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EFFECTS OF CLASS II CORRECTORS AND FUNCTIONAL APPLIANCES ON THE PERIODONTAL HEALTH OF THE MANDIBULAR INCISORS – A PROSPECTIVE CONE-BEAM COMPUTED TOMOGRAPHY (CBCT) STUDY

By

David Charles Duevel

A THESIS

Presented to the Faculty of

the University of Nebraska Graduate College

in Partial Fulfillment of Requirements

for the Degree of Master of Science

Medical Sciences Interdepartmental Area
Oral Biology

Under the Supervision of Professor Thyagaseely (Sheela) Premaraj

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December 2018

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ACKNOWLEDGMENTS

First and foremost, I would like to thank Dr. Sheela Premaraj for her help and all of the work she put into this project. You were incredibly helpful in all aspects of this venture, including IRB submission, patient recruitment, and document revisions. Words cannot express how grateful I am for your help with this thesis.

I would also like to thank the other members of my advisory committee. Thank you Dr. Prem, Dr. Reinhardt, Dr. Giannini, Dr. Oakley, and Dr. Kim for all of the support and guidance during this process. This thesis would not have been complete without all of your valuable contributions.

There are many others at UNMC who have helped make this project come to fruition, too. Many thanks to Dr. Vishwanath, who helped with landmark analysis and cephalometric tracings. Thank you to Kim Theesen, who helped create many of the images seen in this project. I owe a great deal gratitude to our radiology techs, Karen Knap and Kathy Baker. They helped with all the cone-beam images, and their assistance was exceptional. And to Kaeli Samson, thank you for the incredible work you did for our statistical analysis. Your work was second to none, and I appreciate all of the long hours you spend on this project.

I would also like to recognize my co-residents for helping me recruit patients for this study. Without their help and support, I would not have been able to accrue enough patients to make this a worthwhile study.

And last but certainly not least, I would like to thank my parents. Mom and Dad, thank you for your unwavering support during this educational journey. Your hard work and sacrifices as parents have provided me with unrivaled educational opportunities. Thank you for pushing me to be my best, and supporting me when times were tough. I hope that I have made you proud. I love you.

EFFECTS OF CLASS II CORRECTORS AND FUNCTIONAL APPLIANCES ON THE PERIODONTAL HEALTH OF THE MANDIBULAR INCISORS – A PROSPECTIVE CONE-BEAM COMPUTED TOMOGRAPHY (CBCT) STUDY

David C. Duevel, D.D.S., M.S.

University of Nebraska, 2018

Advisor: Thyagaseely (Sheela) Premaraj, B.D.S., Ph.D.

The purpose of this investigation was to evaluate the effects of Class II correctors and functional appliances on the dentoalveolar support of the mandibular incisors during orthodontic treatment. Twenty six patients who were treated with a Forsus™, Herbst, or MARA participated this study. Lateral cephalometric radiographs, limited field-of-view CBCTs, and periodontal measurements were collected both the day of appliance activation and day of appliance deactivation. Ten hard tissue measurements on all four mandibular incisors were collected at each time point on CBCT images. Bone thickness increased at 6 and 9 mm apical from the cementoenamel junction (CEJ) on the buccal ($p=0.0005$ and $p=0.0003$, respectively) and 3 and 6 mm apical from the CEJ on the lingual ($p=0.0031$ and $p=0.021$, respectively) during treatment. No significant changes to the vertical height of buccal ($p=0.2622$) or lingual ($p=0.1145$) bone occurred during treatment. Locations and magnitudes of hard tissue changes suggest that a combination of uncontrolled tipping of the incisors and dentoalveolar bending occurs during Class II correction with these appliances. Soft tissue outcomes were difficult to ascertain, and may be related to uncontrollable hygiene variables. This study suggests that appropriate use of these appliances does not cause negative clinical or radiographic sequelae in the short-term.

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CHAPTER 1: INTRODUCTION

Orthodontic treatment has been associated with some periodontal side effects, most notably on the facial surfaces of the mandibular incisors. Some believe that it comes as a result of the amount of proclination that the lower incisors undergo during treatment (Yared et al., 2006). Patients with Class II malocclusions have lower incisors in proclined positions and Class II correction treatment modalities have been shown to predispose mandibular anterior teeth to further proclination and flaring (Basdra et al., 1996, Baysal et al., 2013, Woitchunas et al., 2012, Miller et al., 2013).

Measurement of alveolar bone levels using two-dimensional radiographs does not accurately predict the facial bone levels of lower anterior teeth. Historically, orthodontists analyzed the position and angulation of the lower incisors with the help of two-dimensional lateral cephalometric radiography (Steiner, 1960). Certain norms have been set in place that suggest the healthy positioning of the lower incisors relative to their dentoalveolar support (Tweed, 1954). However, with the recent advent and utilization of cone-beam computed tomography (CBCT) in orthodontics, changes are now able to assessed in the alveolar bone in three dimensions during orthodontic tooth movement. This technology allows for better visualization of the movements of the teeth during orthodontic therapy, and the information that is gathered from it will inevitably allow researchers to confirm or contradict some of the most closely held orthodontic principles that were based on research from two-dimensional radiography.

Bone dimensions on the facial surface of lower anterior teeth can be adequately measured using new cone-beam computed tomography (CBCT) modalities (Leung et al., 2010). Cone-beam computed tomography (CBCT) can effectively image the facial region of teeth and visualize the anatomy of the bone in three dimensions. As with any other dental radiographs, patients who undergo CBCT radiographs are exposed to radiation in areas of anatomical interest. CBCT is revolutionary because it allows for viewing an image of both hard and soft tissue in three dimensions, and thus allows for greater information gathering compared to other conventional dental radiographs that only project a two-dimensional rendering. With the advent of CBCT imaging, past research studies in orthodontics that were carried out with data gathered from 2D imaging are now given scrutiny. The arrival of 3D imaging has allowed the orthodontic profession to gather new insights into treatment of patients, and hopefully will allow for a more thorough assessment of the changes that occur in hard and soft tissues of the facial region during active orthodontic treatment.

It has also been reported that tooth movement during orthodontics and its effects on alveolar bone support can be measured and quantified using CBCT and lateral cephalometric data (Garlock et al., 2016). However, there is little to no data or information to evaluate patients who could be at risk for compromises in periodontal health with Class II malocclusions that are treated with Class II correctors. Therefore, there is a critical need to evaluate how commonly used Class II orthodontic appliances may place patients' periodontal support at risk. Herbst, MARA, and Forsus™ are all appliances that are currently used to help treat patients with Class II malocclusion, where the lower jaw is relatively posterior to the upper jaw. Herbst appliances have previously been shown to help Class II correction and did so with minimal anterior alveolar changes (Ruf et al., 1998). MARAs have been shown to effectively treat Class II malocclusion, but no data were presented on the dentoalveolar changes (Pangrazio et al., 2012). Similar to the MARA, Forsus™ appliances have benefited Class II patients, but there is limited data with regards to their effects on clinical bone support (Jones et al., 2008).

Herbst and MARA, or functional appliances, are used to facilitate/modify growth of the lower jaw when an individual is at their peak growth phase (which usually coincides with their pre-pubertal stages) by positioning the lower jaw forward. In this position, the condyles in the temporomandibular joints are brought forward and downward. Forsus™, or any other Class II corrector, can be used as an alternative to Class II elastics (Miller et al., 2013). In some cases, it is used when the patient is past pubertal growth, where the growth potential is minimal or less in magnitude (Aras et al., 2011). Forsus™, therefore will have more effect on the teeth than the jaws (Aras et al., 2011). However, all three appliances will have effects on lower teeth and the teeth will be moved forward in the lower jaw. Herbst and MARA are choices for growing patients, whereas Forsus™ is commonly used for dentoalveolar changes in correcting class II malocclusion. Growth potential is assessed by the Cervical Vertebral Maturation Stages (CVMS), which is reliant on the lateral cephalometric radiographs taken routinely for treatment of orthodontics. This assessment, along with the pre-pubertal assessment of recent observable changes in growth and changes in secondary sexual characteristics, will allow for categorizing the patients for the choice of appliance (Baccetti et al., 2005). This is routinely done in orthodontic practice for correction of class II malocclusion. The choice between a MARA or a Herbst is a clinician's preference.

The rationale for this project is that research is needed to help identify the patients who are at risk for periodontal compromises in the mandibular anterior region before the start of treatment. In addition, CBCT analysis of bone levels in the lower anterior region will be accurate and will allow for evaluating the position of the teeth in the alveolar bone in three dimensions, whereas any other routine radiographs taken during orthodontic treatment will not reveal this information. Periodontal damage can go unnoticed and patients can finish treatment with compromised periodontal health, which could have long-term effects. This study will be able to help gather data that could eventually help determine which patients could be at risk before the treatment, so that adequate measures could be taken during treatment. This research is potentially innovative because little data are available regarding the effect of Class II appliances on mandibular dentoalveolar housings even though they are some of the most commonly used orthodontic appliances today.

The purpose of this study is to use three-dimensional cone-beam computed tomography to determine whether proclination of mandibular incisors during treatment with either functional appliances or non-compliant Class II correctors affects the dentoalveolar housing.

The null hypothesis is that functional appliance and Class II corrector therapy will not compromise dentoalveolar dimensions in the mandibular incisor region.

