Skeletal and Dental Changes from a Compliance-Based Orthotropic Treatment Approach with Exercises to Improve Orofacial Posture

by

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ABSTRACT

Objective: To investigate the skeletal and dental changes that occur using a compliance-based orthotropic treatment approach with orofacial posture exercises aimed at controlling vertical facial skeletal growth in the mixed dentition.

Methods: 102 patients were consecutively treated under the same two-phased protocol by one clinician experienced in the technique. The first phase involved the use of upper and lower removable expansion appliances, supplemented by a series of daily compliance-based exercises designed to improve oral posture and strengthen orofacial musculature. The second phase consisted of the Mew Biobloc removable appliance designed to train for a closed mouth posture at rest. Lateral cephalometric radiographs were taken before treatment (T1) and at the completion of active treatment (T2). For the untreated control group, the AAOF Craniofacial Growth Legacy Collection database was thoroughly searched, and the lateral cephalometric radiographs of 75 patients closely matched for age, sex, and timeframe between T1 and T2 were selected. Using the Dolphin computer software, conventional skeletal and dental landmarks were digitally traced on all cephalograms. Changes in 13 skeletal and dental measurements were calculated and compared between the groups.

Results: Concerning sagittal skeletal measurements, the treatment group had a statistically significant 1.09° greater decrease in SNA and 1.47° greater decrease in ANB than the control ($p < .001$). There was no difference in SNB and mandibular body length. Concerning vertical skeletal measurements, only the mean differences in gonial angle and lower facial height were statistically significantly different. Compared to the treatment group, the control group had a 1.23° greater decrease in gonial angle ($p = .043$) but a 1.62mm greater increase in lower facial height ($p < .001$). There were statistically significant differences in all four dental measurements, most noticeably in incisor proclination. The treatment group experienced 8.49° greater proclination of maxillary incisors and 4.71° greater proclination of mandibular incisors, but 1.21mm and 1.17mm less overjet and overbite, respectively, compared to the control group ($p < .001$). There was no statistically significant difference between males and females in the combined mean change in cephalometric measurements.

Conclusions: There is insufficient evidence to conclude that the treatment protocol has a meaningful effect on skeletal and dental changes. It is unlikely that the differences in the sagittal and vertical skeletal measurements were clinically significant after factoring in measurement errors, especially when considering the long treatment lengths. The treatment group did experience clinically significant incisor proclination. Sex also did not affect the magnitude of skeletal and dental changes over time, as males and females experienced the same growth changes regardless of whether they were in the treatment or control group.

PREFACE

This thesis is an original work by Faraz Tavoossi. No part of this thesis has been previously published.

The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board with ID No. Pro00084145 on May 10, 2019.

DEDICATION

This work is dedicated in loving memory of my grandfather, Mohammad-Vali Tavoossi, who taught me the importance of family and to never stop appreciating the finer things in life.

ACKNOWLEDGEMENTS

I would first like to express my greatest gratitude to my supervisors, Dr. Manuel Lagravere and Dr. Carlos Flores-Mir. They have played a critical role in my education and professional development for many years, not only as a graduate student but also during my time in dental school. They always challenged me to become a better clinician and researcher, and I owe a large part of my success to them. It is through their patience, support, and mentorship that I was able to complete this thesis.

I would like to acknowledge Dr. Simon Wong for his willingness to provide us with full control of the analysis and interpretation of his cases. He has put many years of work into developing and fine-tuning this treatment protocol; his dedication towards it and his patients is commendable. A special thank you to Dr. Giseon Heo as well for her expertise and guidance with the statistical analyses.

A big thank you also goes to the Faculty of Graduate Studies and Research and the Canadian Institutes of Health Research for the funding I received. This funding was of great assistance in reducing the financial burden during my time as a graduate student.

Last but not least, I would like to thank my parents Mitra and Farid, my sister Sara, and my fiancé Endeep. It is through their love and support that I have made it this far. They have never stopped supporting me and believing in me. I will never be able to repay them for all they have sacrificed for me to pursue my dreams.

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1.1 Statement of the Problem

Excessive vertical facial skeletal growth, also commonly referred to as a high-angle, dolichofacial or hyperdivergent growth pattern, can be associated with various classic features of a long face such as an increased lower face height, retrognathic mandible, narrow maxillary arch, anterior open bite, excessive display of the upper teeth and gingiva, and lip incompetence.[1,2] These functional and esthetic problems become quite complex and challenging to treat with non-surgical orthodontic treatment. In fact, of all aspects of dentofacial development, vertical growth is often considered the most difficult to manage in orthodontics.[1,3] This is primarily related to how most current orthodontic treatment techniques tend to result in extrusive tooth movements, which causes the mandible to rotate downward and backward, thereby further increasing the vertical dimension.[4,5,6]

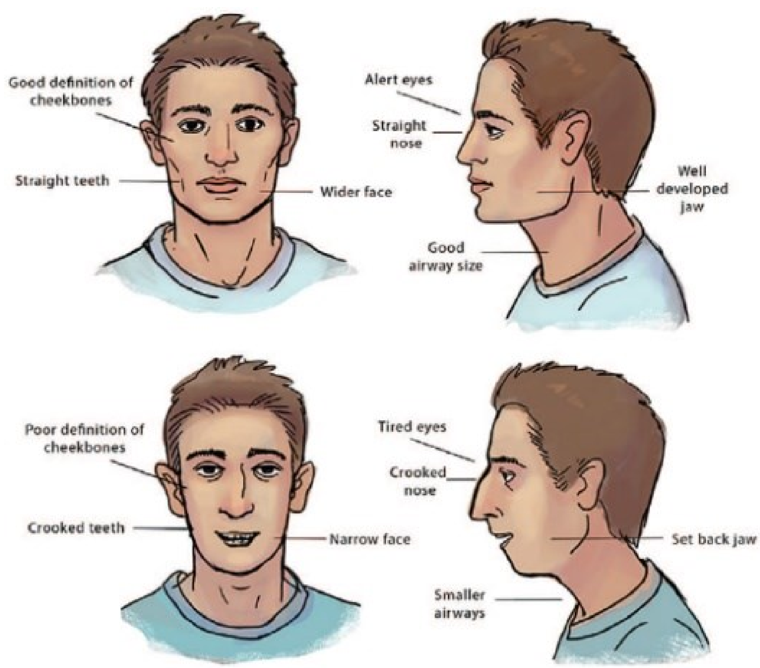

Figure 1.1 Difference in facial development between a horizontal grower (top) and a vertical grower (bottom). Reprinted with permission from Stanford University Press.[7]

Control of the vertical dimension is critical for effectively managing patients with hyperdivergent growth patterns.[4] Nevertheless, as discussed further in Chapter 2, there is controversy in the orthodontic literature concerning the efficacy and long-term stability of different treatments focused on doing so. Various non-surgical treatment modalities such as headgear and skeletal anchorage devices have been proposed to control the vertical dimension.

However, few, if any, have been proven to be clinically significant in their portrayed effects. Although it is not supported in the literature, some clinicians believe that early treatment should be initiated while there is remaining facial growth potential to prevent further vertical growth, and ideally even allow for forward rotation of the mandible. The concern is that if treatment is delayed and the potential for facial growth modification is lost, complex orthodontic treatment with potential surgical correction may remain as the only feasible option.[4,8,9] That being said, because vertical growth is the last to stop, patients who undergo early treatment are susceptible to relapse following orthodontic treatment as vertical facial growth still occurs.[10] Early attempts to control excessive vertical facial growth would have to extend for inordinately long periods to outlast growth, which may not be reasonable when considering the patient's perspective.[11] This is another essential factor that adds a layer of complexity when managing a hyperdivergent growth pattern.

The etiology of a hyperdivergent growth pattern is complex and multifactorial, including both genetic and environmental factors.[8] It has been suggested that weak orofacial muscles and open mouth postures can increase vertical facial growth.[12] This hypothesis is supported by the ideology of orthotropics or "forwardontics", which believes that early intervention with relatively non-invasive techniques to establish proper orofacial posture can produce phenotypic skeletal changes and redirect the growth of the jaws, face and airway down a more favourable path.[7] However, there is conflicting evidence and opinions in the literature on whether it is even possible for a hyperdivergent growth pattern to be changed. Therefore, it is important to investigate treatment claims further by looking closely at the skeletal changes. If a treatment protocol is proven to control vertical growth reliably, predictably, and consistently in susceptible growing patients, orthodontists could intervene early and potentially redirect the skeletal growth pattern down a more favourable path.

1.2 Growth and Development

To better understand vertical facial skeletal growth, it is essential to first review key concepts related to the growth and development of the jaws. The maxilla develops entirely by intramembranous ossification through apposition of bone at sutures, and by surface modeling and remodeling (Figure 1.2).[11] The growth of the cranial base has a critical impact on the forward and downward development of the maxilla up until about six years of age. Because the maxilla is attached to the anterior aspect of the cranial base, as the cranial base grows it pushes the maxilla in a downward and forward direction relative to the cranium. Once cranial base growth stops, the maxilla continues to develop through sutural growth into adolescence. Growth of the surrounding soft tissues also appears to impact the downward and forward translation of the maxilla. As the maxilla develops downward and forward, anterior surfaces (except for the anterior nasal spine) undergo bone resorption while bone is deposited at posterior-superior sutures.

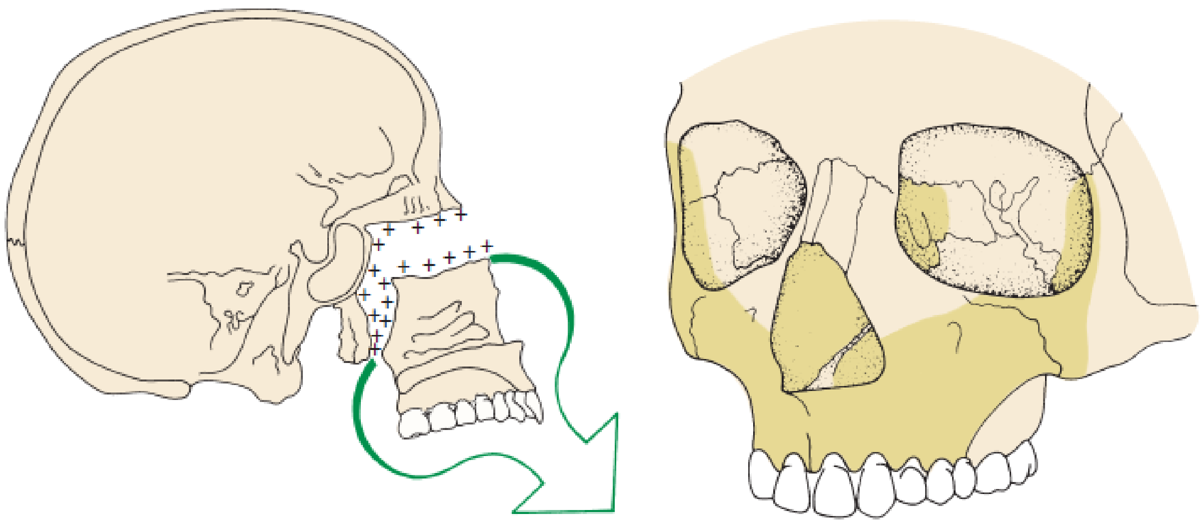

Figure 1.2 Diagrams illustrating the growth and development of the maxilla. Left – The maxilla is translated downward and forward, and new bone is deposited (+) at sutures connecting it to the cranial base. Right – The anterior (dark yellow) surfaces of the maxilla tend to undergo resorption as part of the surface modeling process. Reprinted with permission from Elsevier.[11]

On the other hand, the mandible develops through intramembranous and endochondral ossification. The main sites of growth of the mandible are the posterior surface of the ramus, the condyle, and the coronoid process.[11] The mandible grows in length as bone is resorbed from the anterior aspect of the ramus and deposited along the posterior aspect (Figure 1.3). In addition, the ramus also grows in height through endochondral ossification occurring at the cartilage covering the surface of the condyle. The net effect is an upward and backward increase in the size of the mandible, translating the mandible in a downward and forward direction.

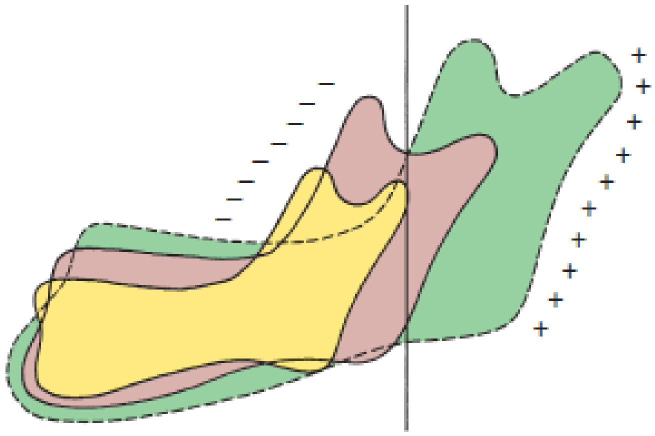

Figure 1.3 Diagram illustrating the growth and development of the mandible. Areas of bone resorption (-) and deposition (+) are highlighted. The mandible grows upward and backward as it translates downward and forward. Reprinted with permission from Elsevier.[11]

The maxilla and mandible continue to grow in length and height throughout puberty. However, vertical growth continues for longer than sagittal growth and often extends into adulthood.[11] It can be appreciated that both the maxilla and the mandible develop downward and forward, which is essential for achieving good facial balance. When imbalances in the directionality of growth occur during the development of the jaws, various orthodontic problems can arise. One example of this is when there is excessive vertical growth of the maxilla. This tends to cause the mandible to rotate downward and backward, which disrupts its normal downward and forward translation, resulting in a hyperdivergent growth pattern (Figure 1.4).[2,13] Figure 1.5 shows a cranial base superimposition of an individual with a hyperdivergent growth pattern.

