders. Sensors. 2022;22(10):3811.

[65] Szyszka-Sommerfeld L, Machoy M, Lipski M, Woźniak K. The diagnostic value of electromyography in identifying patients with pain-related temporomandibular disorders. Frontiers in Neurology. 2019;10:180.
[66] Gębska M, Dalewski B, Pałka Ł, Kołodziej Ł. Surface electromyography evaluation of selected manual and physical therapy interventions in women with temporomandibular joint pain and limited mobility. Randomized controlled trial (RCT). Injury. 2023;54(8):110906.
[67] Szyszka-Sommerfeld L, Sycińska-Dziarnowska M, Spagnuolo G, Woźniak K. Surface electromyography in the assessment of masticatory muscle activity in patients with pain-related temporomandibular disorders: a systematic review. Frontiers in Neurology. 2023;14:1184036.
[68] Shigemitsu R, Ogawa T, Sato E, Oliveira AS, Rasmussen J. Kinematic classification of mandibular movements in patients with temporomandibular disorders based on PCA. Computers in Biology and Medicine. 2025;184:109441.
[69] Massaroto Barros B, Biasotto-Gonzalez DA, Bussadori SK, Gomes CAFdP, Politti F. Is there a difference in the electromyographic activity of the masticatory muscles between individuals with temporomandibular disorder and healthy controls? A systematic review with meta-analysis. Journal of oral rehabilitation. 2020;47(5):672-82.
[70] Scolaro A, Khijmatgar S, Rai PM, Falsarone F, Alicchio F, Mosca A, et al. Efficacy of kinematic parameters for assessment of temporomandibular joint function and disfunction: A systematic review and meta-analysis. Bioengineering. 2022;9(7):269.
[71] Siu WS, Shih YF, Lee SY, Hsu CY, Wei MJ, Wang TJ, et al. Alterations in kinematics of temporomandibular joint associated with chronic neck pain. Journal of Oral Rehabilitation. 2022;49(9):860-71.
[72] Santana-Mora U, Cudeiro J, Mora-Bermúdez M, Rilo-Pousa B, Ferreira-Pinho J, Otero-Cepeda J, et al. Changes in EMG activity during clenching in chronic pain patients with unilateral temporomandibular disorders. Journal of Electromyography and Kinesiology. 2009;19(6):e543-e9.
[73] National-Academies-of-Sciences -E, -and-Medicine. Measuring Sex, Gender Identity, and Sexual Orientation. Washington, D.C: National Academies Press; 2022. https://doi.org/10.17226/26424
[74] McManus L, De-Vito G, Lowery M. Analysis and Biophysics of Surface EMG for Physiotherapists and Kinesiologists: Toward a Common Language With Rehabilitation Engineers. Front Neurol. 2020(11):576729. https://doi.org/10.3389/fneur.2020.576729
[75] Ohrbach R, Larsson P, List T. The jaw functional limitation scale: development, reliability, and validity of 8-item and 20-item versions. Journal of orofacial pain. 2008;22(3):219–30.
[76] Assiri K. Relationships between personality factors and DC/TMD Axis II scores of psychosocial impairment among patients with pain related temporomandibular disorders. Scientific Reports. 2024;14(1):26869.
[77] Heikkinen EV, Kakko N, Näpänkangas R, Vuollo V, Harila V, Sipilä K. Prevalence of temporomandibular disorders (TMD) and their association with sociodemographic factors and depression/anxiety symptoms in Northern Finland Birth Cohort 1986. CRANIO®. 2024:1-11.
[78] Paludo B, Trevizan PC, Boamah NAA, Rigo L. Prevalence of Temporomandibular Disorder and its association with anxiety in academics: a cross-sectional study. Sao Paulo Medical Journal. 2024;143(1):e2023338.
[79] Daykin N, Mansfield L, Meads C, Julier G, Tomlinson A, Payne A, et al. What works for wellbeing? A systematic review of wellbeing outcomes for music and singing in adults. Perspectives in public health. 2018;138(1):39-46.

[80] van Selms MK, Reda B, Visscher CM, Manfredini D, Lobbezoo F. The effect of singing on pain and psychological well-being in a patient population with pain-related temporomandibular disorders. Journal of Oral Rehabilitation. 2022;49(9):841-8.
[81] Yap AU, Kim S, Lee Bm, Jo JH, Park JW. Correlates of jaw functional limitation, somatization and psychological distress among different temporomandibular disorder diagnostic subtypes. Journal of Oral Rehabilitation. 2024;51(2):287-95. https://doi.org/10.1111/joor.13606
[82] Szyszka-Sommerfeld L, Machoy M, Lipski M, Woźniak K. Electromyography as a means of assessing masticatory muscle activity in patients with pain-related temporomandibular disorders. Pain Res Manag. 2020;2020:97509151.
[83] Berni K, Dibai-Filho A, Pires P, Rodrigues-Bigaton D. Accuracy of the surface electromyography RMS processing for the diagnosis of myogenous temporomandibular disorder. J Electromyogr Kinesiol. 2015;25:596–6023.
[84] Szyszka-Sommerfeld L, Sycińska-Dziarnowska M, Budzyńska A, Woźniak K. Accuracy of surface electromyography in the diagnosis of pain-related temporomandibular disorders in children with awake bruxism. J Clin Med. 2022;11:13234.
[85] Li B, Zhou L, Guo S, Zhang Y, Lu L, Wang M. An investigation on the simultaneously recorded occlusion contact and surface electromyographic activity for patients with unilateral temporomandibular disorders pain. J Electromyogr Kinesiol. 2016;28:199–2075.
[86] Mapelli A, Zanandréa-Machado B, Giglio L, Sforza C, De-Felício C. Reorganization of muscle activity in patients with chronic temporomandibular disorders. Arch Oral Biol. 2016;72:164–716.
[87] Pires P, Rodrigues-Bigaton D. Evaluation of integral electromyographic values and median power frequency values in women with myogenous temporomandibular disorder and asymptomatic controls. J Bodyw Mov Ther. 2018;22:720–67.
[88] Tartaglia G, Rodrigues M, da-Silva M, Bottini S, Sforza C, Ferrario V. Masticatory muscle activity during maximum voluntary clench in different research diagnostic criteria for temporomandibular disorders (RDC/TMD) groups. Man Ther. 2008;13:434–08.
[89] Rodrigues D, Siriani A, Berzin F. Effect of conventional TENS on pain and electromyographic activity of masticatory muscles in TMD patients. Br Oral Res. 2004;18:290–510.
[90] Tartaglia G, Lodetti G, Paiva G, De-Felicio C, Sforza C. Surface electromyographic assessment of patients with long lasting temporomandibular joint disorder pain. J Electromyogr Kinesiol. 2011;21:659–64.
[91] Mapelli A, Machado BC, Garcia DM, Rodrigues Da Silva MA, Sforza C, de Felício CM. Three-dimensional analysis of jaw kinematic alterations in patients with chronic TMD - disc displacement with reduction. J Oral Rehabil. 2016;43(11):824-32. https://doi.org/10.1111/joor.12424