Figure 1.1: Intraoral photographs of a MARA **(Pangrazio-Kulbersh et al., 2003)**

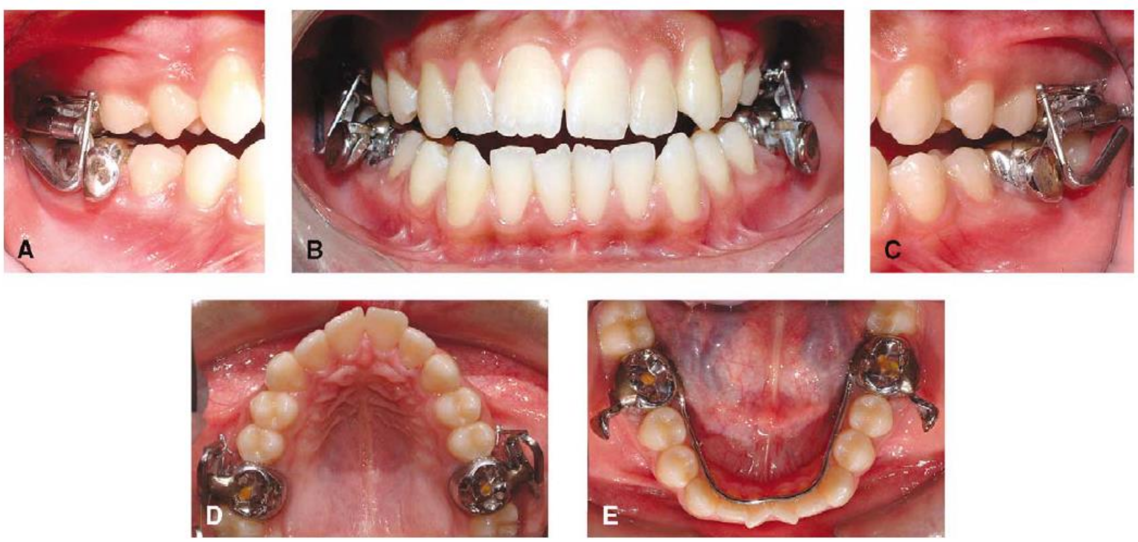


Figure 1.2: Intraoral photographs of a Herbst **(Photos courtesy of Dr. David Hamm)**

Figure 1.3: Intraoral photographs of a Forsus™ **(Miller et al., 2013)**

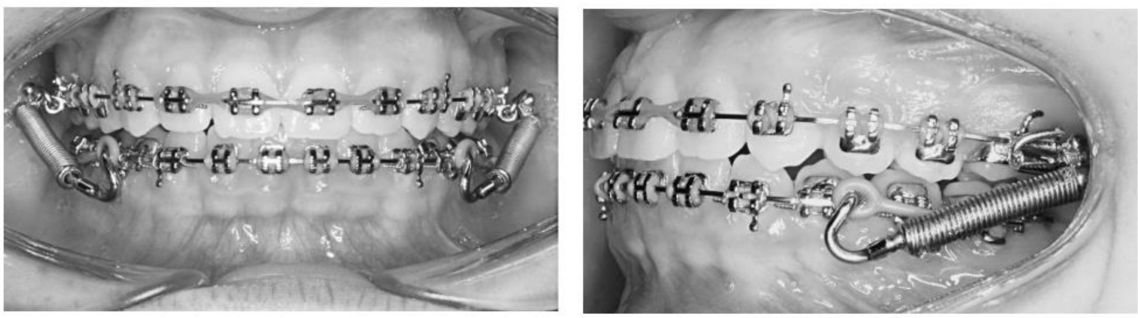
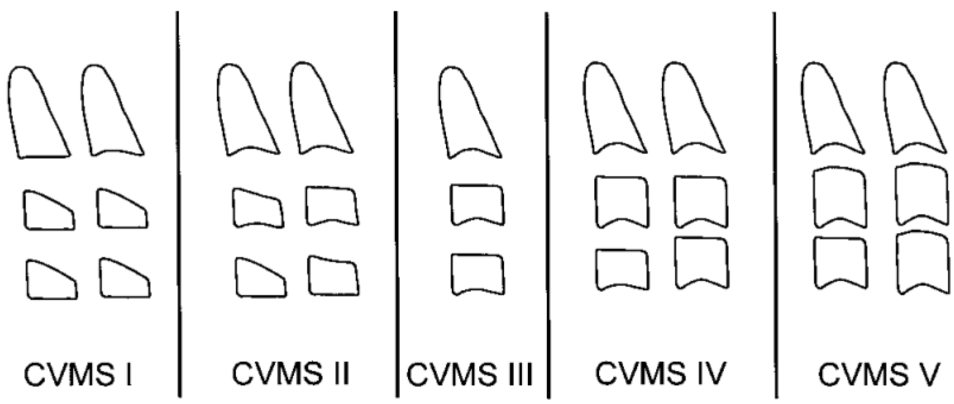


Figure 1.4: Cervical Vertebral Maturation Stages (CVMS) based on the development of cervical vertebrae C2, C3, and C4 **(Baccetti et al., 2002)**



CHAPTER 2: LITERATURE REVIEW

2.1. Class II Malocclusion

Class II malocclusion is one of the most prevalent malocclusions seen in the orthodontic office (LeCornu et al., 2013). Some estimates suggest that as high as 25-30% of the population exhibits Class II characteristics, making them a significant percentage of the patient base that is seen for orthodontic care (Perinetti et al., 2015). The Class II arch relationship can be a result of a skeletal discrepancy, a dental discrepancy, or a combination of both (McNamara, 1981). From a skeletal perspective, the maxilla can be orthognathic (normal) or prognathic (hyperplastic) and the mandible can be retrognathic (hypoplastic) or orthognathic (normal). The skeletal diagnosis of a class II could be due to problems in a single jaw or in both jaws. The most commonly found skeletal Class II relationship is a normal, or orthognathic maxilla, and a hypoplastic or retrognathic mandible (McNamara, 1981). From a dental perspective, the dental arches and teeth can be in an innate Class II position where teeth are maligned to compensate for an underlying skeletal discrepancy. In order to properly treat the cause of malocclusion, it is necessary to determine the cause of the problem.

Class II malocclusion can be further divided into two divisions: Division 1 and Division 2. Class II Division 1 patients present with flared maxillary incisors, increased overjet, and variable overbite (Bishara, 2006). Class II Division 2 patients present with retroclined maxillary incisors, decreased overjet, and increased overbite (Bishara, 2006). Obviously, both phenotypes have at least a unilateral molar relationship where the maxillary first molar is mesial to the mandibular first molar.

Patients with a Class II discrepancy, especially with an underlying skeletal issue, have some notable extraoral soft tissue features. Common characteristics of this population include a retruded or deficient chin, convex profile, everted lower lip, and acute labiomental fold (Proffit et al., 2003). Anterior facial heights can vary widely – from low mandibular plane angle, brachyfacial patterns to dolicofacial and long faced in nature (Proffit et al., 2003).

As is the case with any growth pattern, Class II growers show a constant Class II growth pattern throughout life (Bishara, 2006). This phenomenon is known as the “constancy of the facial growth pattern,” and was first reported by Brodie in the 1930s (Moore, 1959). Each patient’s growth pattern is established sometime around 3 months of life and very rarely deviates from that form in subsequent years (Hans et al., 2015). In other words, if orthodontic correction is not sought out, molar and skeletal relationships will continue to persist in a Class II fashion (Bishara, 2006). The differential growth between the maxilla and mandible may change over time, but it will not positively affect the discrepancies that create the malocclusions (Bishara, 2006). Yet, orthodontic treatment which attempts to modify growth can allow for favorable outcomes and changes (Moore, 1959).

2.2. Correction of Class II Malocclusion

2.2.1. Growth Modification

One of the most common ways to correct a Class II malocclusion in growing children and adolescents is to use growth modification. Growth modification involves restricting or stimulating growth preferentially to correct a skeletal or dental discrepancy (Proffit et al., 2013).

Growth modification for Class II patients consists of either an extraoral headgear appliance or an intraoral functional appliance (Proffit et al., 2013). Headgear is used to restrict maxillary growth, and thus is beneficial in a situation where a patient’s Class II pattern is the result of maxillary excess (Proffit et al., 2013). Conversely, functional appliances protrude and position the mandible in a forward position and would best be utilized in a situation when mandibular retrognathism is diagnosed (Proffit et al., 2013). In either case, these appliances are used in growing children and adolescents to modify their remaining growth potential in a manner that will help correct the underlying Class II pattern.

Growth modification appliances apply forces on the teeth and the jaws. Over an extended period of time, the forces from these appliances allow for modeling and remodeling of bone to occur (LeCornu et al., 2013). Specifically in the case of functional appliances like the Herbst and MARA, remodeling at the condyle and glenoid fossa is seen in a manner that is conducive to Class II correction (LeCornu et al., 2013). Three-dimensional imaging allows for us to evaluate the changes that have occurred in all three planes by superimposing pre-treatment and post-treatment radiographs. Recent studies in patients treated with Herbst appliances have shown that the glenoid fossa models anteriorly, leading to a more protruded mandible (LeCornu et al., 2013). In addition, increased condylar and ramal growth have been demonstrated in patients treated with functional appliances (Souki et al., 2017). Overall, appropriate intervention with functional appliances on growing patients could bring forth distinct modeling to correct the jaw discrepancies.

One of the most important concepts to grasp when discussing growth modification by functional appliances is that final mandibular growth and magnitude is no different than if an appliance was not used at all (Proffit et al., 2013). The use of a functional appliance stimulates growth in a manner that allows for the mandible to reach peak growth potential and size faster than usual, but does not ultimately “grow” the jaw to a magnitude that would not have been otherwise unattainable (Proffit et al., 2013). One distinction that should be noted is that functional appliances not only affect mandibular growth, but they also restrict maxillary growth in a “headgear-like” fashion. With the combination of mandibular protrusion and growth and maxillary restriction, a Class II discrepancy can be corrected and maintained in a favorable fashion (Proffit et al., 2013).

2.2.2. Dentoalveolar Compensation

A commonly utilized orthodontic method to correct malocclusions is by dentoalveolar compensation. Dentoalveolar compensation is the process by which the teeth and alveolar housings are modified to correct underlying skeletal discrepancies (Ceylan et al., 2003). Simply put, the correction of an orthodontic problem almost entirely by the movement of teeth is a hallmark of dentoalveolar compensation.

Dentoalveolar compensation to correct arch discrepancy occurs when a Class II malocclusion is treated with Class II elastics. Serial cephalometric studies show that treatment with Class II elastics mostly produced dental changes. During Class II correction with elastics, overjet was corrected by 71% dentoalveolar changes and 29% skeletal changes (Janson et al., 2013). Though the movement of the teeth relative to each arch can allow for correction of molar relationships and overjet discrepancies, Class II elastic therapy is well known to produce dentoalveolar side effects, including lower incisor flaring, occlusal table rotation, and anchorage loss (Janson et al., 2013).

2.2.3. Extraction Orthodontics

Another option for correction of an arch discrepancy is by removing teeth. When dental changes remedy a skeletal discrepancy, orthodontic camouflage occurs. Moreover, one of the most common ways in orthodontics to camouflage a malocclusion is via extraction therapy. Extraction treatment to correct Class II malocclusion usually involves the removal of two teeth (two maxillary premolars) or four teeth (two maxillary premolars and two mandibular premolars) (Janson et al., 2004). The extraction pattern involving two teeth would finish with a molar occlusion of Class II, whereas a four tooth extraction pattern results in a final molar occlusion of Class I. The reasoning for extraction patterns is highly individualized, and can be dependent on many factors, including but not limited to, growth potential of the patient, crowding, overbite and overjet, anchorage requirements, and cephalometric discrepancy (Janson et al., 2004). As an example, in a patient with increased overjet and a Class II molar relationship, an appropriate treatment plan may include extraction of upper premolars and retraction of the upper canines and incisors to resolve the overjet (Proffit et al., 2013). With that being said, much more diagnostic information and treatment planning would have to occur to make sure that the extraction camouflage plan would not deleteriously affect function, esthetics, or tissue health (Proffit et al., 2013).