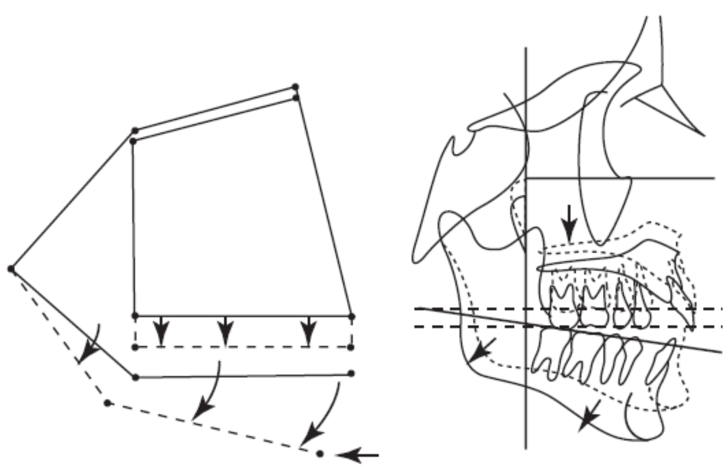

Figure 1.4 Effect of excessive vertical growth of the maxilla on the rotation of the mandible. Reprinted with permission from Elsevier.[13]

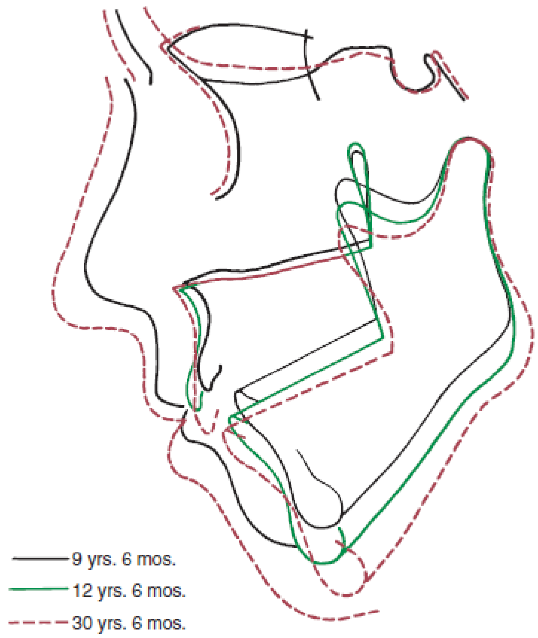

Figure 1.5 Cranial base superimpositions of an individual with excessive vertical facial skeletal growth. Reprinted with permission from Elsevier.[11]

1.3 Objectives

The overall objective of this thesis is to investigate the skeletal and dental effects of a compliance-based orthotropic treatment approach with orofacial posture exercises aimed at controlling vertical facial skeletal growth in growing individuals in the mixed dentition. This treatment protocol, designed and implemented by Simon Wong, is essentially a modified version of John Mew's orthotropic Biobloc technique with added daily exercises to improve orofacial posture. Pre- and post-treatment lateral cephalometric images will be traced and analysed, and changes in skeletal and dental measurements will be compared to images of a matched, untreated control group.

1.4 Research Questions

Primary research question:

1. Regardless of sex, is there a difference in vertical facial skeletal growth change between the treatment and control groups after adjusting for time?

Secondary research questions:

2. Regardless of sex, is there a difference in other facial skeletal and/or dental changes between the treatment and control groups after adjusting for time?
3. After adjusting for time, are there any differences between males and females in the treatment and control groups?

1.5 Hypotheses

The following are the null (H_0) and alternative (H_a) hypotheses proposed for the research questions:

1. **H_0**: There is no difference in vertical facial skeletal growth change between the treatment and control groups, regardless of sex and after adjusting for time.
   H_a: There is a difference in vertical facial skeletal growth change between the treatment and control groups, regardless of sex and after adjusting for time.
2. **H_0**: There is no difference in other facial skeletal and/or dental changes between the treatment and control groups, regardless of sex and after adjusting for time.
   H_a: There is a difference in other facial skeletal and/or dental changes between the treatment and control groups, regardless of sex and after adjusting for time.
3. **H_0**: After adjusting for time, there is no difference in the facial skeletal and/or dental changes between males and females in the treatment and control groups.
   H_a: After adjusting for time, there is a difference in the facial skeletal and/or dental changes between males and females in the treatment and control groups.

Chapter 2 – Literature Review

2.1 Introduction

The orthotropic treatment approach being investigated in this thesis is a novel approach in the management of vertical facial skeletal growth as it involves the use of exercises designed to improve orofacial posture. As a result, the treatment effects and efficacy have not yet been reported in the orthodontic literature. However, this approach incorporates aspects of the Biobloc technique, which was published by John Mew. Furthermore, many previous studies have reported on various other approaches for hyperdivergent growth management, as well as potential etiological factors, including the effects of poor orofacial posture. Therefore, it is important for a narrative review of the literature to be conducted in order to better understand what we currently know about the following questions:

1. What does the literature suggest about the etiology of a hyperdivergent growth pattern?
2. What does the literature suggest about potential sequelae associated with a hyperdivergent growth pattern?
3. What does the literature suggest with respect to various conventional treatment approaches used in the management of a hyperdivergent growth pattern?
4. What does the literature suggest regarding the effects of myofunctional therapy and other orofacial posture treatment approaches, including the Biobloc technique?
5. What does the literature suggest with respect to treatment timing?

2.2 Etiology of a Hyperdivergent Growth Pattern

It is widely accepted in the orthodontic literature that the etiology of a hyperdivergent growth pattern, and malocclusion in general, is complex and multifactorial with genetic and environmental factors playing significant roles.[1,8] In 1978, Proffit postulated that the major primary factors in the dental equilibrium appear to be resting pressures of the tongue and lips, and that "respiratory needs influence head, jaw and tongue posture, thereby altering the equilibrium."[14] One common example that is known to disrupt the oral equilibrium is a finger-sucking habit in the primary and mixed dentitions. Prolonged finger sucking alters the position of the tongue and lips and places an extrinsic force on the dentition, resulting in proclined upper incisors, retroclined lower incisors, increased overjet, decreased overbite, narrow palate, and posterior crossbite.[11] Most of these can resolve spontaneously if the habit is stopped before the eruption of the permanent incisors, as this allows for the natural equilibrium to be restored.

2.2.1 Nasopharyngeal Airway Obstruction

The link between oral habits and a hyperdivergent growth pattern is less clear.[1] However, the literature generally supports the idea that interferences with normal breathing alters normal growth and development, which can result in a hyperdivergent growth pattern. This is mainly seen in the form of local environmental factors, such as nasal allergies or hypertrophic tonsils, which cause chronic nasopharyngeal airway obstruction (Figure 2.1). The nasal airway obstruction changes the mode of respiration to be primarily oral, which in turn, has effects on head, tongue, and mandibular posture.[1] Harvold et al.[15] tested this hypothesis on monkeys in the 1980s. They created mouth breathing in monkeys by obstructing their nasal airways with nose plugs and found that the mouth breathing monkeys developed common traits, including increased lower face height, steeper mandibular plane, and larger gonial angle compared to control. Research has shown that humans with nasal obstructions also develop these similar clinical traits.

Figure 2.1 Lateral cephalometric radiograph of a 13-year-old male showing adenoid hypertrophy with significant obstruction of the nasopharyngeal airway associated with a hyperdivergent growth pattern.

Allergic rhinitis is the most common cause of chronic airway obstruction in children, followed by enlarged adenoids.[16] Two systematic reviews[17,18] reported that although the data is insufficient to establish a possible causal relationship between rhinitis and malocclusion, there does appear to be a link, so early diagnosis and management of nasal obstruction is important to potentially prevent altered facial growth. More specifically, multiple studies[16,19–22] found that mouth breathing children have increased facial heights, narrower maxillary arches with cross-bite tendencies, increased gonial angles, and retrognathic jaws compared to children who breathe through the nose.

The link between nasopharyngeal airway obstruction from enlarged adenoids, mouth breathing, and vertical growth has also been well documented in the literature. Children with obstructing adenoids tend to have more a downward and backward rotation of the mandible.[23–25] Similarly, several studies[23–27] have also found that children with enlarged tonsils have increased lower facial heights, steeper mandibular plane angles, and more retrognathic mandibles. In a 5-year follow-up study, Linder-Aronson[19] found that children with hypertrophic adenoids who underwent adenoidectomy had improvement in the inclination of the mandibular plane relative to the maxilla, as well as in the inclination of the upper and lower incisors and the width of the maxillary arch. It appears that this change is more related to increased horizontal mandibular growth as opposed to changes in the direction of growth of the maxilla.[26–28] Zettergren-Wijk et al.[29] studied changes in dentofacial morphology following adenotonsillectomy in young children with obstructive sleep apnea and also found that early diagnosis and treatment can result in normalization of dentofacial development. A more recent systematic review by Becking et al.[30] mirrors these findings that hypertrophic tonsils, and nasopharyngeal airway obstruction in general, are risk factors for the development of dentofacial deformity and that adenotonsillectomy can provide normalization of dentofacial development. However, the evidence remains inconclusive due to the high risk of bias, as well as clinical and methodological heterogeneity of the included studies. This normalization of dentofacial development following adenotonsillectomy in growing individuals is likely related to a return to a more normal nasal respiratory pattern, which restores the equilibrium of the jaws and teeth.[11] This is also supported by a study conducted by Ågren et al.[31] who found that respiratory recordings were normalized or improved in the majority of children following adenotonsillectomy. However, it is important to note that individuals with previous chronic nasal obstruction, may continue to breathe through the mouth even after the obstruction has been treated, as they have developed a mouth breathing habit.[11]

It seems intuitive that if nasopharyngeal obstructions were directly associated with vertical growth, then hyperdivergent individuals would tend to have reduced nasal airway volumes and airflow. Nonetheless, there is conflicting information in the literature regarding this. Vig et al.[32] found that hyperdivergent individuals had higher mean nasal resistance compared to normodivergent individuals, but there was no significant difference in nasal airflow. However, these results should be interpreted with caution due to the small sample size. On the other hand, Fields et al.[33] found that hyperdivergent individuals had similar nasal airway cross-sectional areas but significantly less nasal respiration, whereas Joseph et al.[34] found their hyperdivergent group actually had narrower anteroposterior airway dimensions, not only in the nasopharynx but also in the oropharynx at the level of the soft palate and mandible. The latter study attributed this anatomical difference to retrusion of the jaws, which is a common skeletal feature in hyperdivergent individuals. Typically, mouth breathing is associated with an open mouth posture or lip incompetence at rest. However, Vig et al.[32] also reported that lip posture is not an accurate indicator of respiratory mode as individuals with lips apart at rest can still have normal levels of nasal airflow. Nonetheless, in 2004, Mew[12] reported on evidence suggesting that weak orofacial muscles and open mouth postures in general, not just mouth breathing, can cause increased vertical growth and malocclusion.

2.2.2 Weak Masticatory Muscles

The four primary muscles of mastication include the masseter, temporalis, medial pterygoid, and lateral pterygoid muscles. These are the group of muscles responsible for moving the mandible and are critical in the process of chewing as they function in harmony to bring the teeth together and grind food.[35] Weak muscles of mastication or reduced masticatory forces have also been linked with hyperdivergent growth tendency.[1] This was noted in a clinical study in patients with myotonic dystrophy by Kiliaridis et al.[36] They found that individuals with myotonic dystrophy who had weak masticatory muscles had an increased prevalence of malocclusions and vertical craniofacial morphology, which included a steep mandibular plane angle. This difference was more noticeable in patients with an early onset of the disease. Ingervall and Thilander[37] reported that individuals with increased masseter and temporalis muscle activity during chewing had small lower face heights. This was partially supported in a study with Weijs and Hillen.[38] They found that the masseter and medial pterygoid muscles are large in brachycephalic individuals with short faces and flat jaw angles, while the temporalis and lateral pterygoid muscles did not appear to have a correlation with facial morphology. Similarly, Van Spronsen et al.[39] also reported that the biggest effect comes from the masseter and medial pterygoid muscles – the cross-sectional areas of the masseter, medial pterygoid, and anterior temporalis muscles in hyperdivergent individuals were 30%, 22% and 15% smaller than control. Two other studies[40,41] found that individuals with decreased masseter and medial pterygoid muscle volumes had steeper mandibular and occlusal planes and increased gonial angles, while the converse was true with higher muscle volumes. However, Kiliaridis and Kälebo[42] found the relationship between thin masseter muscles and vertical facial morphology to be true only mainly in women. Interestingly, when looking at bite forces and facial morphology, Proffit and Fields[43,44] reported that hyperdivergent adults have significantly less occlusal forces during chewing than normodivergent adults, whereas the occlusal forces for hyperdivergent and normodivergent children are similar. Ingervall and Minder[45] further studied bite forces in children and found that girls with large bite forces had smaller mandibular and gonial angles, but this correlation was much weaker in boys.

2.2.3 Deviations from Normal Orofacial Posture

The exact mechanism whereby mouth breathing and weak masticatory muscles result in hyperdivergent growth tendencies is still not fully understood. However, they both appear to be related to changes in head, mandible, and tongue posture associated with an open mouth resting position.[1] For example, individuals with a nasopharyngeal airway obstruction must lower their mandibles and tongues and tip their heads back in order to facilitate oral respiration.[11,46] Behlfelt et al.[47] found that children with enlarged tonsils had an extended head posture, inferiorly positioned hyoid bone, and an anteroinferior tongue position. Solow and Sandham[48] also found that head posture seems related to mandibular development as individuals with larger cranio-cervical angles have steeper mandibular planes and increased face heights than those with smaller cranio-cervical angles (Figure 2.2). If these unfavourable postural changes are

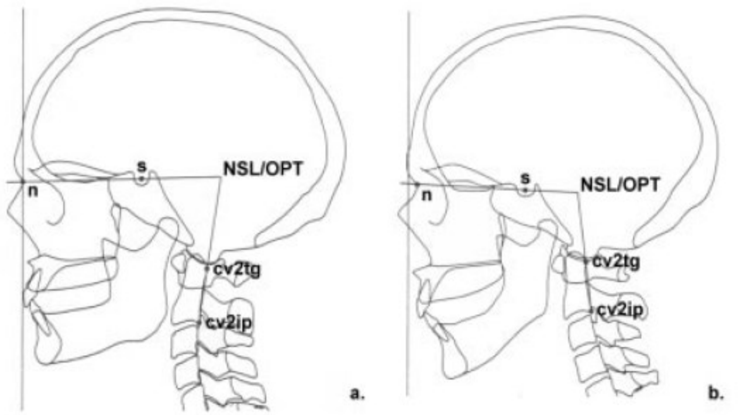

Figure 2.1 Difference in facial morphology between an individual with a small cranio-cervical angle (left) and an individual with a large cranio-cervical angle (right). Reprinted with permission from Oxford University Press.[48]

maintained, especially in a growing individual, then compensations in the jaws and dentition can occur, and growth can be affected.[1,11] For example, an inferiorly positioned mandible increases the mandibular plane angle, and over time, can result in supra-eruption of the posterior teeth, downward and backward rotation of the mandible, an increase in lower face height, and a narrower maxillary arch due to increased pressure from the stretched cheeks. Another hypothesis that can explain this phenomenon is the soft-tissue stretching hypothesis. The postural change associated with airway obstruction causes soft-tissue stretching, which applies differential forces on the craniofacial bones, resulting in morphological changes (Figure 2.3).[48] The role that weak muscles of mastication play in this process is less obvious but can be attributed to reduced muscle strength, making it more difficult to maintain proper orofacial posture.[1]

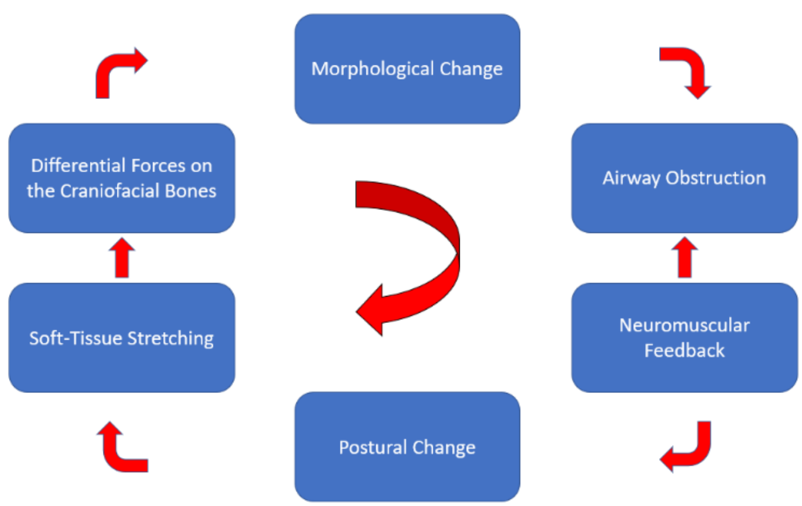

Figure 2.3 The soft-tissue stretching hypothesis. Adapted from Solow and Sandham.[48]

Although upon review of the literature, there does appear to be some association with deviations from normal respiration and weak muscles of mastication to vertical facial skeletal growth, it is clear that objective and well-controlled studies are needed in order to increase our understanding of the interactions between these variables.[46,49] In other words, mouth breathing or an open mouth posture may contribute to the development of orthodontic problems but cannot be attributed as a primary etiologic factor.

2.3 Potential Sequela of a Hyperdivergent Growth Pattern

As previously discussed, a hyperdivergent growth pattern is typically associated with various facial features such as an increased lower face height, retrognathic mandible, narrow maxillary arch, anterior open bite, excessive display of the upper teeth and gingiva, and lip incompetence.[1,2] However, in addition to abnormal facial growth, malocclusion, and orthodontic problems, other sequelae have also been implicated with a hyperdivergent growth pattern, including potential negative impacts on health. This section will investigate what is suggested in the literature with respect to potential long-term ramifications associated with a hyperdivergent growth pattern.

2.3.1 Link Between Hyperdivergent Growth Pattern and Sleep-Disordered Breathing

The previous section explored the link between nasopharyngeal airway obstruction, mouth breathing, and vertical growth. Additionally, multiple publications in the literature have reported on the link between upper airway obstructions, mouth breathing and sleep disorders in children.[50–58] Sleep-disordered breathing (SDB) is a general umbrella term that includes various sleep-related breathing disorders such as obstructive sleep apnea (OSA). The American Thoracic Society defines SDB as a “wide spectrum of sleep-related conditions including increased resistance to airflow through the upper airway, heavy snoring, marked reduction in airflow (hypopnea), and complete cessation of breathing (apnea).”[59] SDB is fairly common in children, with an estimated prevalence of 1-10%.[54] Although the majority of cases are mild and children tend to outgrow the condition, untreated SDB can result in serious health complications.[50,60]

Olsen et al.[58] reported that acute nasal obstruction caused a statistically significant increase in the number of hypopnea and apnea events during sleep. Sinha and Guilleminault[60] indicated that SDB arises from a narrow airway combined with reduced neuromuscular tone and increased airway collapsibility. Two other studies[52,57] reported that mouth opening and oral respiration during sleep increases upper airway collapse, which may contribute to SDB. This appears related to decreased contractile efficiency of the upper airway musculature.[51] It has also been previously published that children with OSA exhibit both mouth breathing and an extended head posture in an attempt to increase airflow during respiration.[29,31] Oeverland et al.[55] found that patients with SDB were more likely to be mouth breathers during sleep compared to patients without SDB. Interestingly, however, they found that patients with severe SDB had less tendency to breathe through their mouth alone than patients with moderate SDB, contrary to what was expected. Joseph et al.[34] also concluded that hyperdivergent patients had a narrower anteroposterior airway dimension. These findings suggest that an open mouth posture and a vertical facial skeletal development could potentially increase the likelihood of SDB.

Furthermore, several studies have also investigated the facial morphology in patients with SDB and found many similarities between that and the morphology of the hyperdivergent phenotype. Ali et al.[53] reported that increased lower face heights and steeper mandibular plane angles resulted in increased chances of SDB symptoms in children. They concluded that the combination of a long face with a retrognathic mandible might be diagnostic facial features of SDB (Figure 2.4). Lowe et al.[61] studied facial morphology specifically in patients with moderate

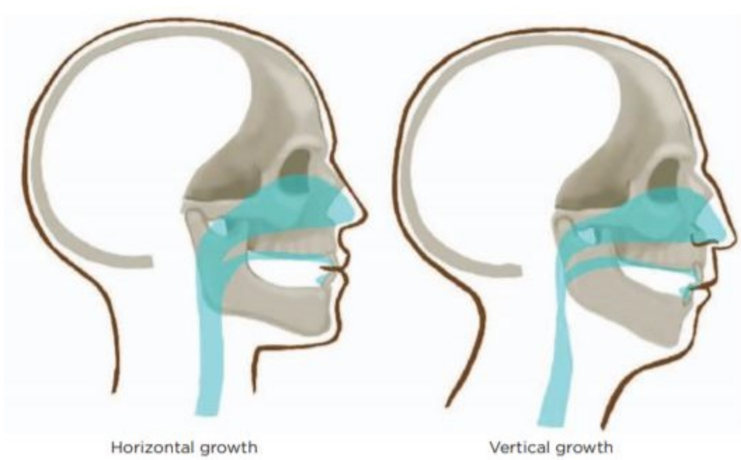

Figure 2.4 Vertical growers (right) have more retruded mandibles and more restricted airways, which may predispose them to SDB. Reprinted with permission from Stanford University Press.[7]

to severe OSA and found that they had retruded maxillas and mandibles, as well as steep occlusal and mandibular planes, increased gonial angles, and increased lower face heights – all of which are also associated with a hyperdivergent growth pattern. Similarly, Zettergren-Wijk et al.[29] found that children with OSA had a more posteriorly inclined mandible, increased lower anterior face height, reduced airway space, and a less pronounced nose. They concluded that OSA in young children has an unfavourable effect on facial development, but almost complete normalization can be achieved with early diagnosis and treatment. Rivlin et al.[62] found that not only did patients with OSA have a posterior displacement of the mandibular symphysis, but they also had smaller mandibles overall. On the other hand, while Andersson and Brattström[63] did find that patients with OSA had a backward rotation of the mandible, reduced posterior airway, and decreased posterior facial height, they did find posterior displacement of the mandible or an increased lower anterior facial height.

SDB can have serious potential long-term health consequences in children. It has been well documented in the literature that SDB is associated with significantly reduced quality of life in children but that patients can show dramatic improvement with early diagnosis and intervention.[64–67] SDB in children can lead to growth disturbances, cognitive deficits, and behavioural problems, including difficulty paying attention, irritability, excessive daytime somnolence, and poor academic performance.[50,51,54,60,68–70] If left untreated, SDB can also lead to an increased risk of mood disorders such as depression and cardiovascular disease, including hypertension, cor pulmonale, and even cardiac failure and death in severe cases. Therefore, early recognition of symptoms and diagnostic facial features followed by timely referral to the appropriate specialists is critical for these patients. SDB management often requires a multidisciplinary approach involving family physicians, sleep medicine physicians, and otolaryngologists.

2.3.2 Link Between Hyperdivergent Growth Pattern and Facial Attractiveness

Facial appearance is considered to be the most important determinant of physical appearance.[9] Patients with excessive hyperdivergent growth patterns have not only functional orthodontic problems but also significant esthetic problems associated with their facial morphology. Because excessive vertical facial skeletal growth results in a downward and backward rotation of the mandible, these individuals tend to have retruded chins, convex profiles, and increased lower face heights. Czarnecki et al.[71] reported that facial profiles that were excessively convex or had very recessive chins were the least preferred. Michiels and Sather[72] also found that convex profiles or profiles with increased vertical features were judged as being the most unattractive. The chin, upper lip and nose were the regions of the face that had the greatest effect on the overall judgement of appearance. Similarly, Johnston et al.[73] concluded that images of individuals with an increased lower face proportion were perceived as being significantly less attractive and judged as more likely to need orthodontic treatment compared to those of reduced lower face proportion. Lastly, Maple et al.[74] also found that deviations from normal anteroposterior and vertical facial dimensions have an influence on the perception of facial attractiveness. The more extreme the deviation, such as a significant convex or concave profile, the less attractive the individual is perceived to be.

These studies highlight the impact of normal craniofacial growth and development, specifically with respect to chin and jaw projection, on achieving a balanced and esthetic facial profile. Furthermore, Antoun et al.[75] concluded that individuals with hyperdivergent facial types are more likely to self-report poorer oral-health-related quality of life, especially for social aspects, compared to normodivergent individuals. Therefore, not only does it become important to treat these patients for functional and esthetic purposes but also for possible associated psychosocial factors that may follow them into adolescence and adulthood.

2.4 Conventional Management of a Hyperdivergent Growth Pattern

According to Sankey et al.,[4] "control of the vertical dimension is probably the single most important factor in the correction of the hyperdivergent case." Various treatment modalities exist in orthodontics, with the aim of controlling the vertical dimension. This section will review the different modalities and investigate what is said in the literature with respect to treatment outcomes. As discussed in Chapter 1, excessive downward growth of the maxilla causes the mandible to rotate downward and backward. Therefore, an ideal treatment, if there is adequate vertical mandibular ramus growth remaining, would involve limiting maxillary posterior vertical growth by inhibiting posterior tooth eruption, which would allow the mandible to rotate in an upward and forward direction (Figure 2.5).[11]

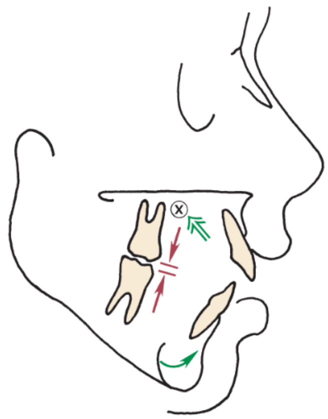

Figure 2.5 Illustration showing ideal treatment outcomes for controlling excessive vertical growth. Theoretically, by restricting the eruption of posterior teeth, the downward growth of the maxilla is limited, allowing for upward and forward growth of the mandible. Reprinted with permission from Elsevier.[11]

2.4.1 High-Pull Headgear

High-pull headgear is a traditional orthopedic appliance used to help control excessive vertical growth in growing patients (Figure 2.6). Although it can have orthopedic effects if worn consistently for approximately 12 to 14 hours a day, it is not used as frequently in modern clinical practice due to the significant compliance required and limited cooperation in children. High-pull headgear works by delivering an extraoral force to the maxilla, specifically a distal and intrusive force to the maxillary molars. This can limit eruption of the maxillary molars, which can decrease downward growth of the maxilla, thereby promoting horizontal mandibular growth (Figure 2.7).[2,11] However, when used alone, its effectiveness may be limited as it does not control the eruption of mandibular posterior teeth, which may work against the redirection of the

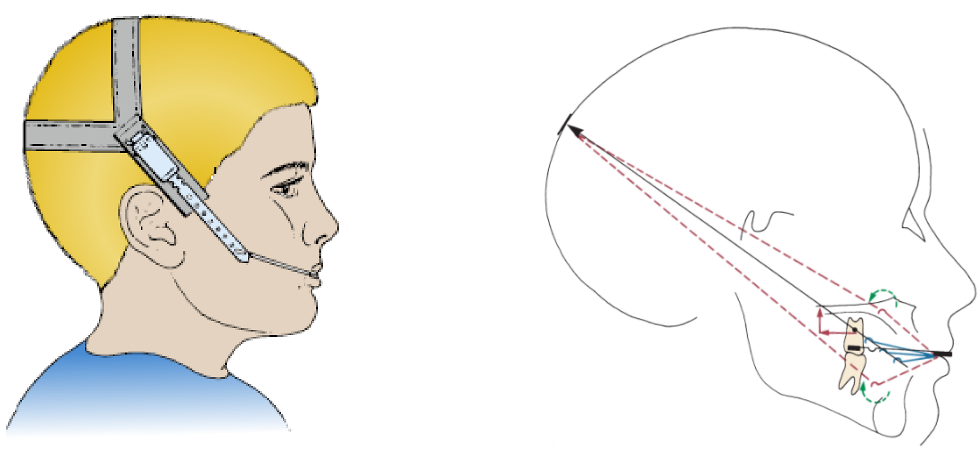

Figure 2.6 Left – Patient wearing high-pull headgear. Right – Illustration showing the forces applied on the maxilla and maxillary molars from high-pull headgear. Reprinted with permission from Elsevier.[2 (left), 11(right)]

mandible in an upward and forward direction. Another approach is the use of high-pull headgear to a maxillary splint which allows the vertical force to be applied to all maxillary teeth, not just the molars. However, this technique also does not control the eruption of mandibular posterior teeth. The findings in studies investigating this technique by Caldwell et al.[76] and Orton et al.[77] supported this. They found that while there was effective vertical control of the maxillary dentition and some maxillary molar intrusion, there was no noticeable change in mandibular position at the end of treatment. While both studies reported no significant change in mandibular plane angle, Caldwell et al.[76] also mentioned that at least there was no significant increase in mandibular plane angle after the treatment. Interestingly, no reports on the use of high-pull headgear with a mandibular splint could be found in the literature.

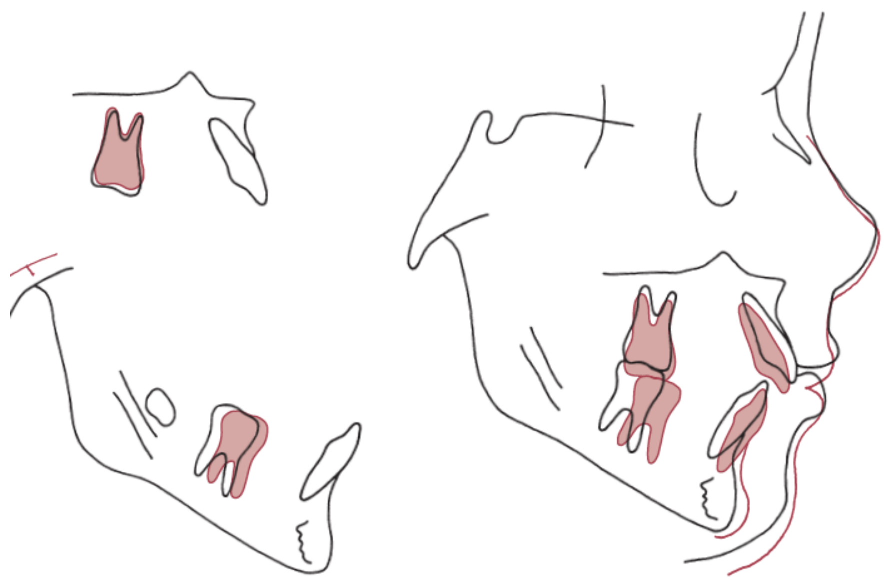

Figure 2.7 Cephalometric superimposition showing a favourable response to high-pull headgear in a patient with excessive lower face height. The maxilla and maxillary molars did not move downward, and the mandible grew anteriorly. Reprinted with permission from Elsevier.[11]

It is apparent that the true effectiveness of high-pull headgear for vertical control is largely anecdotal with conflicting evidence in the literature. For example, Baumrind et al.[78–80] reported that while there was intrusion of the maxillary first molar and a reduced rate of increase in lower face height in the high-pull treatment group, the high-pull headgear actually appeared to produce a slight increase in the mandibular plane angle, although not statistically significant. Firouz et al.[81] found that high-pull headgear not only resulted in significant distal movement and intrusion of the maxillary molars, but also restricted horizontal and vertical maxillary growth. On the contrary, Erin Bilbo et al.[82] concluded that while high-pull headgear restricted maxillary horizontal growth during treatment, it had no effect on vertical skeletal changes. Antonarakis and Kiliaridis[83] also reported no change in maxillary and mandibular plane angles during treatment with high-pull headgear with a wide variation in changes in vertical skeletal relationships. While they did acknowledge dentoalveolar changes, they concluded that these changes might not be able to make a predictable difference in vertical skeletal patterns. Similarly, Burke and Jacobson[84] also found that there were no differences in mandibular plane angle or facial height changes, and that changes in maxillary molar height did not appear to affect the mandibular plane angle. Furthermore, a systematic review by Jacob et al.[85] concluded that while high-pull headgear does provide vertical eruption control and distalization of the maxillary molars, there do not seem to be any effects on the mandible. Therefore, without clear evidence that high-pull headgear has any effect on the mandible, its effectiveness in controlling the vertical dimension and improving the direction of growth of the mandible becomes questionable.