Another possibility, though rare, is the extraction of second molars. The argument for extraction of second molars instead of premolars is that the extraction of these teeth not only helps alleviate crowding and occlusal discrepancies, but also creates enough space in the arch to accommodate 3rd molar eruption (Basdra et al., 1996). When there are other orthodontic problems to be solved other than just an anterior-posterior discrepancy (e.g. crowding), extraction therapy may be necessary regardless and could potentially decrease the overall time of treatment (Janson et al., 2007).

One of the commonly debated aspects of extraction therapy involves the effect of extractions on extraoral soft tissue structures and the patient's profile. Overall, there is data to support that the patients who undergo extraction therapy do indeed end up with more upright incisors, more retrusive lips, and flatter profiles; however, overall these changes do not seem to cause negative esthetic effects (Bishara, 2006). When comparing profiles of patients that had no extractions, two premolars extracted, and four premolars extracted, it appears that the four premolar extraction plan may have the most effect on soft tissue, though overall the effects may be limited (Janson et al., 2015).

2.2.4. Orthognathic Surgery

Orthognathic surgery in conjunction with comprehensive orthodontic therapy is another treatment option for Class II patients seeking treatment. It is estimated that among all orthodontic patients (Class I, II, and III), roughly 5% should be candidates for orthodontics in conjunction with orthognathic surgery (Proffit et al., 2003). In a recent study, roughly 3.6% of 8-11 year olds, 3.7% of 12-17 year olds, and 4.3% of 18-50 year olds displayed a severe or extreme overjet (greater than 7mm) (Proffit et al., 2013). This increased overjet suggested that these Class II patterns might warrant surgical correction.

In the case of Class II patients, the skeletal discrepancy may arise as a mandibular deficiency, and maxillary excess, or a combination of both (Hupp, 2014). When a mandibular deficiency is noted, the gold standard of treatment currently involves a mandibular advancement with a bilateral sagittal split osteotomy (BSSO) (Hupp, 2014). Often times in severe retrognathic patients a mandibular advancement will correct the occlusal discrepancy, but it does not always help improve chin projection. Adjunctive genioplasty or rhinoplasty surgeries may be needed in those situations to help create a more esthetically pleasing profile (Proffit et al., 2003). In the case of maxillary excess, a maxillary setback or osteotomy may be a solution (Hupp, 2014). However, due to the potential for airway restriction during jaw setback surgeries, this may be contraindicated (Tselnik & Pogrel, 2000). Setback surgeries are also lower on the hierarchy of long-term stability, and the potential for relapse in these situations should be assessed (Bailey et al., 2004).

Most comorbidities of Class II orthognathic surgeries are related to the mandibular surgeries. Mandibular surgeries can involve both intraoral and extraoral incisions, which can lead to injuries to the facial nerves, trigeminal nerves, bleeding complications, as well as the potential for facial scarring (Hupp, 2014, Proffit et al., 2003). Due to the highly vascularized nature of the maxilla and the maxillary surgery being mostly intraoral, there are usually fewer complications during these surgeries (Hupp, 2014).

Remaining growth potential and facial esthetic outcome goals should be determined while planning for surgery. Surgery should be delayed until the patient is done growing in cases where the patient displays growth that is excessive; whereas surgery can be done much earlier in patients where growth is deficient (Hupp, 2014). If patient esthetics or a convex profile is of upmost importance or concern, then surgical correction should be considered preferentially to growth modification (Ruf & Pancherz, 1999).

2.3. Class II Correction by Growth Modification and Functional Appliances

2.3.1. Skeletal and Dental Effects

During functional appliance therapy, jaw discrepancies can be overcome by a combination of skeletal and dental changes. When the initial studies on functional appliances by Pancherz and others were originally published, there was great enthusiasm due to the data reflecting notable skeletal change. His preliminary data suggested that changes occurring in overjet were about 56% due to skeletal changes and about 44% due to dental changes (Pancherz, 1982). In the molar region, 43% of correction was due to skeletal change, and 57% was due to dental changes (Pancherz, 1982). As more data became available, Pancherz published papers suggesting that his original data may have been skewed towards more skeletal changes than what were actually occurring (Ruf & Pancherz, 1999). His group’s follow-up study shows that overjet was corrected roughly by an average of 30.5% skeletal change and by an average of 69.5% dental change (Ruf & Pancherz, 1999). In the molar region, they determined that the average correction was 33% skeletal and 67% dental in nature (Ruf & Pancherz, 1999). These follow-up studies also noted that some relapse did occur, and it was often related to the amount of dental changes that happened during Herbst therapy (Pancherz, 1991).

Pancherz’s more recent and modified study may have some more validity, as other studies recently confirmed his findings (Baysal & Uysal, 2014). A study of 20 Herbst patients found that 37% of molar correction was skeletal, and 63% of molar correction was dental (Baysal & Uysal, 2014). In the anterior region, overjet was corrected by 29% skeletal changes and by 71% dental changes (Baysal & Uysal, 2014). Another study of 22 patients revealed that overjet correction was 66% dental and 34% skeletal. That same study found that molar relationship correction was 64% dental and 36% skeletal (Wigal et al., 2011). Based on the long-term data that is currently available, it is reasonable to conclude that about 1/3 of Class II correction by functional appliances in growing patients is due to skeletal changes, and 2/3 of correction is achieved by dentoalveolar compensation.

For the most part, similar functional appliances create similar skeletal and dental changes. Studies comparing MARA and Herbst appliances show reasonably comparable outcomes when analyzing general dental and skeletal effects (Pangrazio-Kulbersh et al., 2003). To some degree, both maxillary and mandibular skeletal effects are seen in these appliances reflecting a maxillary headgear effect and mandibular elongation (Ghislanzoni et al., 2011). The skeletal changes are maintained by modeling of the condyle and the glenoid fossa (Al-Jewair, 2015). Dental effects include distal movement of the maxillary teeth, mesial movement of the mandibular teeth, and proclination of the lower incisors (Pancherz, 1997).

2.3.2. Extraoral Soft Tissue Effects

Extraoral soft tissue changes occur frequently and notably in patients that undergo growth modification by functional appliances. Classical Herbst studies depict decreased facial convexity in both adolescences and young adults who completed orthodontic treatment (Ruf & Pancherz, 1999). Furthermore, notable outcomes include upper lip retrusion and lower lip and chin protrusion (Rego et al., 2017). A systematic review assessing soft tissue change in functional appliances found similar results but noted that the available papers were lacking and weak in evidence (Flores-Mir et al., 2006). An increase in lower facial height was also a common theme seen in patients treated with Herbst appliance (Baccetti et al., 2009).

In all, though, the changes in extraoral soft tissues may be relatively small. In a study where dental students, art students, and parents of orthodontic patients rated facial change and attractiveness, profiles were rated as improved only 2/3rds to 3/4ths of the time (O'Neill et al., 2000). More significantly, this change was not significantly different from those patients that did not undergo functional appliance therapy, and thus the authors warned against making promises to patients with regards to positive effects on profile after functional appliance therapy (O'Neill et al., 2000).

2.4. Class II Correction Using Non-Compliant Class II Correctors

2.4.1. Skeletal and Dental Effects

Non-compliant Class II correctors such as the Forsus™ are known to induce lower incisor proclination (Zymperdikas et al., 2016). In fact, when compared to fixed functional appliances, these subtype of Class II correctors have been shown to produce the most lower incisor proclination during treatment (Zymperdikas et al., 2016). Some groups have found average proclination of lower incisors after just a few months of therapy to be in the range of 11 degrees of proclination (Ali Gunaya et al., 2011).

Studies similar to the original Pancherz work concludes that almost all overjet and molar correction that occurs with Forsus™ and similar appliances is due to dental changes (Aslan et al., 2014). Other studies have also found that the Forsus™ appliance does not show as much mandibular skeletal growth as is seen in functional appliances such as the Herbst (Aras et al., 2011). When compared to removable functional appliances, such as the Twin Block, the Forsus™ did not show as much relative skeletal change (Giuntini et al., 2015). One group’s working hypothesis is that the Forsus™ springs are not rigid enough to consistently deliver the forces needed to maintain mandibular protrusion, which is ultimately needed to provide condylar remodeling and mandibular growth (Aras et al., 2011). Other groups suggest that the negligible amount of skeletal changes seen in Forsus™ appliance therapy may be due to the minimal amount of time (less than 6 months) that the appliance is active (Franchi et al., 2011).

Another notable effect of the Forsus™ appliance is its ability to tip the occlusal plane (Karacay et al., 2006). Rotation of the mandible is often seen, and the occlusal plane is thus rotated backwards (Servello et al., 2015). In some studies, the occlusal plane changes can average almost 5 degrees in a clockwise fashion (Ali Gunaya et al., 2011).

2.4.2. Extraoral Soft Tissue Effects

Because Forsus^{TM} appliances do not produce a notable skeletal change, it would be reasonable to assume that extraoral soft tissues effects are consequently minimal. Perhaps the most significant soft tissues changes from Forsus^{TM} therapy occurs at the lips (Ali Gunaya et al., 2011). The retraction of the upper incisors and proclination of the lower incisors during treatment causes the upper lip to become less procumbent, and a decrease in lower lip entrapment (Ali Gunaya et al., 2011). If minimal skeletal changes do occur, the improvement in soft tissue pogonion and the protrusion of the lower lip due to lower incisor position would also improve a Class II profile (Karacay et al., 2006). All of these aforementioned soft tissue changes would be considered esthetically favorable.

2.5. Mandibular Incisor Proclination during Class II Correction

Historically, orthodontists used a lateral cephalometric radiograph to diagnose and treatment plan malocclusions (Steiner, 1960). One of the many facets of this process includes analyzing lower incisor position and proclination. Perhaps one of the most well known measurements for lower incisor position is the angulation between the lower incisor and the mandibular plane, or the Incisor to Mandibular Plane Angle (IMPA). Charles Tweed proposed that the average value of this angle should be kept at around 90 degrees, and this has been accepted as a goal for incisor angulation since (Tweed, 1954).