2.4.2 Functional Appliances with Posterior Bite Blocks

Another treatment modality used in the management of excessive vertical growth is functional appliances with posterior bite blocks. Proffit defined a functional appliance as an appliance that "changes the posture of the mandible, holding it open or open and forward."[11] The pressures created by the stretch of muscles and soft tissues are transmitted to the teeth and jaws, allowing for tooth movement and growth modification. The bite blocks not only prevent the eruption of posterior teeth in both arches, but they also open the bite and cause soft tissue stretching, which could exert an intrusive force on the posterior teeth and allow for autorotation of the mandible.

Weinbach and Smith[86] found that patients who received this type of functional appliance treatment experienced less of an increase in facial height than expected, as well as reductions in facial convexity, overjet, and eruption of maxillary molars. However, there is little information in the literature concerning the long-term stability of these treatment effects. Freeman et al.[87] studied the effects of a combination treatment approach with a functional appliance and high-pull headgear in patients with increased vertical dimension. Counterintuitively, they found that the combination treatment worsened the hyperdivergent facial pattern by increasing the mandibular plane angle and the inclination of Frankfort horizontal relative to the occlusal plane. They concluded by recommending against the use of this combination therapy for hyperdivergent patients when the goal is to control the vertical dimension.

2.4.3 Orthodontic Treatment with Extractions

Extraction of teeth in conjunction with orthodontic treatment has also been proposed as a way of reducing the vertical dimension in hyperdivergent patients.[3,9] This is believed to happen through a phenomenon known as the "wedge" effect in which extraction of second premolars allows for the mesial movement of the molars during space closure. Theoretically, with the posterior teeth located more anteriorly in the arch in an area of greater interocclusal dimension, there should be increased mandibular autorotation and decreased lower face height. However, this too has conflicting results in the literature. Garlington and Logan[88] found that there was a significant decrease in lower anterior face height in patients who underwent enucleation of the mandibular second premolars in the mixed dentition. Aras[89] also reported that extraction of second premolars or first molars resulted in closing rotation of the mandible while no significant mandibular rotational change occurred with first premolar extractions. Staggers[90] also found that there was no difference in vertical changes in patients who had first premolars extracted. On the other hand, studies by Klapper et al.,[91] Al-Nimri,[92] and Kim et al.[93] all concluded that while second premolar extraction was associated with mesial movement of the molars, there did not appear to be a significant reduction in facial vertical dimension in patients with either first or second premolar extractions. That being said, non-extraction treatment with distal movement of maxillary molars is found to increase the vertical facial skeletal dimensions.[91,94]

2.4.4 Skeletal Anchorage

For patients with severe hyperdivergent growth patterns or patients that have completed growth, typically the only successful and predictable treatment plans involve either skeletal anchorage or orthognathic surgery to surgically reposition the jaws. Recently over the years, skeletal anchors such as temporary anchorage devices (TADs) and miniplates have become more commonly used tools for managing complex malocclusions. TADs are miniscrew-like devices that are typically made of titanium or stainless steel. Although they do not osseointegrate like traditional dental implants, when inserted into the maxilla or mandible, they can provide some degree of skeletal anchorage to allow for complex orthodontic movements. For example, in the application of controlling the vertical dimension, TADs in the maxilla and/or mandible can be used to intrude posterior teeth (Figure 2.8). Similar to the headgear effect, in theory, this can allow for an upward and forward rotation of the mandible, thereby reducing the vertical dimension.

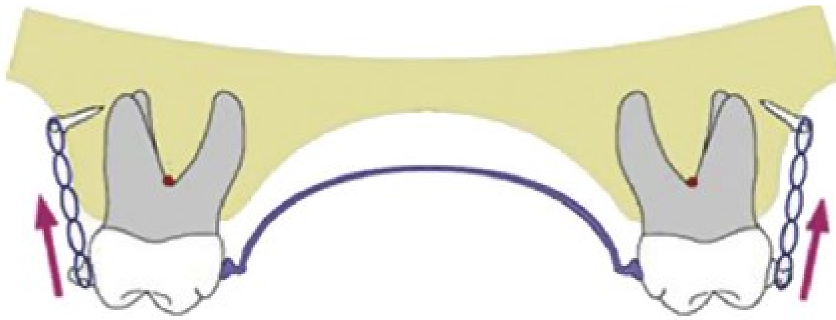

Figure 2.8 Transverse view of TADs placed in the maxillary buccal alveolar bone for molar intrusion. Reprinted with permission from Elsevier.[95]

Two studies conducted by Buschang et al.[5,96] investigated different approaches using TADs for maxillary and mandibular molar intrusion in growing hyperdivergent patients with slightly conflicting results. One study reported consistent and substantial orthopedic effects, including decreased mandibular plane angle, gonial angle, and facial convexity,[5] while the other reported deceased mandibular plane angle but no change in gonial angle or lower facial height.[96] However, both papers concluded that these techniques could successfully control the vertical dimension and improve facial profile, especially if supra-eruption of the lower molars is controlled. Xun et al.[97] also investigated a similar technique using TADs for the intrusion of maxillary and mandibular molars and found significant decreases in mandibular plane angle and anterior facial height. Scheffler et al.[98] investigated the use of TADs specifically in the maxilla with a maxillary splint for posterior intrusion. They found that while this method did provide correction of moderate to severe anterior open bites, the intruded teeth had 0.5-1mm of relapse, and controlling the vertical position of the mandibular molars during this process is necessary to obtain a reduction in face height. Nonetheless, they acknowledge that orthognathic surgery is more likely to produce a reduction in anterior face height. Umemori et al.[99] and Sugawara et al.[100] studied the use of titanium miniplates for the intrusion of mandibular molars and found that they could predictably correct skeletal open bites and achieve mandibular autorotation with reductions in mandibular plane angle and anterior facial height.

While these techniques could potentially be an effective alternative to orthognathic surgery without the risks and financial burdens associated with surgery, there is no consensus on whether a non-surgical treatment approach can provide similar predictability and stability compared to surgery. Kuroda et al.[101] compared treatment outcomes between molar intrusion with miniplate skeletal anchorage to double jaw orthognathic surgery in adult patients with severe anterior open bite. They found that there were no significant differences in treatment results, with both skeletal anchorage and surgery achieving similar reductions in facial height. According to Baek et al.,[95] however, intrusion of maxillary molars with TADs is generally unstable, with a relapse rate of 23%; the majority of relapse occurring within the first year of retention. Furthermore, a systematic review by González Espinosa et al.[102] agreed that although anterior open bite treatment with molar intrusion using skeletal anchorage is relatively unstable, with relapse rates ranging from 10-30%, the relapse levels are similar to those reported in orthognathic surgery. However, the level of certainty based on the meta-analysis ranged from very low to low.

In conclusion, there is conflicting evidence on control of the vertical dimension in orthodontics and more clinical research is required. As discussed, various treatment modalities exist; however, there is no consensus in the literature with respect to treatment effects and efficacy. Given these uncertainties and patients' demand for faster, more predictable treatment outcomes without surgery, the search for better methods of controlling the vertical dimension continues.

2.5 Myofunctional Therapy and Other Orofacial Posture Treatment Approaches

The Academy of Orofacial Myofunctional Therapy defines myofunctional therapy as "an interdisciplinary practice that works with the muscles of the lips, tongue, cheeks and face and their related functions such as breathing, sucking, chewing, swallowing, and some aspects of speech."[103] The premises of myofunctional therapy is somewhat related to the practice of orthotropics, which was created by Mew. However, while myofunctional therapy is focused on muscle function, orthotropics is focused on orofacial posture.[7] Orthotropists believe that weak orofacial muscles, poor oral posture, and abnormal tongue habits cause alignment issues with the jaws and teeth, and that facial growth can be guided by addressing these issues and establishing good resting oral posture. The term "orthotropics" has been more recently renamed to "forwardontics" by Sandra Kahn to include all treatments that focus on the forward development of the teeth and jaws.

In the book *Jaws: The Story of the Hidden Epidemic*, Kahn and Ehrlich claim that if begun early enough, forwardontics has the ability to redirect the growth of the jaws, face and airway, and promotes "development of the face to prevent dental crowding, allows the mouth to function optimally and averts sleep-disordered breathing."[7] However, they acknowledge that this process takes a long time as well as compliance from the patient and a competent clinician. They also discuss how forwardontics has been relatively ignored by the research community and that conclusions often need to be drawn from small samples. In this section, reports of various myofunctional and orofacial posture treatment approaches in the literature will be explored, including the Biobloc technique, which is Mew's orthotropic technique that the treatment protocol being investigated in this thesis is largely based on.

2.5.1 Myofunctional Therapy and Prefabricated Myofunctional Appliances

In 1987, Ingervall and Bitsanis[104] evaluated masticatory muscle and facial growth changes in children who underwent daily chewing exercises with a tough chewing material for one year. Although they had a small sample size, they found that these children had a significant increase in masticatory muscle activity and bite force with an average anterior mandibular rotation of 2.5° in 9 out of 12 cases. This suggests that masticatory muscle training could positively affect facial growth. However, there were no signs of reduced vertical growth of the maxilla or reduced rate of molar eruption. Das and Beena[105] also found that children who had adenotonsillectomy and then underwent six months of circumoral lip seal exercises had increased muscle thickness and were more likely to become nasal breathers. A systematic review by Koletsi et al.[106] concluded that although early intervention with orthodontic and myofunctional therapy in the deciduous and mixed dentitions appears to be a promising approach for normalizing mouth posture and lip closure, there is insufficient high-quality evidence with long-term follow-up in the literature. Another systematic review by Homem et al.[107] also agreed that there is a lack of consistent studies and scientific evidence supporting the effectiveness of myofunctional therapy in conjunction with orthodontic treatment.

Three systematic reviews have also shown that myofunctional therapy could potentially serve as an adjunct to other treatments for obstructive sleep apnea.[108–110] Camacho et al.[108] reported that myofunctional therapy decreased the apnea-hypopnea index by approximately 50% in adults and 62% in children. Furthermore, children treated for OSA with adenotonsillectomy and palatal expansion were more likely to develop recurrent OSA in the future if they did not receive any myofunctional therapy. Similarly, Bandyopadhyay et al.[109] reported that myofunctional therapy not only decreased apnea-hypopnea index by 43% but also increased mean oxygen saturation in children with mild to moderate OSA. A Cochrane review by Rueda et al.[110] concluded that while the certainty of the evidence ranges from very low to moderate, myofunctional therapy may reduce daytime sleepiness and increase sleep quality in the short term.

Figure 2.9 Myobrace® Appliance (Myofunctional Research Co., Australia).

Prefabricated myofunctional appliances, such as the Myobrace (Figure 2.9), are intraoral appliances which, in theory, could potentially address soft tissue dysfunction, improve tongue resting posture, and improve airway volume.[111] They are designed to promote a closed mouth posture and nasal breathing. However, their effectiveness is a controversial topic with conflicting evidence and opinions in the literature. According to a systematic review by Mohammed et al.,[111] although the quality of evidence is low, prefabricated myofunctional appliances are generally less effective than activator appliances in treating Class II, division 1 malocclusions. They noted that while prefabricated myofunctional appliances are cost effective, they have issues with low patient acceptance and compliance. Johnson et al.[112] evaluated the dental and skeletal effects between the Myobrace and Twin Block appliances in the treatment of Class II, division 1 malocclusion. Myobrace had more dentoalveolar changes than skeletal changes in the Class II correction. Both appliances caused an increase in anterior and posterior facial heights, but Myobrace resulted in a greater decrease in the mandibular plane angle. Das and Reddy[113] and Usumez et al.[114] both also found that the appliances caused an increase in facial heights, suggesting that they could potentially be worsening a hyperdivergent growth pattern. Although they did note forward rotation of the mandible, this was not statistically significantly different when compared with the control. Both studies also concluded that the effects of prefabricated myofunctional appliances were primarily dentoalveolar. Lastly, two studies[115,116] investigated oropharyngeal airway changes in Class II retrognathic children after treatment with Myobrace and found that it increased oropharyngeal airway dimensions. However, neither study investigated the significance this had on symptoms of sleep disorders. Evidently, more high-quality studies with larger sample sizes and longer follow-ups are needed to establish a stronger connection.

With respect to a unique treatment protocol aimed directly at the early management of excessive vertical growth, Sankey et al.[4] published one in 2000. They used a non-extraction treatment approach consisting of lip seal exercises, a bonded palatal expansion appliance that also functioned as a posterior bite block, and a lower lip bumper appliance in 38 children (average age of 8.2 years) with severe hyperdivergent growth patterns. Patients with poor masticatory muscle forces also wore a high-pull chin cup for 12 to 14 hours a day. They found that the treatment group had significant orthopedic effects, including forward rotation of the mandible with improvement in chin projection, decreased gonial angle, inhibited anterior facial height growth, relative intrusion of the maxillary molars, and increased eruption of the maxillary and mandibular incisors. However, the long-term stability of their treatment effects was not reported.

2.5.2 Biobloc Technique

The Biobloc technique was invented and published by Mew in 1979 with the objective of promoting horizontal growth of the jaws by training for closed mouth postures in growing children.[117,118] The treatment involves an initial phase with removable appliances used to expand the maxilla and increase the width of both upper and lower arches in order to create more room for the tongue. This is then followed by a second phase involving the use of the Biobloc appliance, designed to posture the mandible forwards, as well as improve oral posture by inducing the patient to keep their mouth closed with lips sealed and maintain their tongue resting on the palate. Once functional correction has been achieved, the patient enters the retention phase where appliance use is reduced to part-time.

Studies investigating the Biobloc technique are quite scarce in the literature with relatively small sample sizes. Singh et al.[119] evaluated changes in posterior airway space in patients following treatment with the Biobloc technique. They reported a 31% and 23% increase in the nasopharyngeal and oropharyngeal airway dimensions, respectively. A study by Trenouth et al.[118] compared cephalometric changes of patients treated with the Biobloc technique to matched normative data and found significant reductions in overjet, overbite, and ANB angle, which appeared to be entirely due to an increase in SNB. Furthermore, while there was also a statistically significant reduction of 0.37° in the angle formed between articulare – gonion – menton, this change was not clinically significant. No other major vertical measurements were included in their analysis. In fact, there are no studies that investigated the effects of the Biobloc technique specifically on vertical facial skeletal growth.

2.6 Timing of Treatment

Appropriate timing for treatment of excessive vertical growth always poses a challenge. Similar to treatment methods, there is also conflicting and limited information in the literature regarding ideal timing. As mentioned in Chapter 1, some clinicians feel that early treatment should be initiated not only because there is the growth potential for correction, but also for potential psychosocial benefits.[9] The belief is that when growth potential remains, further vertical growth could be limited, and the growth of the mandible could potentially be redirected into a more forward direction. While the study by Sankey et al.[4] showed that early treatment in young hyperdivergent patients could be successful, the long-term stability of these treatment effects remains unknown. One legitimate concern is that if treatment is delayed and the potential for growth modification is lost, complex treatment with skeletal anchorage or potentially even surgical correction may remain the only feasible option.[4,8,9] Phelan et al.[120] advised to wait until the pubertal growth spurt before starting treatment in patients with open bite tendencies.

However, because vertical facial growth is the last to stop, typically extending into adulthood, patients who undergo early treatment are very susceptible to relapse following orthodontic treatment. This was demonstrated in a longitudinal 10-year post-retention evaluation of adolescents treated for anterior open bites by Lopez-Gravito et al.[10] They found that more than 35% of patients had an open bite relapse of 3mm or more and also demonstrated an increased anterior facial height over time. Furthermore, it has been shown that early treatment is potentially less efficient in certain situations as it does not reduce average treatment times once a patient is in permanent dentition, nor does it reduce the proportion of complex cases requiring extractions or orthognathic surgery.[121]

When determining whether early intervention is beneficial, it is important to consider not only the orthodontic problems and potential consequences of delaying treatment, but also the required level of compliance and the patient's level of maturation and motivation.[122] An uncooperative child patient would drastically affect the ability to achieve favourable early treatment outcomes, especially for treatments requiring significant compliance such as myofunctional exercises and removable appliances. Therefore, patient selection becomes a critical aspect of planning early treatment as well. Moreover, as Proffit suggested, early attempts to control excessive vertical growth would have to extend for inordinately long periods in order to outlast growth which could lead to patient burnout.[11] Buschang, Sankey and English summarized it well: "Growth is clearly a critical period that holds great potential for orthopedic and orthodontic corrections as well as relapse toward the original condition."[9] It is important to note that regardless of what appliance or modality is used, long-term retention is paramount to preventing relapse since vertical growth can extend into adulthood.

Chapter 3 – Methods

3.1 Study Sample

Ethics approval was granted by the University of Alberta Health Research Ethics Board (PRO00084145) for this retrospective cohort study. The treatment group of 102 patients was consecutively treated in private practice by one clinician (Simon Wong) experienced in the proposed technique. Inclusion criteria consisted of mixed dentition children with malocclusion who had not yet reached their pubertal growth spurt. The patient and family also had to be motivated with no perceivable potential issues with compliance as agreed upon through the practice's informed consent process. Pubertal status was assessed for girls by asking their parents if they had reached menarche and for boys by evaluating their physical size and voice changes. Cases were excluded if the patient had already entered puberty. No specific malocclusions were excluded on the premise that the treatment protocol should effectively control excessive vertical facial skeletal growth in all different types of malocclusions. Lateral cephalometric radiographs taken before treatment (T1) and at the end of active treatment (T2) were digitally traced, and changes in skeletal and dental measurements were calculated. These were compared to a matched, untreated control group consisting of 75 individuals who underwent normal craniofacial growth. The control group lateral cephalometric radiographs were obtained from the Burlington Growth Collection of the American Association of Orthodontists Foundation (AAOF) Craniofacial Growth Legacy Collection. Table 3.1 shows the distribution of the sample.

Table 3.1 Distribution of the sample.

	Sex		Age (Years)		
	Male	Female	T1 (Range)	T2 (Range)	T2–T1 (Range)
Treatment (n = 102)	46	56	8.44 ± 1.19 (5.50 – 11.75)	12.57 ± 1.30 (9.42 – 15.50)	4.13 ± 1.08 (1.67 – 7.00)
Control (n = 75)	35	40	8.49 ± 1.24 (6.00 – 11.08)	12.63 ± 1.18 (9.08 – 15.42)	4.14 ± .81 (2.92 – 6.00)

3.2 Treatment Protocol

All patients in the treatment group were treated under the same clinician's two-phase protocol. The first phase involved the use of maxillary and mandibular removable expansion appliances (Figure 3.1). These appliances were typically anchored off the primary second molars, but the permanent first molars were used in cases where the primary second molars had exfoliated or were close to exfoliation. Patients were instructed to wear the appliances at least 18 hours a day. The expansion was activated by using a key to turn the jackscrews, with each turn causing a 90° rotation of the jackscrew. The jackscrew used in the upper appliance opened 0.9mm per 360° rotation, while the one in the lower appliance opened 0.35mm per 360° rotation. Parents were instructed to do one-half turn of the jackscrews (45°) every night before bed, resulting in a maxillary arch expansion rate of 0.9mm per 8 days and a slower mandibular arch expansion rate of 0.35mm per 8 days. The anterior arms of the expansion appliances were also activated by the clinician to tip and procline the incisors, creating a deliberate open bite. Because it has been reported that true mandibular rotation is greatest during the transition from late primary to early mixed dentition,[123] this was done to recreate the natural transition open bite that occurs after the primary incisors exfoliate and before the permanent incisors erupt into full contact as a child enters early mixed dentition. Fixed appliances were also occasionally used in the protocol; however, their use was minimal, limited to upper anterior bracketing to aid in esthetic control very early on in the process if needed.

Figure 3.1 Removable expansion appliances used in the first phase of the treatment protocol.

Patients were seen routinely by the clinician every two to three weeks to monitor progress and adjust the appliances as needed. This first phase would progress until the following clinical criteria were met: an intermolar width (measured between the mesiopalatal cusps of the maxillary first molars) of at least 42mm was achieved, mandibular posterior teeth were uprighted to level the curve of Wilson, and maxillary and mandibular incisors were aligned and tipped forward into a reverse curve of Spee with an anterior open bite of at least 4mm. Relative intrusion of the maxillary first molars was also done in hyperdivergent patients through sequential activation of the occlusal rest wires. Hyperdivergent children also had their maxillary primary molars extracted if they were near the end of mixed dentition, or occlusally equilibrated if they were near the beginning of their mixed dentition period.

The first phase was also supplemented by a series of daily compliance-based exercises called GOPex (good oral posture exercises). Simon Wong designed these exercises to correct orofacial posture and lay the physiologic foundation for tonal control of the oral and oropharyngeal musculature. The GOPex exercises train children to breathe through their nose only at rest, chew thoroughly with their lips together before swallowing, swallow with their tongue resting on their palate and their teeth together, and keep their mouths fully closed at rest.[7] Essentially, these exercises are designed to help children find and maintain correct oral posture; having relaxed lips in contact with teeth together lightly and the tongue resting on the roof of the mouth. Table A.1 (Appendix A) summarizes the various GOPex exercises and their objectives.

The second phase of the treatment protocol involved using the Mew Biobloc removable appliance designed to train for a closed mouth resting posture (Figure 3.2). The legs of the appliance train patients to keep their teeth in contact "voluntarily" because it becomes uncomfortable when teeth are separated. Like the expansion appliances in the first phase, this appliance also had to be worn for at least 18 hours a day. Depending on the patient's dental development stage, this appliance can have various designs. In children transitioning out of late mixed dentition at this stage, appliances would anchor on the maxillary first molars and incisors, allowing for correction of premolar and canine positions with finger springs as needed, whereas in children who were still in stable mixed dentition, the appliance would anchor off the maxillary second primary molars. When the incisors returned to contact with a more normal overbite and overjet, the posterior occlusion was refined using a new appliance anchoring off the maxillary first premolars with finger springs used to mesialize the second premolars and first molars. Once a stable occlusion was achieved, final records were taken, and the patient would enter the retention phase of treatment. Patients in the retention phase are still currently being followed-up by the clinician to monitor long-term stability.

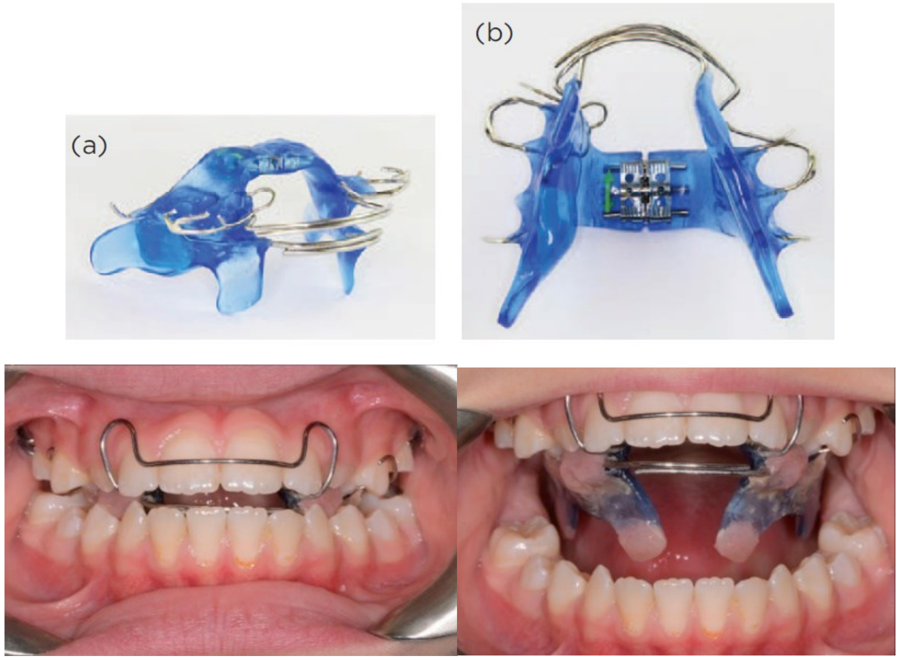

Figure 3.2 The Mew Biobloc removable appliance used in the second phase of the treatment protocol.[7]

3.3 Data Collection and Analysis

For the treatment group, lateral cephalometric radiographs were taken before treatment (T1) and at the completion of active treatment (T2). The AAOF Craniofacial Growth Legacy Collection database was thoroughly searched for the untreated control group, and the lateral cephalometric radiographs of 75 patients closely matched for age, sex, and timeframe between T1 and T2 were selected from the Burlington Growth Collection. Using the Dolphin computer software, conventional skeletal and dental landmarks were digitally traced on all cephalograms. Table B.1 and Figure B.1 (Appendix B) show examples and definitions of the cephalometric landmarks used. Before this, reliability testing was done to determine the intra-rater reliability of the chosen cephalometric measurements. Ten cephalograms were randomly selected from the treatment group and traced three times each by the same researcher. The repeated cephalometric tracings were done one week apart, in a blinded fashion.

The landmarks were used to calculate 13 linear and angular sagittal skeletal, vertical skeletal, and dental measurements (Table 3.2). Changes in these measurements (T2–T1) were then calculated and compared between the treatment and control groups. Because cephalometric studies on early treatment of hyperdivergent growth are very limited in the literature, the measurements chosen in this study were modelled after the study by Sankey et al.[4] to allow for comparisons to be drawn. However, instead of multiple different facial height measurements, our study included angular measurements of the maxillary and mandibular incisors as the treatment protocol is hypothesized to affect those.

Table 3.2 Sagittal skeletal, vertical skeletal, and dental cephalometric measurements used in the analysis.

Measurement	Definition
Sagittal Skeletal	
SNA	Angle formed between sella, nasion and A-point
SNB	Angle formed between sella, nasion and B-point
ANB	Angle formed between A-point, nasion and B-point
Mandibular body length	Linear distance from gonion to gnathion
Vertical Skeletal	
Mandibular plane angle	Angle formed between a line connecting sella to nasion and the mandibular plane (gonion to menton)
Gonial angle	Angle formed between articulare, gonion and menton
Y-Axis	Angle formed between nasion, sella and gnathion
Lower facial height	Linear distance from the anterior nasal spine to menton
Mandibular ramus height	Linear distance from articulare to gonion
Dental	
U1 to palatal plane	Angle formed between the long axis of the maxillary incisors (line from the incisal tip to the root apex) to the palatal plane (anterior nasal spine to posterior nasal spine)
L1 to mandibular plane (IMPA)	Angle formed between the long axis of the mandibular incisors (line from the incisal tip to the root apex) to the mandibular plane (gonion to menton)
Overjet	Horizontal distance between the incisal tips of the maxillary and mandibular incisors
Overbite	Vertical distance between the incisal tips of the maxillary and mandibular incisors

3.4 Statistical Analysis

Statistical analyses were completed using the IBM SPSS Statistics software version 27 with the significance level set at $\alpha = 0.05$. To assess intra-rater reliability, the intraclass correlation coefficient (ICC) was calculated for each cephalometric measurement using a single measures, two-way mixed model. Mean measurement errors were also calculated using the average differences between the repeated measurements.

This study has two explanatory variables, each with two levels: intervention (treatment and control) and sex (male and female). The T2–T1 change in each cephalometric measurement was calculated for all patients, resulting in 13 continuous response variables. Given the wide range of total treatment times in the treatment group and that time is a critical factor for growth, the difference in age between T2 and T1 (in years) was also used as a continuous covariate in this study.

Despite the control group being carefully selected to match for age, sex, and difference in time between T1 and T2 cephalograms, it is possible that there were initial differences between each group's initial cephalometric measurements that could influence the results. Therefore, before proceeding with the main statistical analysis, a preliminary MANOVA was done to assess for any initial differences between the groups at T1.

A two-way multivariate analysis of covariance (MANCOVA) was selected for the main statistical analysis to assess the difference in skeletal and dental changes between the treatment and control groups and between males and females. The following are the null hypotheses for the MANCOVA:

1. **H_0**: the combined mean change in the cephalometric measurements is the same between the treatment and control groups, after adjusting for T2–T1 difference in age.
2. **H_0**: the combined mean change in the cephalometric measurements is the same between males and females, after adjusting for T2–T1 difference in age.
3. **H_0**: there is no interaction between group and sex on the combined mean change in the cephalometric measurements, after adjusting for T2–T1 difference in age.

The model assumptions for MANCOVA were evaluated before proceeding with the analysis. Statistically significant terms in the MANCOVA model were further investigated by follow-up univariate ANCOVAs, and Bonferroni correction was used for post hoc pairwise comparisons.

Chapter 4 – Results

4.1 Intra-Rater Reliability

Table 4.1 summarizes the reliability testing results, including ICC values and mean measurement errors for each cephalometric measurement. Overall, the ICC values were consistently high, ranging from .920 to .988. Of all cephalometric measurements, the IMPA and overbite dental measurements had the highest ICC values at .988. The highest for sagittal skeletal and vertical skeletal were the SNB and mandibular plane angles at .963 and .984, respectively. SNA had the lowest overall ICC value at .920 followed by lower facial height at .940.

Mean measurement errors were also relatively low, ranging from 0.28mm (overjet) to 1.17mm (mandibular body length) for linear measurements and 0.37° (SNB) to 1.45° (upper incisor to the palatal plane) for angular measurements. In the sagittal skeletal category, mandibular body length had the highest overall mean measurement error at 1.17mm while SNB had the lowest at 0.37°. In the vertical skeletal category, gonial angle had the highest overall mean measurement error at 1.13° while Y-Axis had the lowest at 0.39°. Lastly, in the dental category, upper incisor to the palatal plane had the highest overall mean measurement error at 1.45° while overjet had the lowest at 0.28mm.

Table 4.1 Reliability testing results.