There is good long-term data to suggest that lower incisor proclination occurs during functional appliance therapy. Pancherz et al. found an average increase of IMPA to be around 5.2 degrees (Pancherz & Bjerklin, 2014). Ruf et al. analyzed 98 Herbst patients (392 lower incisors) and determined that the average proclination was 8.9 degrees, but ranged widely from 0.5 to 19.5 degrees (Ruf et al., 1998). Rodrigues et al. found it to be around 5.0 degrees, Valant et al. at 2.5

degrees, Wigal et al. found it to be 7.6 degrees, and Hansen et al. determined that the average proclination to be about 11 degrees (Rodrigues de Almeida et al., 2005, Valant & Sinclair, 1989, Hansen, 2003, Wigal et al., 2011). Overall, there is a general agreement that significant dentoalveolar compensation occurs at the lower incisors during functional appliance therapy.

Data for Forsus™ appliances is more limited since they are a newer appliance, but the available data suggests that Forsus™ does increase the lower incisor proclination (Aslan et al., 2014). Aslan et al. reported an average of 9.3 degrees of proclination after Forsus™ correction (Aslan et al., 2014). Another group found similar results, noting that their data demonstrated an average of 10.7 degrees (Ali Gunaya et al., 2011). Franchi found 5.4 degrees of proclination (Franchi et al., 2011). One group noted that the longer a Forsus™ appliance was active, the more lower incisor proclination was seen (Miller et al., 2013). Overall, it is apparent that lower incisor proclination readily occurs during Forsus™ therapy.

Because Forsus™ is a non-compliant appliance alternative to Class II elastics, it is important to compare the two treatment modalities. In a study comparing the effectiveness of a Forsus™ appliance against compliant Class II elastic wear, it was shown that lower incisors proclined 2.5 degrees more in the Forsus™ group (6.3 degrees increase with Forsus™, 3.8 degree increase with elastics) (Jones et al., 2008). However, this difference in proclination change between the two groups was not found to be statistically significant (Jones et al., 2008).

A final point that needs to be made regarding Class II correction is that relapse does occur (Hansen, 2003). Some degree of lower incisor proclination does rebound after the appliances are removed (Pancherz & Bjerklin, 2014). One study estimated incisor rebound to occur as much as 63% (Pancherz & Bjerklin, 2014). It has been suggested that relapse potential can be decreased by maintaining the appliance in for a long enough timeframe to allow for adequate bone modeling (LeCornu et al., 2013). Another opinion is that relapse will be minimized if the appliance therapy is adequately timed with pubertal growth (Baccetti et al., 2009).

2.6. Effects of Orthodontic Tooth Movement on Normal Periodontium

There is a fair amount of data available that assesses how orthodontic tooth movement affects the periodontal support; however, the results and conclusions of these studies are often conflicting. The two outcomes of these types of studies are that orthodontic tooth movement either does or does not cause periodontal compromises.

Some data suggests that the proclination of teeth (especially those >95 degrees) and thin gingival tissues (<0.5 mm in thickness) were correlated with more recession in adults who competed orthodontic treatment (Yared et al., 2006). Yet, this same study could not find other correlations to common clinical diagnostics such as recession or keratinized gingiva (Yared et al., 2006).

Another group found a statistically significant difference in gingival recession occurring in orthodontic patients but warned that the difference may not be clinically relevant (Joss-Vassalli et al., 2010). This same group suggested that orthodontists should focus less on the final inclination of the teeth, and more on the change in inclination during treatment (Joss-Vassalli et al., 2010). In contrast, Djeu et al. reported that the degree of proclination was not associated with increased gingival recession of clinical crown length (Djeu et al., 2002). However, it also has been shown that increased recession occurred in lingually tipped, or retroclined, lower incisors (Vasconcelos et al., 2012). This finding was interesting and contrary to other data, but definitely worth noting.

Another confounding factor to the situation of orthodontic treatment affecting periodontal support is the underlying factor that there may be minimal to no bone support in the incisor region before orthodontic tooth movement begins (Wehrbein et al., 1996). Obviously, a lack of bone support will not be amendable to favorable orthodontic outcomes. The age at which orthodontic treatment began may also have some role in post-treatment recession risk, as older patients seem to be at greater danger for periodontal defects (Renkema et al., 2013). While orthodontics may play a role in the development of localized recession, other factors such as gingival inflammation and biotype cannot be overlooked (Slutzkey & Levin, 2008).

Arguably, the most comprehensive review of effects of orthodontic treatment on periodontal health comes from a JADA Systematic Review published in 2008 (Bollen et al., 2008). Twelve studies were included in this review, and outcomes that were analyzed included pocket depths, gingivitis, alveolar bone loss, periodontal pocket depth, gingival recession, and attachment loss (Bollen et al., 2008). After analyzing the data, the researchers could not find a positive correlation or effect of orthodontic tooth movement on periodontal outcomes (Bollen et al., 2008). To date, this systematic review may be the strongest evidence to suggest that conventional orthodontic treatment may not cause negative periodontal sequelae.

With regards to periodontal concerns specifically arising from Class II correctors and functional appliances, there is some data to suggest the effects may be minimal. Ruf et al. completed one of the most comprehensive studies on lower incisor proclination in 1998. That group analyzed 392 lower incisors from 98 patients treated with Herbst appliances and found that 97% of teeth showed no signs of increased recession (Ruf et al., 1998). Of the 3% of teeth that showed recession, the average change was 0.4 mm (Ruf et al., 1998). Their overall conclusion was that proclination of lower incisors in growing children did not seem to cause gingival issues (Ruf et al., 1998).

2.7. Assessment of Periodontium by Cone-Beam Computed Tomography

Within the last decade, the dental and orthodontic fields implemented the use of CBCT for diagnosis, treatment planning, and various research endeavors. Measuring alveolar bone levels using two-dimensional radiographs, such as lateral cephalometric radiographs, will not accurately predict the facial bone levels of lower anterior teeth. But with new cone-beam computed tomography (CBCT) modalities, bone dimensions can be adequately measured in this region (Leung et al., 2010). The best imaging occurs in the cases where the voxel size can be significantly minimized (Patcas et al., 2012). Furthermore, CBCT data has been shown to be accurate at measuring bone magnitude up to 0.1 to 0.2 mm (Molen, 2010).

While CBCT data is intriguing, some authors argue that it may still have some issues in overestimating bone loss and fenestrations (Sun et al., 2011). Specifically, at larger voxel sizes (like 0.4 mm), some changes in bone thickness may be misjudged by up to 1.5 mm (Patcas et al., 2012). Yet, it was found that when the voxel size was decreased to 0.25 mm or less, the accuracy was significantly increased (Sun et al., 2011). However, CBCT images are better for measuring bone heights compared to bone thickness (Timock et al., 2011).

CBCT studies on bone level and support in the lower incisor region suggest that the alveolar housing is thin and predisposed to potential issues (Gracco et al., 2010). Particularly worrisome alveolar units are seen in patients with a symphysis that is thin and long, as they were found to be at a higher risk for bone loss after orthodontic tooth movement (Gracco et al., 2010). Dehiscence and fenestrations are known to be more frequent in these patients with a narrow symphysis, too (Gutermann et al., 2014). Other groups noted that patients with a high angle, Class II malocclusions carry this thinner symphysis structure, and may have less mandibular incisor support (Baysal et al., 2013). These hyperdivergent patients need to be adequately diagnosed to not compromise the lower incisor bone support during treatment (Yagci et al., 2012).

A very recent study similar to ours analyzed bone support changes in patients that underwent comprehensive orthodontic therapy (Garlock et al., 2016). Their data was useful for two reasons. First, it confirmed the previous findings that CBCT can reliably be used to describe bony changes that occur during orthodontic treatment. Second, it showed that the level of bone support after orthodontic therapy was more dependent on the pre-treatment support than on the changes in proclination during treatment (Garlock et al., 2016).

CHAPTER 3: SPECIFIC AIMS & RESEARCH HYPOTHESES

3.1. Statement of the Problem

Proclination of lower incisors frequently occurs during orthodontic treatment with functional appliances and Class II correctors. Even though the degree of proclination during treatment can be quantified by two-dimensional angular and linear measurements, clinically relevant changes that are occurring in the dentoalveolar support during orthodontic treatment have yet to be studied in detail. However, with the recent advent of three-dimensional CBCT radiography, one can more accurately measure the changes in the bone support that occur over time. Since this technology is readily available and reliable, it could be utilized to investigate what occurs locally in the mandibular incisor region during orthodontic therapy. This knowledge is essential to predict what changes will occur in the dentoalveolar subunit in patients who are being treated with functional appliances and Class II correctors.

3.2. Central Research Hypothesis

The central research hypothesis is that functional appliance and Class II corrector therapy will not compromise dentoalveolar dimensions in the mandibular incisor region, namely the loss of soft tissue or hard tissue height or thickness.

3.3. Specific Aims

1) To determine how appliance-mediated proclination of mandibular incisors affects bone levels and support.

2) To determine how appliance-mediated proclination of mandibular incisors affects clinical periodontal characteristics.

CHAPTER 4: MATERIALS & METHODS

4.1. Study Design

This study is a prospective, descriptive clinical trial approved by the University of Nebraska Medical Center Institutional Review Board (#667-16-FB). When patients of the Graduate Orthodontic clinic at the University of Nebraska Medical Center College of Dentistry begin orthodontic treatment, they undergo a records appointment including an intraoral and extraoral exam, intraoral and extraoral photographs, a lateral cephalometric radiograph, a pantomograph, and study models. The information from these records is then used to put together a comprehensive orthodontic treatment plan. Patients between the ages of 8 to 18 years old with a treatment plan including the use of a functional appliance or Class II corrector were recruited for this study. Inclusion criteria for this study included any orthodontic patients, aged 8 to 18 years old that have a treatment plan that includes the use of a functional appliance (Herbst or MARA) or a Class II corrector (Forsus™). Exclusion criteria included any patients who did not have a treatment plan that includes these appliances, pregnant patients, patients with recognized and/or diagnosed periodontal conditions, or patients that do not speak English or Spanish (due to informed consent limitations).

Patients who were treatment planned for a Forsus™ were up to a half step Class II molar relationship and may or may not have growth potential (as determined by CVMS methods). The protocol for delivering a Herbst or MARA appliance was that the patient was greater or equal to a half step Class II molar and had growth potential (as determined by CVMS methods). The decision to place a Herbst or MARA appliance was based on faculty preference.

Data from the patients enrolled in the study was collected on the day that the appliance was activated and the day that the appliance was deactivated. At both these time points, records taken included a lateral cephalometric radiograph, a small field-of-view CBCT (FOV from LL3-LR3 only), and periodontal measurements. The periodontal measurements included probing depths, keratinized gingiva, and gingival biotype. Experimental design was based on a previous study by Garlock et al., which utilized CBCT to analyze changes at the lower incisors occurring during orthodontic tooth movement (Garlock et al., 2016).

In situations where an adjunct edgewise appliance was placed with the Class II corrector (e.g. Forsus^{TM}), the orthodontic wires and bracket position were not allowed to be changed from the initial to final time points. In cases where an adjunct edgewise appliance was not initially present when the functional appliance was activated, bonding of brackets and placement of wires was not allowed between the initial and final time points.

Functional appliances (MARA and Herbst) are commonly active for 8-12 months, so that was the goal for our treatment period (Pancherz, 1997, Pangrazio-Kulbersh et al., 2003, McSherry & Bradley, 2000). Class II correctors (Forsus^{TM}) are removed upon achieving hyper-Class I buccal occlusion, so the amount of time these appliances were active was dependent on the time it took to achieve molar and canine correction. Patients in both groups were corrected to a hyper-Class I occlusion, accommodating for relapse that is known to occur when the appliances are removed (Pancherz, 1991).

4.2. Cone-Beam Computed Tomography (CBCT) Measurements

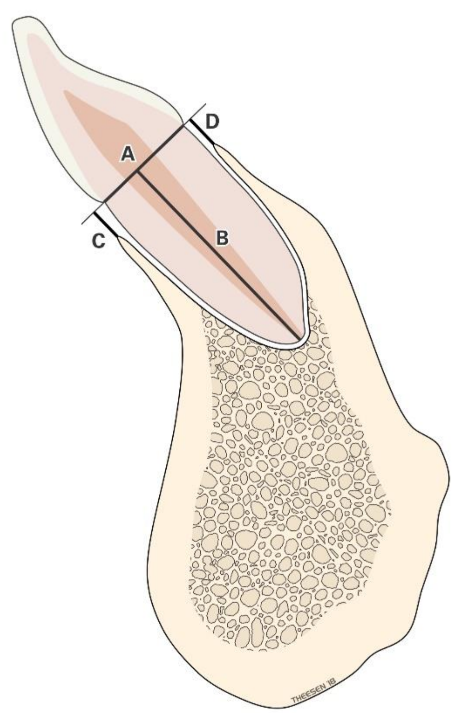
All ten CBCT measurements were taken on all four mandibular incisor at both time points. One patient was missing an incisor, so only three incisors were measured in her case. A Planmeca ProMax 3D Mid (90 kV tube head) unit (Planmeca, Helsinki, Finland) was used to image each patient. Planmeca Romexis software was used to measure the hard tissue linear measurements (Planmeca, Helsinki, Finland). A small field-of-view, normal ultra low-dose protocol (4x5 cm FOV, 200 um voxel size, 4 second scan time, 18 uSv dose) was used for each exposure. To help with imaging quality, a cotton roll was placed in the buccal vestibule anterior to the mandibular incisors to hold the lower lip tissue away during the scans and reduce artifacts.

All 3D images were taken with the patient in a natural head position, which was standardized by two radiology technicians.

The following ten measurements were completed on CBCT images. Using the central pulp chamber and CEJ as reference points, horizontal and vertical linear measurements were taken as follows:

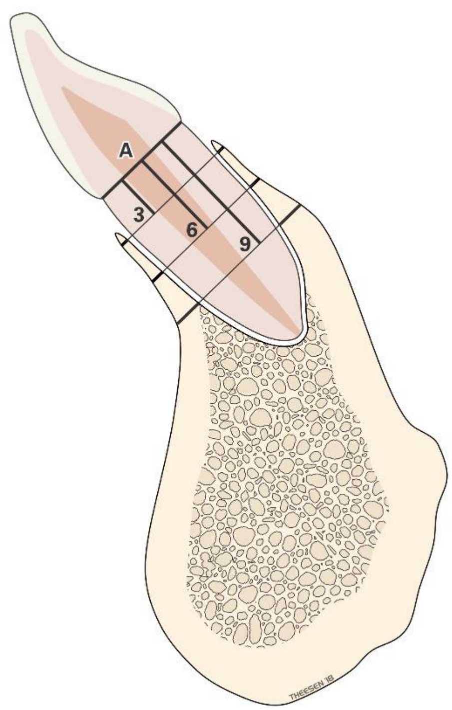
- thickness of the tooth from the buccal to lingual at the CEJ (A)
- length of the root from the CEJ to apex (B)
- distance from the CEJ to the buccal alveolar crest (C)
- distance from the CEJ to the lingual alveolar crest (D)

Figure 4.2.1: The width of the CEJ (A), the CEJ to apex length (B), the CEJ to buccal bone (C), and CEJ to lingual bone (D) were all measured before and after Class II correction



- thickness of the buccal bone at 3 mm apical from the CEJ
- thickness of the buccal bone at 6 mm apical from the CEJ
- thickness of the buccal bone at 9 mm apical from the CEJ
- thickness of the lingual bone at 3 mm apical from the CEJ
- thickness of the lingual bone at 6 mm apical from the CEJ
- thickness of the lingual bone at 9 mm apical from the CEJ

Figure 4.2.2: Hard tissue thicknesses at 3 mm, 6 mm, and 9 mm apical to the CEJ were measured on the buccal and lingual both before and after Class II correction



All ten measurements were made in relation to four mandibular incisors on CBCT images taken both on the day that the appliance was activated and on the day the appliance was deactivated. Areas where there was no bone visible was measured as “0” mm.

Figure 4.2.3: Multi-planar reconstruction of the mandibular incisors after 3D imaging in Planmeca Romexis software (Planmeca, Helsinki, Finland).

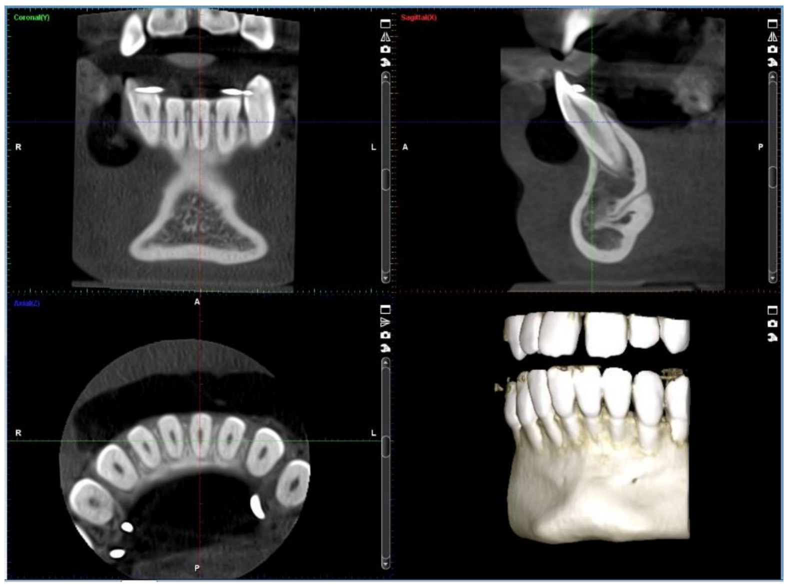


Figure 4.2.4: Image repositioning using the central pulp chamber for vertical and horizontal linear measurements

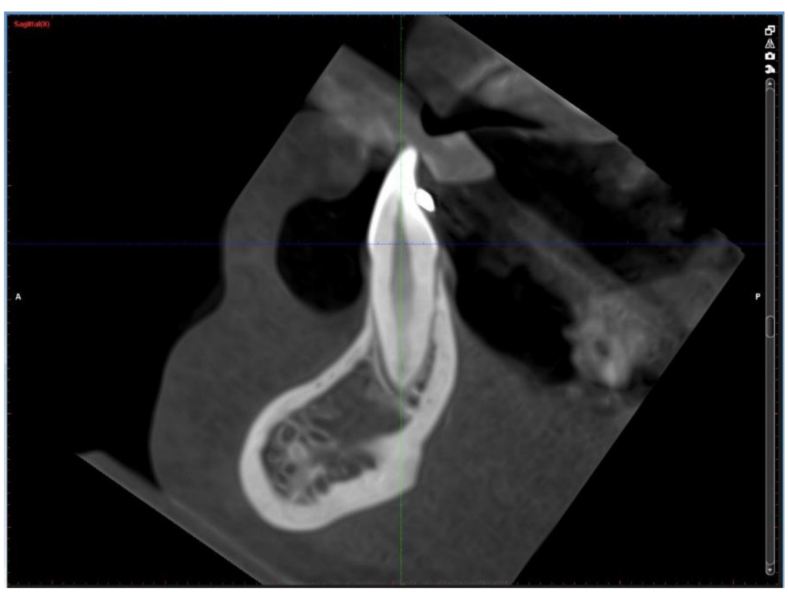


Figure 4.2.5: The width of the CEJ, the CEJ to apex length, the CEJ to buccal bone, and CEJ to lingual bone measurements on a corrected-sagittal CBCT image of LL1