Measurement	Intraclass Correlation Coefficient [95% CI]	Mean Measurement Error
Sagittal Skeletal		
SNA (°)	.920 [.794, .977]	.73 ± .47
SNB (°)	.963 [.896, .990]	.37 ± .25
ANB (°)	.946 [.856, .985]	.62 ± .44
Mand. body length (mm)	.959 [.890, .989]	1.17 ± .58
Vertical Skeletal		
Mand. plane angle (°)	.984 [.955, .996]	.65 ± .28
Gonial angle (°)	.973 [.927, .993]	1.13 ± .31
Y-Axis (°)	.968 [.911, .991]	.39 ± .25
Lower facial height (mm)	.940 [.831, .983]	1.02 ± .48
Ramus height (mm)	.971 [.915, .992]	.79 ± .30
Dental		
U1 to palatal plane (°)	.977 [.934, .994]	1.45 ± .67
IMPA (°)	.988 [.967, .997]	1.03 ± .51
Overjet (mm)	.981 [.945, .995]	.28 ± .18
Overbite (mm)	.988 [.966, .997]	.33 ± .20

4.2 Model Assumptions

Before conducting the main statistical analysis, the model assumptions for MANCOVA were investigated. Firstly, the assumption for independent sampling is met since the data were obtained from different patients in both the treatment and control groups, and there is no indication that the data obtained from one patient influences the data obtained from another patient. Next, the linearity between all pairs of response variables, and between the covariate (Δ age) and each response variable was investigated using matrix scatterplots (Appendix C, Figure C.1). Upon visual inspection of the scatterplots, there is generally an overall linear relationship between each pair of response variables and between the covariate and response variables.

A preliminary MANCOVA was conducted with a custom model including interaction terms between the covariate and the independent variables to evaluate the homogeneity of regression slopes. There was no significant interaction between all these interaction terms (p-values > .05), indicating that the homogeneity of regression slopes assumption was met.

To indirectly evaluate multivariate normality, a boxplot was constructed with the response variables between the groups to visually assess the univariate distribution of the data (Appendix C, Figure C.2). Based on the boxplot, not all variables were normally distributed. Therefore, it was concluded that the data also did not have a multivariate normal distribution, and the multivariate normality assumption was not met. The assumption for homogeneity of variances and covariances was also violated, as assessed by Box's M test ($p < .001$) (Appendix C, Table C.2). However, it is important to note that MANCOVA is robust to violations of multivariate normality and homogeneity of variances and covariances if the groups have relatively large sample sizes of nearly equal size as they do in this case (*n* of the largest group is no more than 1.5 times that of the smallest group).

4.4 Initial Homogeneity Between the Groups

Table 4.2 summarizes the mean differences in age and the cephalometric measurements between treatment and control at T1. There were statistically significant differences in initial mandibular body lengths, lower facial heights, and ramus heights between the treatment and control groups. The treatment group had 6.61mm shorter average initial mandibular body lengths than the control group ($p < .001$). However, this difference did not reflect in any of the other sagittal skeletal measurements as there were no significant differences in SNA, SNB and ANB. The treatment group also had 5.49mm shorter average initial lower facial heights and 1.39mm shorter average initial ramus heights than the control group. However, there were no differences in the initial angular vertical skeletal measurements. There were also no significant differences in the initial dental measurements between treatment and control.

Table 4.2 Preliminary MANOVA to assess for differences between the groups at T1.

Measurement (T1)	**Mean Difference (Treatment – Control)**	**Std. Error**	**p-value**	**95% Confidence Interval for Difference**
Age (Years)	-.08	.18	.658	[-.42, .27]
Sagittal Skeletal				
SNA (°)	-.21	.54	.701	[-1.28, .86]
SNB (°)	-.36	.53	.493	[-1.40, .68]
ANB (°)	.15	.35	.676	[-.54, .83]
Mand. body length (mm)	-6.61	.65	< .001*	[-7.90, -5.33]
Vertical Skeletal				
Mand. plane angle (°)	.33	.72	.653	[-1.11, 1.76]
Gonial angle (°)	.49	.98	.617	[-1.45, 2.44]
Y-Axis (°)	.80	.51	.115	[-.20, 1.81]
Lower facial height (mm)	-5.49	.60	< .001*	[-6.68, -4.30]
Ramus height (mm)	-1.39	.56	.014*	[-2.50, -.28]
Dental				
U1 to palatal plane (°)	1.21	.98	.216	[-.72, 3.14]
IMPA (°)	-.64	.94	.500	[-2.50, 1.22]
Overjet (mm)	.06	.38	.870	[-.69, .81]
Overbite (mm)	-.09	.36	.804	[-.81, .63]

*Indicates a statistically significant difference ($p < .05$)

4.5 T2–T1 Changes in Skeletal and Dental Cephalometric Measurements

The overall descriptive statistics at T1 and T2 are summarized in Table C.1 (Appendix C). The MANCOVA (Table 4.3) showed that there was a statistically significant difference between the treatment and control groups on the combined mean change in the cephalometric measurements after controlling for the difference in age between T2 and T1 (Wilks' Lambda = .469, $F = 12.901$, $p < .001$). On the other hand, there was no statistically significant difference between males and females in the combined mean change in measurements after controlling for the difference in age between T2 and T1 (Wilks' Lambda = .935 $F = .792$, $p = .668$). Similarly, there was no statistically significant interaction between group and sex on the combined mean change in measurements after controlling for the difference in age between T2 and T1 (Wilks' Lambda = .942 $F = .707$, $p = .754$). Therefore, looking at the statistical null hypotheses in Chapter 3, there is sufficient evidence to reject the first null hypothesis, while we fail to reject the second and third null hypotheses. In other words, the combined mean change in the cephalometric measurements was not the same between the treatment and control groups but was the same between males and females, with no interaction between group and sex, after adjusting for T2–T1 difference in age.

Table 4.3 Summary of the MANCOVA test result.

Effect	Wilks' Lambda	F-statistic	Hypothesis df	Error df	p-value
Group	.469	12.901	13.000	148.000	< .001*
Sex	.935	.792	13.000	148.000	.668
Group*Sex	.942	.707	13.000	148.000	.754

*Indicates a statistically significant difference ($p < .05$)

The statistically significant term of group in the MANCOVA was further investigated by follow-up univariate ANCOVAs, and Bonferroni correction was applied to the post hoc pairwise comparisons (Table 4.4). The sagittal skeletal measurements showed a statistically significant difference in SNA but not SNB between the treatment and control groups. SNA increased by 0.97° in the control group but slightly decreased by 0.13° in the treatment group. Although the changes were minor, the overall mean difference between the groups was statistically significant, with SNA decreasing by an average of 1.09° more in the treatment group ($p < .001$). In other words, the treatment group experienced 1.09° less forward growth of the maxilla relative to the cranial base. On the other hand, although SNB did increase in both groups (1.99° in the treatment group and 1.60° in the control group), this difference was not statistically significant. There was also a statistically significant difference in ANB. ANB decreased in both groups but decreased by an average of 1.47° more in the treatment group ($p < .001$). The most significant changes were seen in mandibular body length which also increased by an average of 6.18mm in the treatment group and 6.87mm in the control group. However, the difference between the groups was not statistically significant.

Under vertical skeletal, there were statistically significant differences in gonial angle and lower facial height. Although both treatment and control had reductions in gonial angle, the gonial angle in the control group decreased more, or became more acute, by an average of 1.23° (p = .043). However, it is important to note that this finding is inconsistent with the other angular vertical skeletal measurements as there were no significant differences in mandibular plane angle or Y-Axis between the groups. As for lower facial heights, they increased in both groups, with the treatment group finishing with a 1.62mm less increase in lower facial height than the control group (p < .001). Ramus height also increased in both groups by an average of 4.27mm in the treatment group and 4.38mm in the control group, but this difference was not statistically significant.

Lastly, there were statistically significant differences in all four dental measurements, most noticeably in incisor proclination. The treatment group finished with an average of 8.49° more proclined upper incisors and 4.71° more proclined lower incisors, but 1.21mm and 1.17mm less overjet and overbite, respectively, compared to the control group (p < .001).

Table 4.4 Estimated Marginal Means of T2–T1 changes adjusted for the covariate and pairwise comparisons between the treatment and control groups with 95% confidence intervals and p-values.

	Adjusted Means ΔT2–T1				
Measurement	**Treatment (a)**	**Control (b)**	**Mean Difference (a-b) [95% CI]**	**Std. Error**	**p-value**
Sagittal Skeletal					
SNA (°)	-.13	.97	-1.09 [-1.64, -.55]	.27	< .001*
SNB (°)	1.99	1.60	.39 [-.15, .94]	.27	.154
ANB (°)	-2.11	-.65	-1.47 [-1.93, -1.00]	.23	< .001*
Mand. body length (mm)	6.18	6.87	-.69 [-1.57, .19]	.45	.123
Vertical Skeletal					
Mand. plane angle (°)	-1.66	-1.59	-.07 [-.75, .61]	.35	.841
Gonial angle (°)	-.44	-1.67	1.23 [.04, 2.41]	.60	.043*
Y-Axis (°)	-1.08	-.63	-.45 [-.96, .05]	.26	.079
Lower facial height (mm)	2.66	4.28	-1.62 [-2.28, -.97]	.33	< .001*
Ramus height (mm)	4.27	4.38	-.11 [-.85, .62]	.37	.765
Dental					
U1 to palatal plane (°)	9.03	.54	8.49 [6.32, 10.66]	1.10	< .001*
IMPA (°)	5.40	.69	4.71 [3.08, 6.34]	.83	< .001*
Overjet (mm)	-1.47	-.26	-1.21 [-1.86, -.56]	.33	< .001*
Overbite (mm)	-.26	.91	-1.17 [-1.81, -.52]	.33	< .001*

*Indicates a statistically significant difference (p < .05)

Chapter 5 – Discussion

5.1 Introduction

This retrospective cohort study investigated the skeletal and dental changes associated with a compliance-based orthotropic treatment approach with orofacial posture exercises aimed at controlling vertical facial skeletal growth in growing patients. This treatment protocol had not been previously investigated in the literature. In fact, very few studies exist concerning the early management of a hyperdivergent growth pattern. The measurements chosen in this study were modelled after the study by Sankey et al.,[4] as this was a comparable cephalometric study also investigating a novel treatment approach aimed at controlling a hyperdivergent growth pattern. However, this study included angular measurements of the maxillary and mandibular incisors instead of multiple different facial height measurements, as this treatment protocol is hypothesized to affect those too.

5.2 Method Reliability

Concerning the reliability of the chosen landmarks and cephalometric measurements, the overall ICC values ranged from .920 to .988, indicating excellent intra-rater reliability. The ICC values were comparable to the ones from the cephalometric study by Jacob and Buschang.[124] SNA had the lowest ICC value at .920, likely because A-point is challenging to see in some lateral cephalometric images, thus requiring subjectivity in determining the best position to place it. Mean measurement errors were also relatively low and matched closely to other cephalometric studies.[4,120,124] Upper incisor to the palatal plane had the highest overall mean measurement error at 1.45°, which is not unexpected given that the apex of the upper incisors (superimposition of several apices) can be challenging to distinguish in some cases. Of the vertical skeletal measurements, gonial angle had the largest error at 1.13°, also similar to the cephalometric study by Buschang et al.[96] This is likely related to the difficulty and subjectivity involved in accurately locating gonion in some cases, especially when there is a shadow of the inferior border of the mandible present on the image. This could also explain why mandibular body length had the largest measurement error of all linear measurements at 1.17mm, as this is also based on gonion's position. While some cephalometric measurements had higher errors than others, overall, the mean measurement errors were very reasonable, especially considering the high ICC values. Being able to reliably make measurements within 1.2mm or 1.5° by using landmarks on a 2-dimensional image is an acceptable level of accuracy.

5.3 Interpretation of Results – Males vs. Females

Based on the results of the statistical analyses, there was no significant difference between males and females after adjusting for the difference in age between T2 and T1. Therefore, males and females in this study experienced the same growth changes regardless of whether they were in the treatment or control group. In other words, sex did not affect the magnitude of skeletal and dental changes over time. Some previous studies in the literature support these results. Gomes and Lima[125] also found no significant differences between sexes with respect to mandibular growth during adolescence. Similarly, in the study by Trenouth et al.,[118] there was no significant difference in growth change between males and females based on their cephalometric measurements.

Furthermore, concerning mandibular rotation, Wang et al.[123] noted no sex differences in annual rates of mandibular rotation. Contrarily, although Buschang and Gandini Jr.[126] did report no significant sex difference in anterior growth displacement of the mandible in adolescents between 10 and 15 years of age, they did note some interesting significant differences between males and females. They found that males showed significantly more forward mandibular rotation and had greater ramus growth compared to females. In another cephalometric study investigating vertical craniofacial growth changes in adolescents between 10 and 15 years of age, Jacob and Buschang[124] reported that males underwent greater reductions in mandibular plane angles than females over time. They hypothesize that this could be due to differences in the development of muscle strength between males during adolescence, as weaker orofacial muscles have been associated with hyperdivergent growth. Interestingly, in a longitudinal craniofacial growth study, Chung and Wong[127] reported that while there was no significant difference between males and females in angular measurements, a significant sex difference was noted in some sagittal and vertical skeletal linear measurements. The discrepancy between these studies may be attributed to the difference in average initial ages and observation periods which can undoubtedly affect growth.

5.4 Interpretation of Results – Treatment vs. Control

5.4.1 Sagittal Skeletal and Dental Changes

With respect to sagittal skeletal changes between the treatment and control groups, there was a statistically significant difference in SNA but not SNB. Interestingly, SNA increased in the control group but decreased in the treatment group, with an overall mean difference of 1.09° greater reduction in the treatment group. This reduction in SNA also contributed to the statistically significant difference seen in ANB which decreased by 1.47° more in the treatment group. As for SNB, while it did increase in both groups, the difference was not statistically significant. In a longitudinal study on the craniofacial growth of untreated adolescents, Chung and Wong[127] also found that while SNA and SNB increased, SNB increased more, resulting in a decrease in ANB. However, in our treatment group, the reduction in ANB is not only due to an increase in SNB but also to a decrease in SNA. Furthermore, there was no significant difference in mandibular body length between treatment and control. Therefore, because there was no difference in SNB and mandibular body length, the results suggest that the treatment protocol under investigation influences the maxilla by potentially restricting forward growth of the maxilla rather than promoting forward growth of the mandible.

However, it is important to note that maxillary incisor inclination can affect SNA. Proclination of maxillary incisors with posterior displacement of the roots has been shown to cause posterior movement of A-point.[128–130] Although only one of these studies found that the posterior movement of A-point causes a significant change in SNA,[128] if A-point is posteriorly displaced due to proclined upper incisors, this could theoretically cause a slight decrease in SNA. In this study, there was a significant difference in proclination of upper incisors, with the treatment group having 8.49° more proclination of upper incisors than the control group. This was related to the mechanics used in the treatment protocol, specifically the activation of the anterior arms of the removable appliances, which caused uncontrolled tipping of the incisors. Therefore, it is a real possibility that the more significant reduction in SNA seen in the treatment group was related to posterior displacement of A-point because of upper incisor proclination, as opposed to actual true posterior displacement of the maxilla.

Furthermore, whether these changes are clinically relevant is an important consideration. Although somewhat arbitrary and subjective, it is generally accepted that changes in cephalometric measurements of at least 2° or 2mm are clinically significant. This is also an acceptable threshold to use in this study, given that it is higher than the maximum mean measurement errors. Accordingly, it is unlikely that the treatment protocol resulted in any clinically significant effects on SNA and ANB despite the statistically significant mean differences. In contrast, the increase in incisor proclination was clinically significant.

A similar effect was also seen with the mandibular incisors, although not as severe. The mandibular incisors proclined by an average of 4.71° more in the treatment group compared to the control. Incisor proclination typically results in a decrease in overbite, which could also explain why the treatment group had a statistically significant 1.17mm greater reduction in overbite than the control group. However, the treatment group also had a statistically significant 1.21mm greater overjet reduction as well. This is contrary to what was expected since overjet typically increases when upper incisors undergo greater proclination than lower incisors. This could potentially be explained by the greater reduction in ANB seen in the treatment group. That said, it is important to note that the differences in overjet and overbite are unlikely to be clinically significant. Even so, as previously explained, any measurements relying on A-point should be interpreted with caution given the difficulty in identifying A-point in some images and that incisor inclination could potentially affect the position of A-point.

Although there was no significant difference in both mandibular body lengths and ramus heights between treatment and control, it is worth mentioning that relatively large increases were seen in these measurements. Mandibular body length increased by an average of 6.18mm and 6.87mm, while ramus height increased by an average of 4.27mm and 4.38mm in the treatment and control groups, respectively. Considering that the average difference in time from T1 to T2 was about 4.13 years, the growth rates are calculated to be between 1.50-1.66mm per year for mandibular body length and between 1.03-1.06mm per year for ramus height. Comparatively, Gomes and Lima[125] reported that the growth rates were 2.16mm per year for the mandibular body length and 3.16mm per year for the ramus height. However, their study was conducted during puberty, at a time of peak growth, while ours was started on pre-pubertal patients. This could explain the differences in the magnitude of growth, especially for ramus height. Nonetheless, since these increases are expected to occur with normal growth and because there is no significant difference in the changes, it is concluded that the treatment protocol has no considerable effect on mandibular growth.

5.4.2 Vertical Skeletal Changes

As listed in Chapter 1, the primary objective and research question of this thesis was to assess for any differences in vertical growth between the treatment and control groups. Concerning the angular vertical skeletal cephalometric measurements used in this study, gonial angle was the only one with a statistically significant difference. For the treatment protocol to effectively control vertical growth, we should expect to see angular vertical measurements become more acute in the treatment group. In this study, both treatment and control had reductions in gonial angle from T1 to T2. However, gonial angles became more acute by an average of 1.23° in the control group, although not likely clinically significant. Furthermore, as reported in Chapter 4, gonial angle had a mean measurement error of 1.13°, which was the highest out of the vertical skeletal measurements. Given that the mean measurement error is almost as much as the mean difference between the groups, this result must be interpreted with caution. This result was also not supported by the other angular vertical skeletal measurements as there were no significant differences in mandibular plane angle or Y-Axis. There is conflicting information on this in the literature. Similar to our study, Jacob and Buschang[124] reported that mandibular plane angle decreases by around 1°. In contrast, Bhatia and Leighton[131] showed slight increases in mandibular plane angles in adolescents between 10 and 15 years of age.

Conversely, the linear vertical skeletal measurement of lower facial height increased in both groups. The mean difference was statistically significant with the treatment group having a 1.62mm less increase than the control group. While the angular vertical skeletal measurements do not support that the treatment protocol had any favourable effect on overall vertical growth, the mean difference in lower facial height suggests that the treatment protocol could have some advantageous effect on controlling excessive lower facial vertical skeletal growth. However, this difference, too, is likely not clinically significant. Lower facial height also had a high mean measurement error (1.02mm) relative to the mean difference. Furthermore, recalling from the preliminary MANOVA in Chapter 4 to assess for initial homogeneity between the groups, lower facial height was one of the measurements that was not the same between the groups at T1. The treatment group had an initial lower facial height that was an average of 5.49mm shorter than the control group. Therefore, for all these reasons, the result of lower facial height should also be interpreted with caution.

5.5 Comparison of Treatment Effects to Other Studies

5.5.1 Trenouth et al.[118]

Despite our treatment protocol also utilizing Mew's Biobloc appliance, these results are in contrast to the cephalometric evaluation of the Biobloc technique conducted by Trenouth et al.[118] They reported that the treatment group had no change in SNA, but a significant increase of 4.31° in SNB and a significant decrease of 4.19° in ANB. Because there was no change in SNA, they attribute the ANB correction entirely to the increase in SNB, resulting from forward positioning of the mandible. In our study however, this same functional appliance effect with the Biobloc appliance was not observed given that there was no significant change in SNB. Unfortunately, changes in mandibular body length were not measured in their study.

Similar to our study, Trenouth et al.[118] also reported significant decreases in overjet and overbite from their treatment protocol but their differences were greater, especially in overjet. The overjet in their treatment group decreased by 5.81mm more, and the overbite decreased by 1.80mm more compared to 1.21mm and 1.17mm in our study. Furthermore, while upper incisors were also proclined in their study, they only proclined by 1.71° compared to 8.49° in our study. They also reported no significant change in lower incisor proclination while the lower incisors of the treatment group in our study proclined by 4.71°. This is likely due to them not using the same mechanics used in this treatment protocol to create a deliberate anterior open bite as described in Chapter 3.

Lastly, concerning vertical changes, Trenouth et al.[118] only reported on the gonial angle. Their results for gonial angle changes mirrored ours very closely. They also noted that the gonial angle decreased in both the treatment and control, but the gonial angle in the control group decreased more (became more acute) by 1.50° compared to 1.23° in our study.

Therefore, it appears that the treatment protocol investigated by Trenouth et al.[118] resulted in greater anteroposterior skeletal changes with fewer dental side effects than the treatment protocol in our study. However, given the discrepancies between these studies, it is important to note some key differences. For example, while the treatment protocol in their study also had an expansion phase followed by a second phase with the removable Biobloc appliance designed to train for a closed mouth resting posture, they only expanded the maxilla and did not supplement treatment with orofacial posture exercises. Furthermore, although the mean treatment times were similar, the mean ages at the start of treatment were not the same. The mean age at T1 in the Trenouth et al.[118] study was 10.67 years (range of 13.67 years) compared to 8.66 years (range of 6.25 years) in our study. Their treatment group also had a significantly smaller sample size (35 patients compared to 102 in our study), and their control data was obtained using matched, normative data from another study as opposed to a true control group.

5.5.2 Sankey et al.[4]

In their approach to early treatment of vertical skeletal growth, Sankey et al.[4] investigated a non-extraction treatment approach consisting of lip seal exercises, a bonded palatal expansion appliance that also functioned as a posterior bite block, and a lower lip bumper appliance. Patients with poor masticatory muscle forces also wore a high-pull chin cup for 12 to 14 hours a day. They found that the gonial angle decreased by 1.3° more in the treatment group, resulting in a significant orthopedic effect of increased forward mandibular rotation. This contrasts our study and the study by Trenouth et al.[118] in which the gonial angle decreased more in the control groups. They also noted no significant differences in SNA and ANB, while SNB increased by 0.8° more in the treatment group. Although our study had significant differences in SNA and ANB, but not SNB, the magnitude of the differences between these two studies are more comparable than those of Trenouth et al.,[118] which reported much larger differences in SNA, SNB and ANB.

Interestingly, despite a reduction in gonial angle and forward rotation of the mandible, there was no significant difference in lower facial height between treatment and control in the study by Sankey et al.[4]. This is also in contrast to our study in which the treatment group had a statistically significant reduction in lower facial height by 1.62mm more than the control group. Although their sample size of 38 patients was also smaller than the sample size in our study, their mean treatment duration was significantly less at 1.3 years compared to 4.1 years.

5.5.3 Buschang et al.[5] and Xun et al.[97]

Buschang et al.[5] investigated orthopedic correction of growing retrognathic hyperdivergent patients using miniscrews to intrude maxillary premolars, molars, and mandibular molars. They reported that the treatment group had a significant increase in SNB by 2.1° and a decrease in mandibular plane angle by 3.9°, with the orthopedic phase of the treatment lasting an average of 1.9 years. Similarly, Xun et al.[97] also used miniscrews to intrude maxillary and mandibular posterior teeth for anterior open bite treatment and reported correction of the open bites in an average of 6.8 months. They also noted that the mandibular plane angle was reduced by 2.3°, resulting in a counterclockwise rotation of the mandible and a decrease in anterior facial height. These studies suggest that skeletal anchorage can potentially provide more significant clinical effects on managing the vertical dimension with shorter treatment lengths and requiring less patient compliance. However, it is important to note that these studies did not include long-term follow-up. Because these treatment protocols do not address etiologic factors surrounding hyperdivergent growth, the overall long-term stability of the treatment results is unknown. Furthermore, although skeletal anchorage devices have relatively low failure rates, they do not come without their drawbacks.[132] These include the surgical procedure needed to insert and remove them, added costs, and various complications such as miniscrew fracture, failure, inflammation, infection, and damage to adjacent structures.

5.6 Study Limitations and Recommendations for Future Studies

Although this study had various strengths, including a large sample size, closely matched treatment and control groups, and high intra-rater reliability with low measurement errors, some study limitations should be considered. One of the main limitations of this study is that this was a retrospective cohort study design that is highly prone to selection bias. For example, the patients in the treatment group all came from a single private practice from families motivated to go through the treatment process. The provider had lengthy conversations with these families describing the required long-term commitment level. This implies that the current results are only applicable to highly committed families. Because patients were not randomly selected to undergo this treatment, causal and population inferences cannot be made from this study. Furthermore, because the control group was obtained from a database from the 1950s, it is likely not completely representative of present-day growth as considerable secular increases in growth rates and maturation have occurred in developed countries.[133]

Secondly, 2-dimensional imaging was used in this study which has its limitations concerning the accuracy of measurements. Since lateral cephalograms are 2-dimensional images of 3-dimensional objects, superimpositions of multiple structures make it difficult to identify landmarks, which can affect the results. 3-dimensional imaging such as cone-beam computed tomography would allow for a more accurate analysis of changes but also carries more radiation exposure than a conventional digital lateral cephalogram. Furthermore, incisor proclination is associated with an increased risk of external apical root resorption.[134–137] However, root resorption is challenging to measure on 2-dimensional imaging. Because this treatment protocol was shown to cause significant proclination of incisors, root resorption could be better investigated with 3-dimensional imaging.

Another limitation of this study is related to compliance, which is a substantial component of this treatment protocol. Although the clinician assessed patient compliance levels at appointments, compliance is difficult to monitor objectively. Not only does the compliance required make this treatment protocol challenging to apply clinically to all patients, but variations in compliance among patients could certainly affect treatment outcomes. There were also wide ranges in initial ages and treatment lengths. Ages at T1 ranged from 5.50 to 11.75 years, while treatment lengths ranged from 1.67 to 7.00 years. Although we attempted to control for time by using the T2–T1 difference in age as a covariate in the statistical analyses, patients who were in treatment for a more extended period or patients whose treatment coincided more with their pubertal growth spurt will likely experience greater skeletal changes, thus affecting the results.

Minor variations in treatment protocol are also a consideration. As explained in Chapter 3, the treatment protocol had to be slightly adjusted to address specific patient needs. For example, some patients needed braces on the upper incisors while others did not. The inability to consistently provide the same treatment parameters for each patient is also a limitation that could influence the results. Lastly, as discussed in Chapter 4, despite efforts to match the control group as closely as possible to the treatment group, there were still some initial differences between the groups, which could affect the results. These were specifically with respect to mandibular body lengths, lower facial heights, and ramus heights.

For future studies, randomized clinical trials would ideally be needed to get a better idea of treatment effects and to allow for comparisons to be better drawn between different treatment methods. Efforts should be made to standardize the treatment protocol better and limit variations between patients as much as possible. Long-term follow-up should also be included to assess the stability of skeletal and dental changes over time. Lastly, cone-beam computed tomography would also be beneficial to determine skeletal and dental changes in 3-dimensions, including transverse changes, airway dimension changes, condylar changes, and potential root resorption of the incisors.

5.7 Conclusions

The overall objective of this thesis was to investigate the skeletal and dental effects of a compliance-based orthotropic treatment approach with orofacial posture exercises aimed at controlling vertical facial skeletal growth in growing individuals in the mixed dentition. The treatment group was compared to an untreated matched control group undergoing regular growth**.** Based on the results of this study, the following conclusions can be drawn to answer the research questions outlined in Chapter 1.

1. There were some statistically significant differences in vertical growth change between the treatment and control groups. The treatment group did show a greater reduction in

lower facial height, whereas the control group showed a greater reduction in gonial angle. However, these findings were not supported by the other vertical skeletal measurements and are not likely clinically significant, especially considering the long treatment lengths and factoring in measurement errors.

2. SNA and ANB decreased more in the treatment group while there were no differences in SNB and mandibular body length. However, the differences were small and likely not clinically significant, especially considering measurement errors and that incisor inclination can influence the position of A-point.
3. The treatment group had significantly more incisor proclination than the control group. This difference was clinically significant, with maxillary incisors proclining more than mandibular incisors. Overjet and overbite also decreased more in the treatment group, although these were likely not clinically significant.
4. There were no differences in skeletal and dental changes between males and females in both treatment and control groups.

In conclusion, there is insufficient evidence to conclude that this treatment protocol has a meaningful effect on sagittal skeletal, vertical skeletal or dental changes that is clinically significant. The only outcome that was assuredly clinically significant was the incisor proclination. Sex also did not have an effect on the magnitude of skeletal and dental changes. As summarized by Buschang, Sankey and English, although early treatment of a hyperdivergent growth pattern is possible in theory, "it remains poorly understood and must be approached with caution."[9] Further research with emphasis on long-term follow-up into the retention phase of treatment is planned to better assess treatment effects, as well as stability and potential consequences of early treatment.

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Appendices

Appendix A: GOPex Exercises

Table A.1 Description of the GOPex exercises used in the treatment protocol.

Objective	Exercise	Instructions
Develop nasal-only breathing and maintain a closed mouth at rest	Counting exercise	• Slowly count out loud from 1 to 60, pausing between every number to touch your teeth and lips together • After each count of 5, pause to breathe through your nose • Each time you pause for a breath, close your mouth, and breathe only through your nose • Repeat this once in the morning and once in the evening
	Reading out loud exercise	• Take at least 15 minutes each day to read out loud, pausing at each full stop in the sentence to close your mouth and breathe through your nose
Improve jaw muscle tone	Chewing exercise	• Chew thoroughly at least 15-20 times until your food liquifies • Always chew with lips together and begin your swallow with teeth touching and tongue resting on the hard palate • Reserve 2-3 minutes each meal to fully focus on chewing
	Silicone chewies exercise	• Chew on the silicone chewie supplied for this exercise • Chew hard on the chewie for 30 seconds on each side • Continue for 3 minutes
Find and maintain correct oral posture	Click exercise	• Click your tongue up against the roof of your mouth twice in a row quickly and then immediately close your mouth with teeth and lips touching, and tongue against the hard palate
	N-Spot exercise	• Say the letter “N” then close your teeth and lips together • Your tongue should be fully on the roof of your mouth with the tip touching the palatal tissue just behind the upper front teeth
	Tongue “push-ups”	• With your mouth fully closed, push your tongue firmly against the roof of your mouth • Do groups of 6 “push-ups”, 10 times a day

Appendix B: Cephalometric Landmarks

Table B.1 Description of the skeletal and dental cephalometric landmarks used in the study.