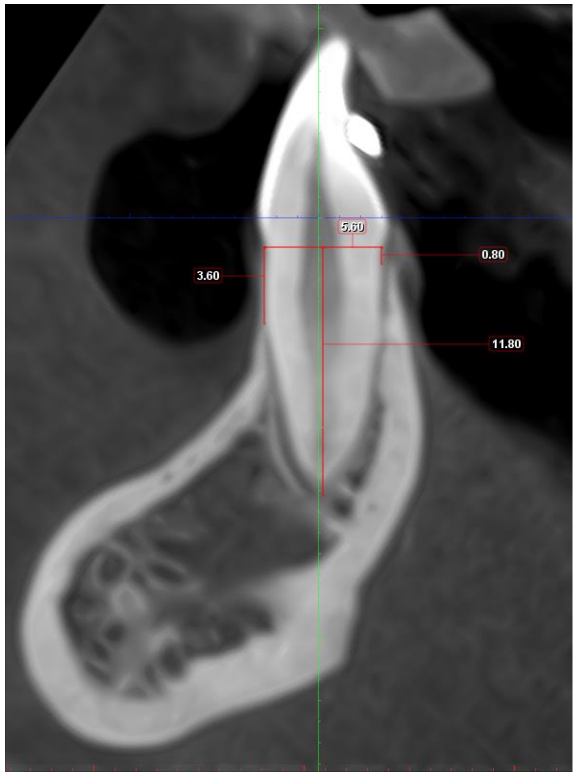
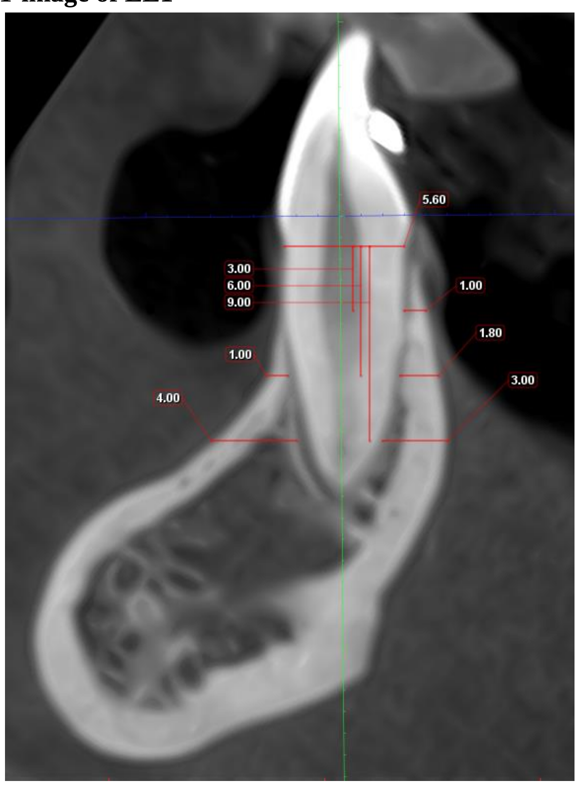


Figure 4.2.6: Hard tissue thicknesses measurements at 3 mm, 6 mm, and 9 mm apical to the CEJ on a corrected-sagittal CBCT image of LL1



4.3. Cephalometric Measurements

Lateral cephalometric radiographs were imaged using a Planmeca ProMax dimax3 ceph (Planmeca, Helsinki, Finland). Cephalometric radiographic measurements were analyzed using Dolphin Imaging 11.8 software (Dolphin Imaging & Management Solutions, Chatsworth, California, USA).

Lower incisor proclination was measured by three methods. The initial two methods are automatically generated from the Dolphin Imaging 11.8 software. The first was using Incisor to Mandibular Plane Angle (IMPA, degrees) (Figure 4.3.1). The second was using Lower Incisor to A Point – Pogonion Line (A-Po, mm) (Figure 4.3.2). The third method used was by superimposing pre-treatment and post-treatment lateral cephalometric radiographs as historically laid out by Pancherz's classic Herbst studies (Pancherz, 1991). This third measurement, ii/OLp, displays lower incisor position as a linear value (Pancherz, 1991) (Figure 4.3.3).

To determine how mandibular growth played into the effect of appliance therapy, growth was measured by radiographic superimposition. The amount of mandibular growth was determined by measuring the distance between articulare on regional mandibular superimpositions (Figure 4.3.4).

One researcher (DD) initially traced all lateral cephalometric radiographs. A board certified orthodontist then checked the radiographs to confirm correct landmark identification (MV). If any discrepancies arose, the researchers conferred until the landmark location was resolved.

Figure 4.3.1: Lower Incisor to Mandibular Plane (IMPA) angle

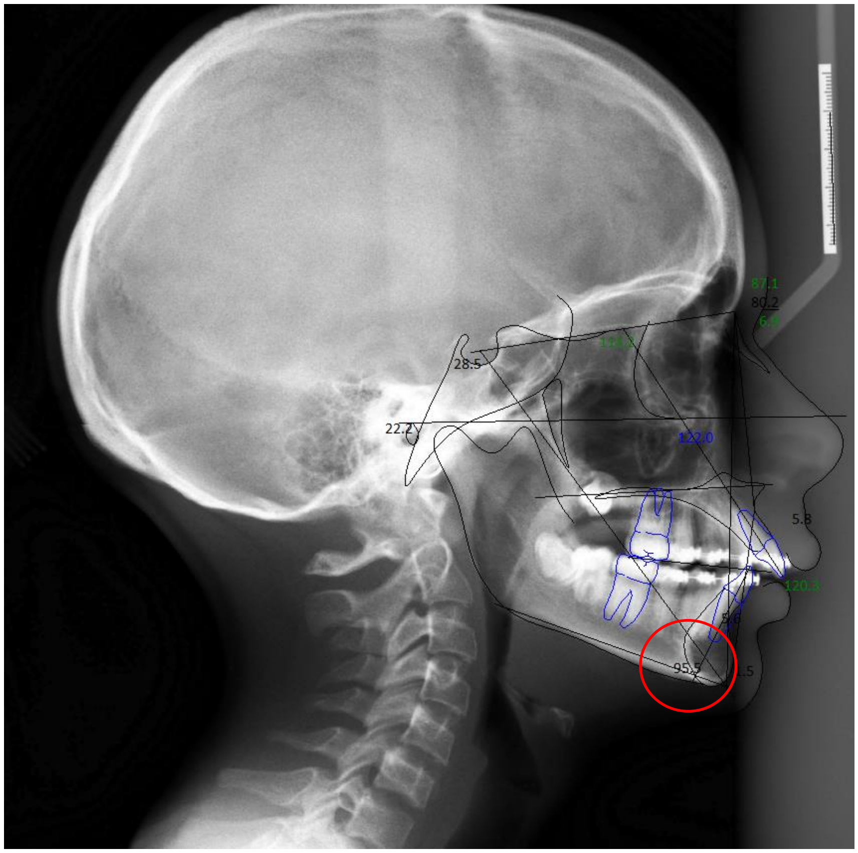


Figure 4.3.2: Lower Incisor to A Point – Pogonion Line (A-Po)
(https://www.slideshare.net/indiandentalacademy/mc-namara)

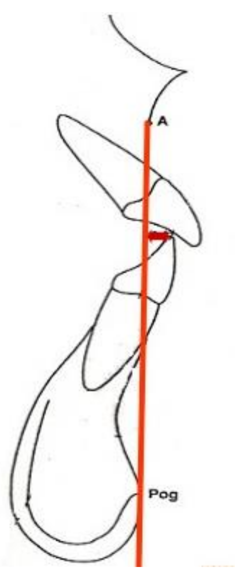


Figure 4.3.3: Pancherz's ii/OLp linear measurement **(Ruf et al., 1998)**

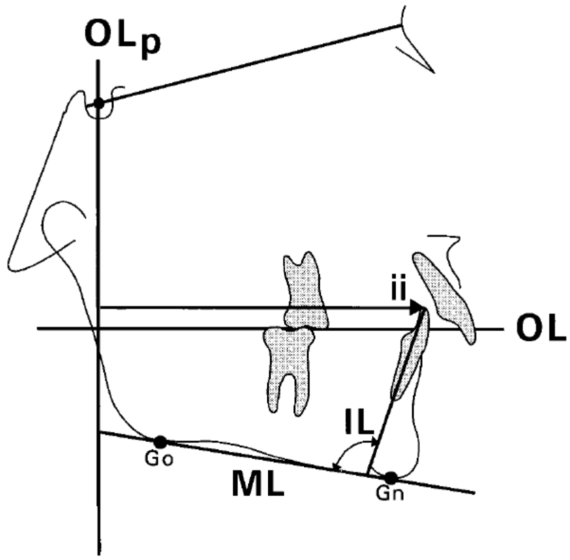
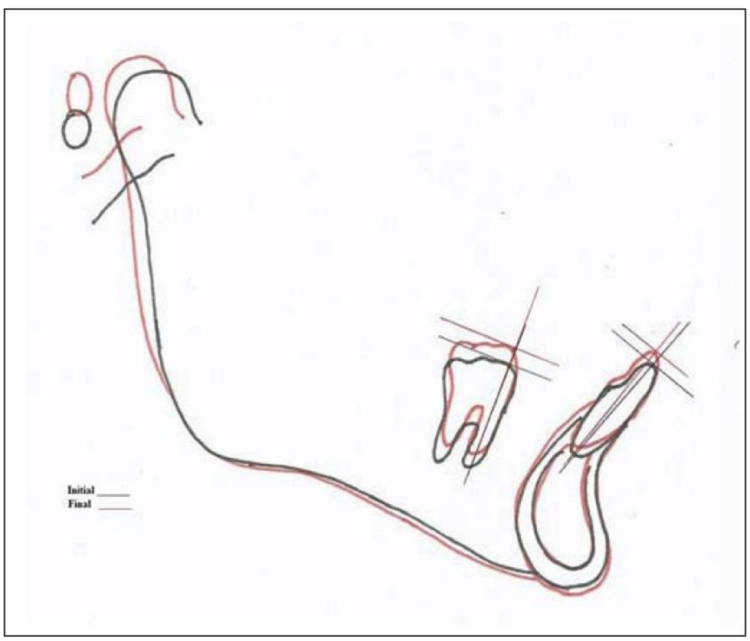


Figure 4.3.4: Mandibular regional superimposition showing mandibular growth near the condyle at articulare **(http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1677-32252015000100071)**



4.4. Periodontal Measurements

Similar to the radiographic measurements, select gingival and periodontal parameters were measured on the day the appliance was activated and the day the appliance was deactivated. Gingival biotype was determined at the beginning of treatment based off the process outlined by De Rouck et al., which uses the maxillary central incisors for determining gingival biotypes (De Rouck et al., 2009). Periodontal probing depths were completed on six sites (MB, B, DB, ML, L, DL) of all four mandibular incisors. Keratinized gingiva was measured on the facial of all four mandibular incisors. For each clinical periodontal measurement taken, a UNC 15 probe was used and each measurement was to the nearest 1 mm.

4.5. Intra-examiner Reliability

Intra-examiner reliability was measured by taking 2 replicate measurements of 4 data points on 18 randomly drawn CBCT records. Records could be either from the pre- or post-treatment scans. The 4 measurements on these records included a horizontal measurement of tooth (CEJ to CEJ), a vertical measurement of tooth (CEJ to apex), a horizontal measurement of bone (buccal thickness 6 mm from CEJ), and a vertical measurement of bone (CEJ to buccal height). Intra-examiner reliability was tested in two manners: method error and intraclass correlations. The method error for determining intra-examiner reliability follows closely with what was done by Garlock et al. in their study relating hard tissue changes to changes during fixed appliance orthodontic therapy (Garlock et al., 2016). Single measures intraclass correlations (ICCs) for absolute agreement were calculated using two-way mixed effects models for each of the areas, using SPSS software, version 23 (IBM Corp., Armonk, NY).