Number	Landmark	Definition
1	Sella (S)	Center of the pituitary fossa of the sphenoid bone
2	Nasion (N)	Intersection of the internasal suture with the nasofrontal suture in the midsagittal plane
3	B-point (B)	Deepest point in the concavity along the anterior border of the mandibular symphysis
4	Gnathion (Gn)	Midpoint between the most anterior and inferior points of the mandibular symphysis
5	Menton (Me)	Most inferior point of the mandibular symphysis
6	Gonion (Go)	Point at the intersection of the mandibular plane and the ramus plane
7	Articulare (Ar)	Posterior border of the neck of the condyle
8	A-point (A)	Deepest point in the concavity on the maxilla between the anterior nasal spine and the alveolus
9	Anterior nasal spine (ANS)	Tip of the anterior nasal spine
10	Posterior nasal spine (PNS)	Tip of the posterior nasal spine
11	U1 tip	Incisal tip of the maxillary central incisor
12	U1 root	Root apex of the maxillary central incisor
13	L1 tip	Incisal tip of the mandibular central incisor
14	L1 root	Root apex of the mandibular central incisor

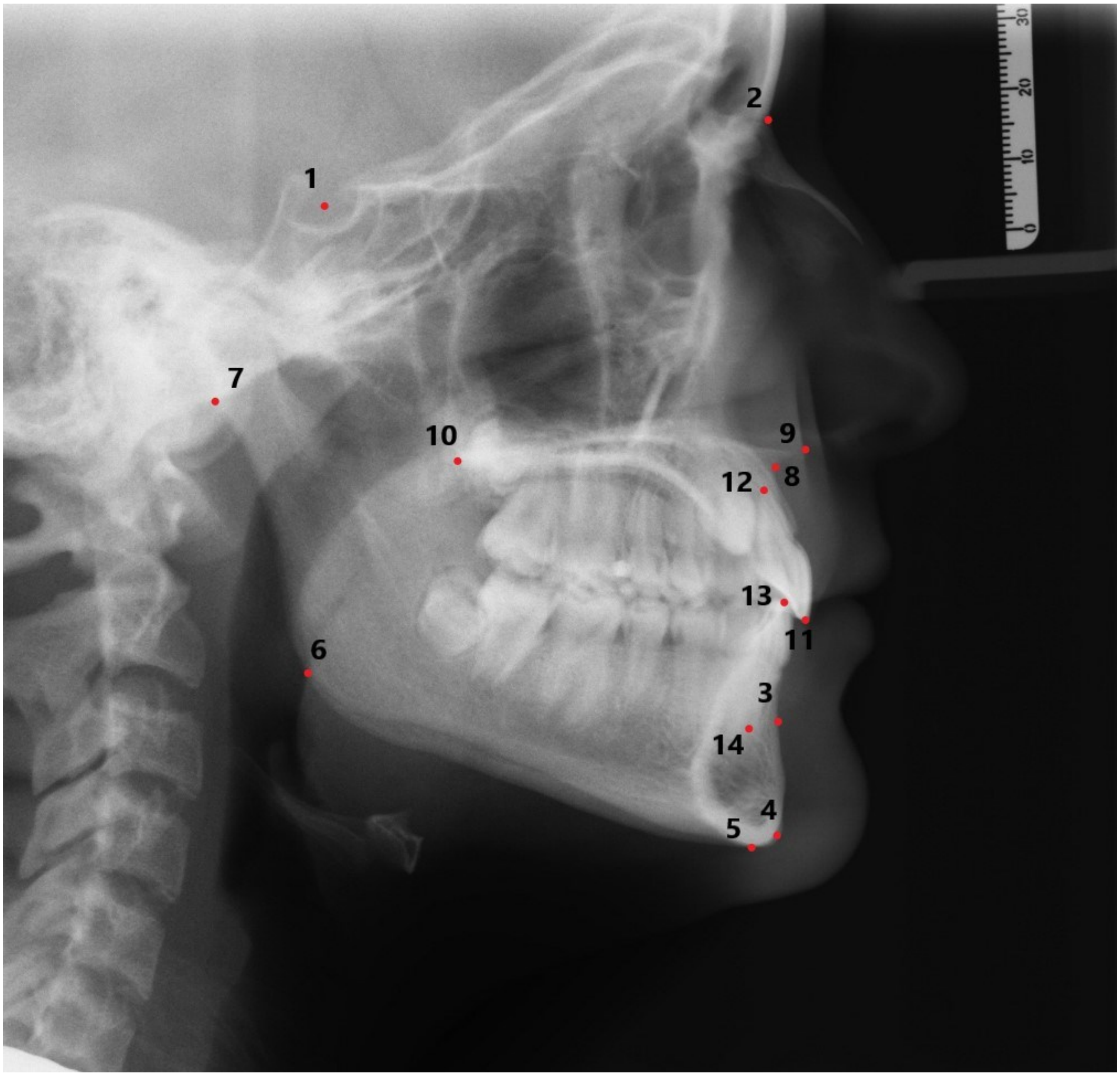

Figure B.1 Lateral cephalogram showing the landmarks (numbers correspond to the list in Table B.1).

Appendix C: Supplementary Statistics

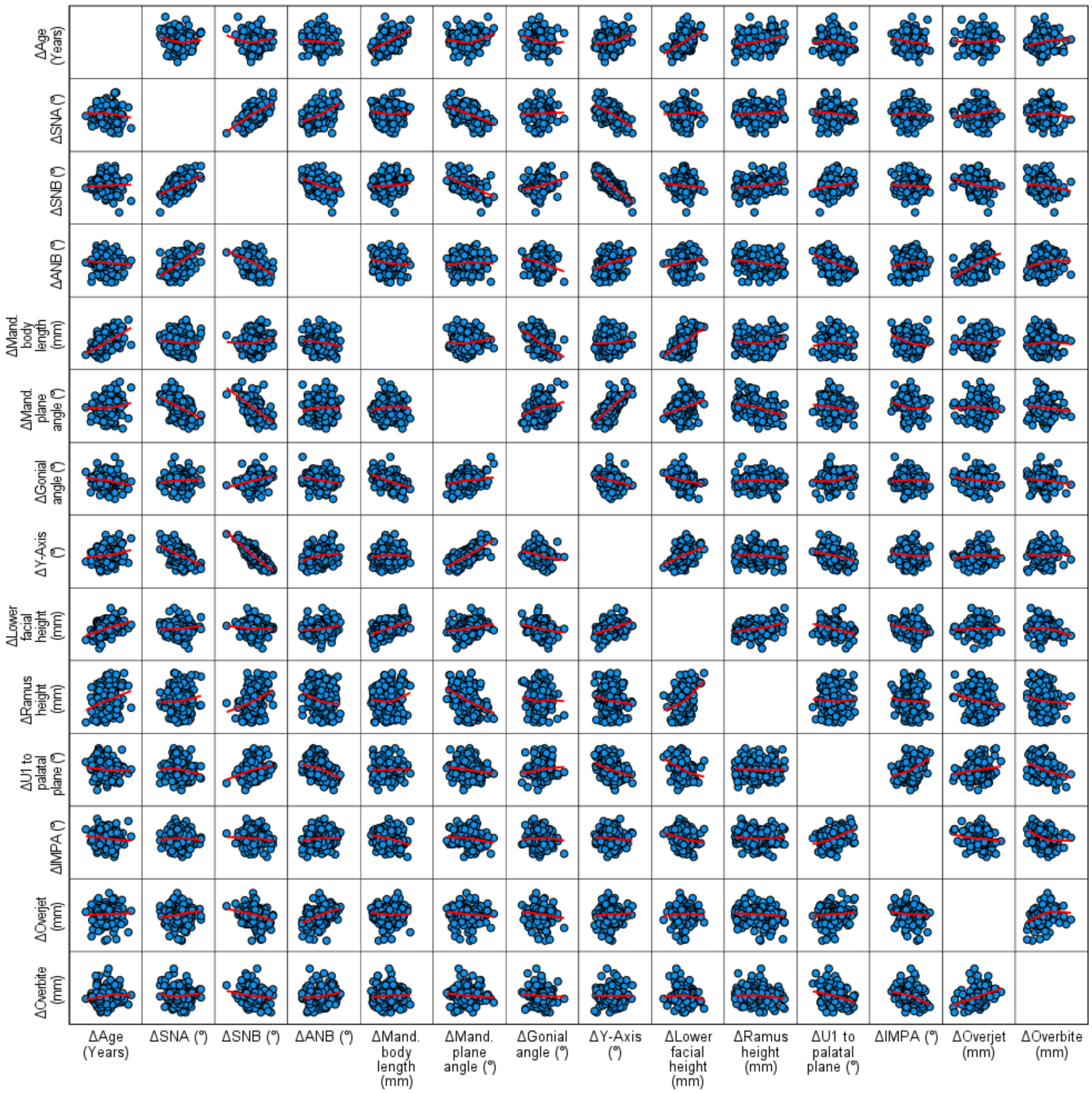

Figure C.1 Matrix scatterplots for evaluation of linearity between each pair of response variables, and between the covariate and each response variable.

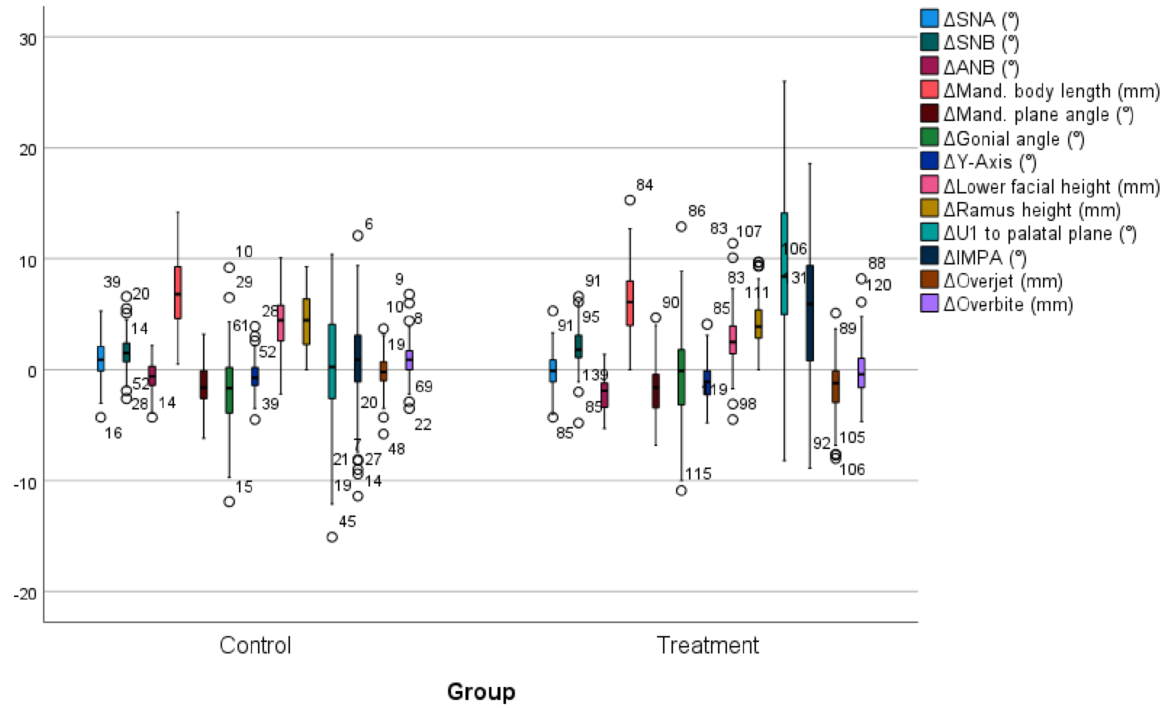

Figure C.2 Boxplot of T2–T1 changes in each response variable between the treatment and control groups.

Table C.1 Descriptive statistics showing the means and standard deviations at T1, T2, and the T2–T1 difference between the treatment and control groups.

	Treatment			**Control**		
Measurement	**T1**	**T2**	**ΔT2-T1**	**T1**	**T2**	**ΔT2-T1**
Skeletal Sagittal						
SNA (°)	80.26 ± 3.52	80.06 ± 3.58	-.19 ± 1.74	80.27 ± 3.66	81.11 ± 3.92	.84 ± 1.78
SNB (°)	75.78 ± 3.22	77.80 ± 3.08	2.02 ± 1.81	76.10 ± 3.63	77.51 ± 3.71	1.40 ± 1.82
ANB (°)	4.48 ± 2.36	2.26 ± 2.32	-2.21 ± 1.68	4.17 ± 2.17	3.59 ± 2.37	-.57 ± 1.39
Mand. body length (mm)	66.45 ± 4.02	72.63 ± 4.72	6.17 ± 3.17	73.16 ± 4.60	80.15 ± 5.49	6.99 ± 3.36
Skeletal Vertical						
Mand. plane angle (°)	36.12 ± 4.55	34.36 ± 4.68	-1.76 ± 2.25	35.91 ± 4.76	34.48 ± 4.55	-1.43 ± 2.11
Gonial angle (°)	127.64 ± 6.22	127.02 ± 6.44	-.62 ± 4.06	127.22 ± 6.54	125.37 ± 6.30	-1.85 ± 3.53
Y-Axis (°)	69.06 ± 3.19	67.94 ± 3.23	-1.12 ± 1.71	68.26 ± 3.26	67.80 ± 3.14	-.46 ± 1.66
Lower facial height (mm)	57.20 ± 3.99	59.76 ± 4.57	2.57 ± 2.35	62.69 ± 3.48	66.94 ± 4.16	4.26 ± 2.26
Ramus height (mm)	35.57 ± 2.94	39.82 ± 3.50	4.25 ± 2.24	36.94 ± 4.33	41.23 ± 4.67	4.29 ± 2.61
Dental						
U1 to palatal plane (°)	109.15 ± 6.07	117.99 ± 6.24	8.91 ± 7.95	107.94 ± 6.38	108.18 ± 6.94	.49 ± 5.26
IMPA (°)	90.57 ± 5.71	96.30 ± 6.06	5.66 ± 5.82	90.53 ± 7.31	91.46 ± 7.38	.94 ± 4.62
Overjet (mm)	4.51 ± 2.46	3.08 ± 1.11	-1.43 ± 2.35	4.45 ± 2.32	4.28 ± 1.87	-.25 ± 1.64
Overbite (mm)	1.87 ± 2.40	1.65 ± 1.30	-.19 ± 2.30	1.96 ± 2.16	2.92 ± 1.98	.92 ± 1.79

Table C.2 Box's test of equality of covariance matrices.

Box's M	**F-statistic**	**df1**	**df2**	**p-value**
452.061	1.406	273	44262.590	< .001

Table C.3 Levene's test of equality of error variances.

Measurement (T2–T1)	**F-statistic**	**df1**	**df2**	**p-value**
SNA (°)	.108	3	161	.955
SNB (°)	.634	3	161	.594
ANB (°)	1.235	3	161	.299
Mand. body length (mm)	.861	3	161	.463
Mand. plane angle (°)	1.160	3	161	.327
Gonial angle (°)	1.326	3	161	.268
Y-Axis (°)	.441	3	161	.724
Lower facial height (mm)	4.253	3	161	.006
Ramus height (mm)	.827	3	161	.481
U1 to palatal plane (°)	3.817	3	161	.011
IMPA (°)	2.621	3	161	.053
Overjet (mm)	2.468	3	161	.064
Overbite (mm)	2.563	3	161	.057