4.6. Statistical Analysis

Medians and interquartile ranges were calculated for stable measurement variables. Wilcoxon Rank Sum tests were used to assess differences in single time point, patient-level characteristics (i.e. months in treatment and mandibular growth) between appliance groups (i.e.

Forsus^{TM} vs. Herbst/MARA). Repeated measurement data (i.e. measurements taken from multiple teeth within a patient or multiple sites within a tooth) were averaged within a patient only for the purposes of graphing.

To assess the reliability of measurements in this study, two measurements were taken from a single patient by the same rater; replicates were measured in four different areas. Single measures intraclass correlations (ICCs) for absolute agreement were calculated using two-way mixed effects models for each of the areas, using SPSS software, version 23 (IBM Corp., Armonk, NY).

Linear models were used to assess associations between patient level variables (e.g. IMPA, biotype, and mandibular growth/rate), and mixed linear models were used to assess associations between tooth- or site-on-tooth-level repeated measurement variables (e.g. CEJ to buccal, probe depth, etc.); model adjusted means and standard errors are presented to account for repeated measures and/or adjustment of variables. When change over time was the outcome of interest, initial measurements were controlled for in the model; when initial measurement was significantly associated with change over time (i.e. final – initial measurement), then model estimated mean differences were calculated for multiple initial values, including the 10th and 90th percentiles, as well as the mean. Finally, adjusted associations between numeric variables were assessed by adding covariates to linear or linear mixed models and obtaining their estimates; when change over time measurements were used as outcomes, the respective initial measurement was included in the model. All analyses (except the ICC calculations) were performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC).

CHAPTER 5: RESULTS

5.1. Subjects

After using the inclusion and exclusion criteria to find eligible participants, 27 patients were recruited for the study. Only one patient declined to participate in the study. Twenty six Class II patients were treated with a Forsus™ appliance (7 males, 5 females), a Herbst appliance (4 males, 4 females), or a MARA (1 male, 5 females). When categorizing for further data analysis, the 8 Herbst patients and 6 MARA patients were combined into a single group of 14 patients with "functional appliances." Utilization of a Herbst appliance versus a MARA in that cohort was based on practitioner preference. The choice of the appliance (between a Forsus™ and "functional appliance" therapy) was based on the protocol laid out in Materials & Methods. All 26 patients who enrolled in the study completed the entire protocol. There were no dropouts.

5.2. Proclination of Mandibular Incisors during Class II Correction

When all three appliances were grouped together (n = 26) and lower incisor proclination was assessed, there was a significant change between initial and final measurements in all three methods tested. When looking at IMPA (degrees), lower incisors were proclined an average of 6.09 degrees (range: +13.5 to -0.7 degrees, $p < 0.0001$) after Class II correction. When looking at Lower Incisor to A-Po (mm), lower incisors were on average 7.60 mm (range: +15.9 to -0.4 mm, $p < 0.0001$) more anterior after therapy. Finally, using Pancherz's classic measurement (ii/OLp), lower incisors proclined forward on average 2.57 mm (range: +4.86 to +0.06 mm, $p < 0.0001$) (Table 5.2.1).

Table 5.2.1: Lower incisor proclination in patients treated with Forsus™ and functional appliances (n = 26)

	Initial Measurement		Final Measurement		Change in Measurement (Final - Initial)		
	Mean	Std Error	Mean	Std Error	Mean	Std Error	P-value
IMPA (degrees)	94.38	0.70	100.48	0.75	6.09	0.75	<0.0001*
Lower Incisor to A-Po (mm)	21.28	0.59	28.88	0.78	7.60	0.78	<0.0001*
ii/OLp (mm)	72.23	0.74	74.80	0.28	2.57	0.28	<0.0001*

Figure 5.2.1: Initial and final IMPA (degrees) of all appliances (n=26) (p < 0.0001*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

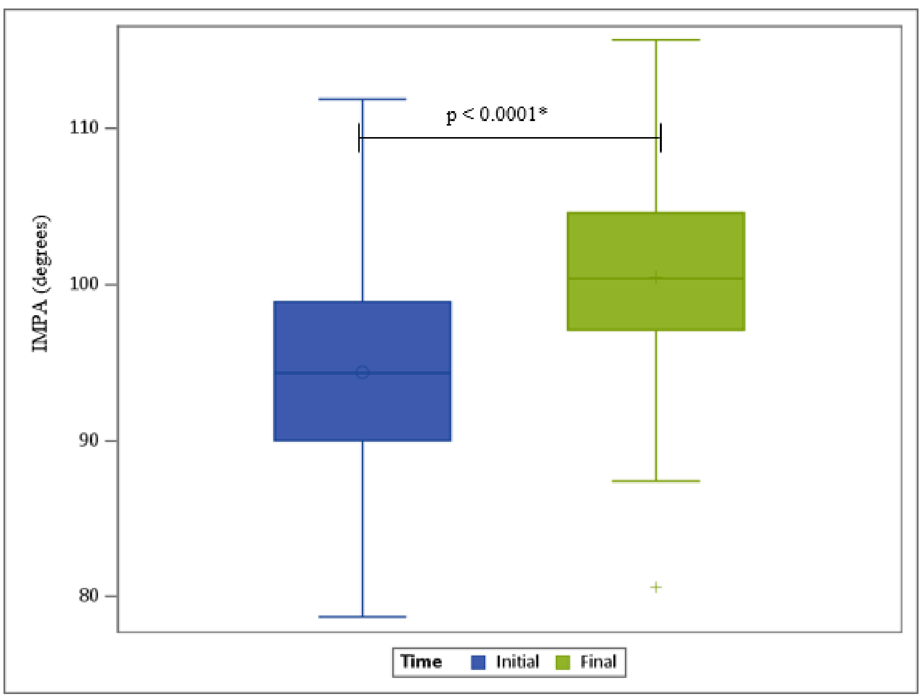


Figure 5.2.2: Initial and final Lower Incisor to A-Po (mm) in all appliances (n=26) ($p < 0.0001$*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

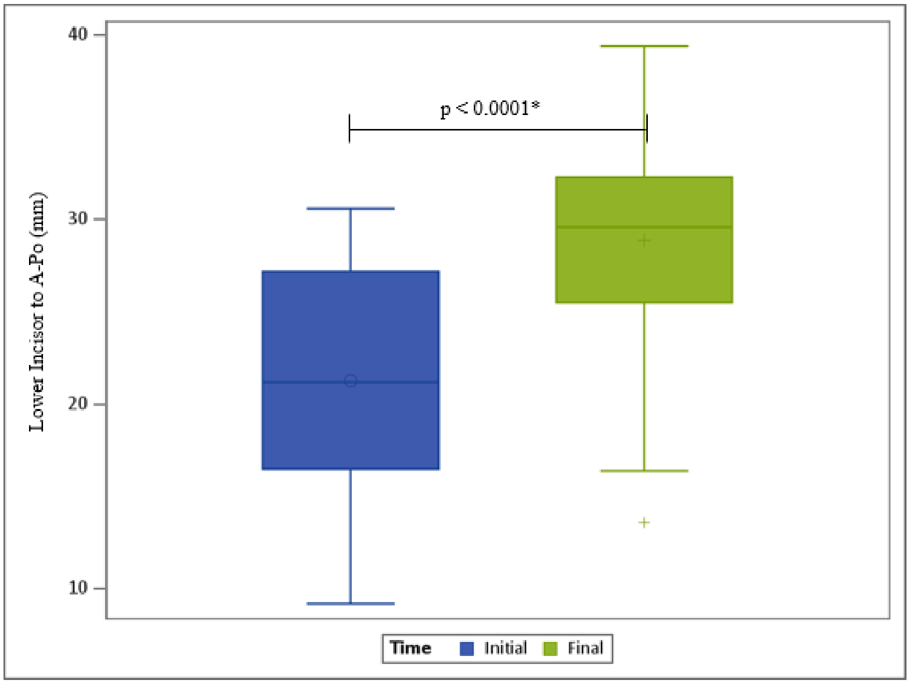
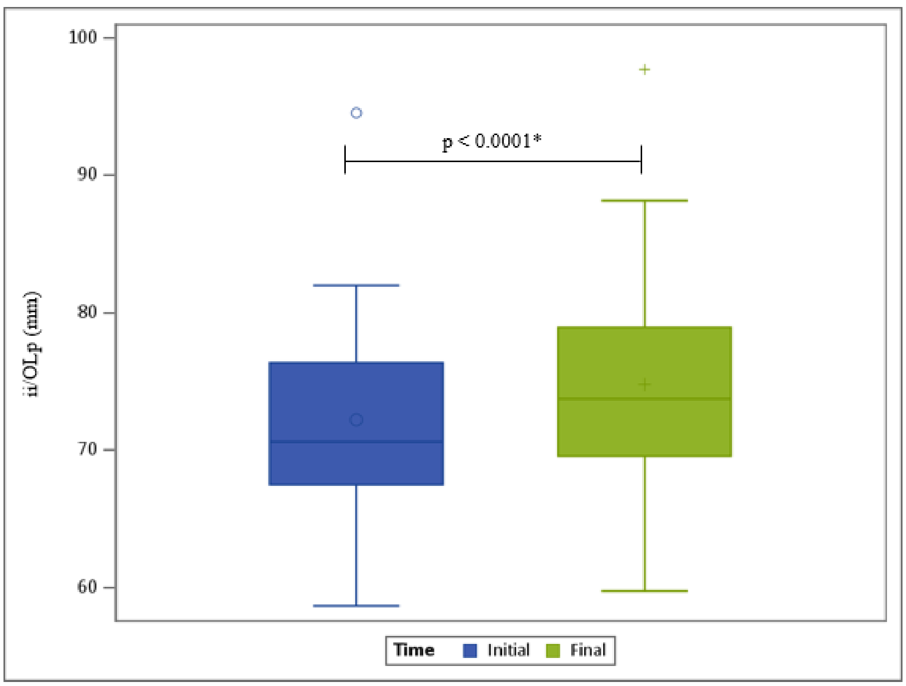


Figure 5.2.3: Initial and final ii/OLp (mm) in all appliances (n=26) ($p < 0.0001$*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.



When comparing the Forsus™ group (n = 12) to the functional appliances group (n = 14), no statistically significant differences were noted between the groups either between initial proclination or changes in proclination during therapy (Table 5.2.2).

Table 5.2.2: Comparison of the amount of lower incisor proclination in Forsus™ vs. Herbst/MARA

		Forsus™ (n=12)		Herbst/MARA (n=14)		Difference Between Groups		
		Mean	**Std Err**	**Mean**	**Std Err**	**Mean**	**Std Err**	**P-value**
IMPA (degrees)	**Initial**	92.36	2.04	96.12	1.89	-3.76	2.78	0.188
	Change (Final-Initial)	7.41	1.10	4.96	1.01	2.45	1.52	0.121
Lower Incisor to A-Po (mm)	**Initial**	21.26	1.77	21.31	1.64	-0.05	2.42	0.984
	Change (Final-Initial)	8.52	1.15	6.81	1.06	1.71	1.56	0.284
ii/OLp (mm)	**Initial**	74.66	2.14	70.14	1.98	4.52	2.91	0.134
	Change (Final-Initial)	2.03	0.41	3.03	0.38	-1.00	0.57	0.095

When all three appliance groups were analyzed together (n = 26), the average time in treatment was 6.42 months (range: +13.8 to +1.6 months). Mandibular growth, which was measured using the changes in the position of articulare from regional mandibular superimpositions, was on average 2.18 mm (range: +6.34 to +0.1 mm) during therapy (Table 5.2.3).

Table 5.2.3: Treatment times and mandibular growth of Forsus^{TM} and functional appliances (n = 26)

	Mean	Std Error
Months in Treatments	6.42	0.78
Mandibular Growth (mm)	2.18	0.33

Comparisons of the Forsus^{TM} (n = 12) and Herbst/MARA (n = 14) groups show a significant difference between the groups in both months in treatment and mandibular growth (Table 5.2.4). Due to small sample sizes of the groups and the type of data being analyzed, non-parametric tests were utilized. Forsus^{TM} appliances were active for a median of 2.99 months, whereas Herbst/MARA appliances were active for a median of 8.17 months ($p < 0.0001$), showing significant differences between the groups in terms of the duration of appliance utilization during treatment. Mandibular growth in the Forsus^{TM} sample was a median of 1.10 mm, whereas the Herbst/MARA sample had a median of 2.77 mm of growth ($p = 0.006$).

Table 5.2.4: Treatment times and mandibular growth of Forsus^{TM} vs. Herbst/MARA

	Forsus^{TM} (n = 12)			**Herbst/MARA (n = 14)**			**P-value (non-parametric)**
	Median	**25th Pctl**	**75th Pctl**	**Median**	**25th Pctl**	**75th Pctl**	
Months in Treatments	2.99	2.07	3.58	8.17	7.60	12.43	<0.0001*
Mandibular Growth (mm)	1.10	0.71	1.54	2.77	1.44	4.72	0.006*

Figure 5.2.4: Differences in months in treatment between the Forsus™ (n=12) and Herbst/MARA (n=14) groups (p < 0.0001*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

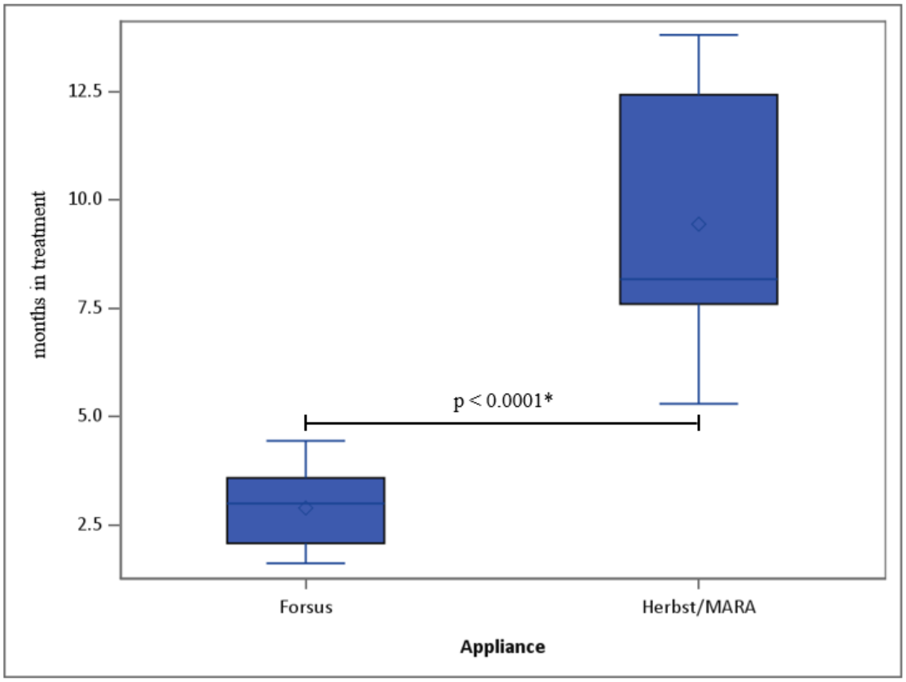
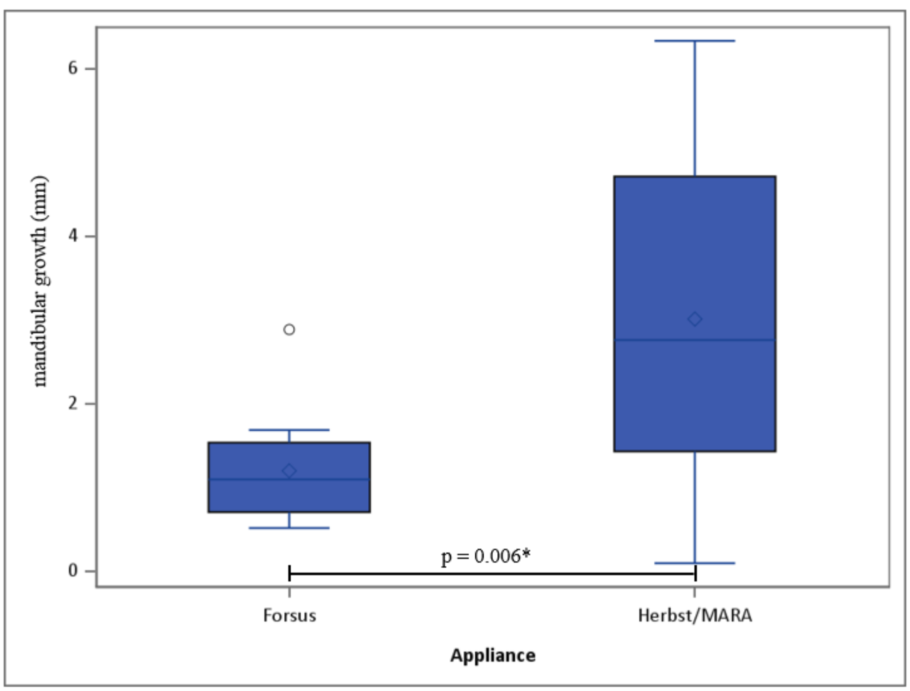


Figure 5.2.5: Differences in mandibular growth (mm) between the Forsus™ (n=12) and Herbst/MARA (n=14) groups (p < 0.006*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.



5.3. Soft Tissue Changes during Class II Correction

Soft tissue changes in all three appliances combined (n = 26) were statistically significant. Probing depths increased on average 0.14 mm (p = 0.03) and keratinized gingiva decreased on average 0.30 mm (p = 0.04) (Table 5.3.1). It should be noted, though, that soft tissue changes were significantly related to initial probing depths and initial keratinized gingival measurements (p < 0.0001).

Table 5.3.1: Soft tissue changes in Forsus™ and functional appliances (n = 26)

	Initial Measurement		Final Measurement		Change in Measurement			
	Percentile or Mean	**Value**	**Mean**	**Std Error**	**Mean**	**Std Error**	**P-value**	**Initial associated with Change P-Value**
Probe Depth	**10%**	1.00	1.88	0.07	0.88	0.07	<0.0001*	<0.0001*
	Mean	1.82	1.95	0.06	0.14	0.06	0.03*	
	90%	3.00	2.06	0.07	-0.94	0.07	<0.0001*	
Keratinized Gingiva	**10%**	2.00	2.40	0.19	0.40	0.19	0.05	<0.0001*
	Mean	3.83	3.54	0.14	-0.30	0.14	0.04*	
	90%	6.00	4.88	0.21	-1.12	0.21	<0.0001*	

Figure 5.3.1: Initial and final probing depths (mm) in all appliances (n=26) (p = 0.03*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

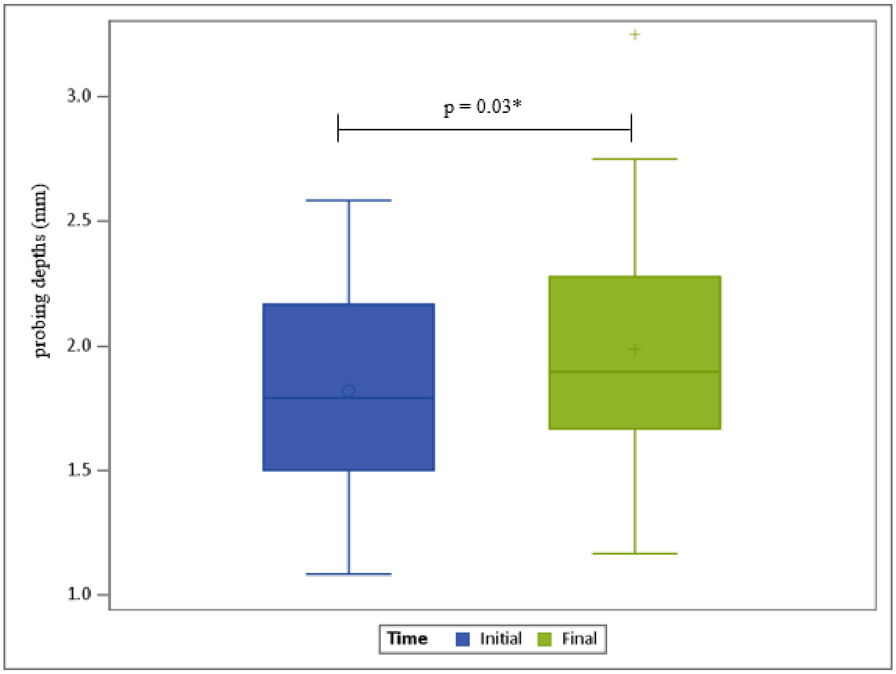
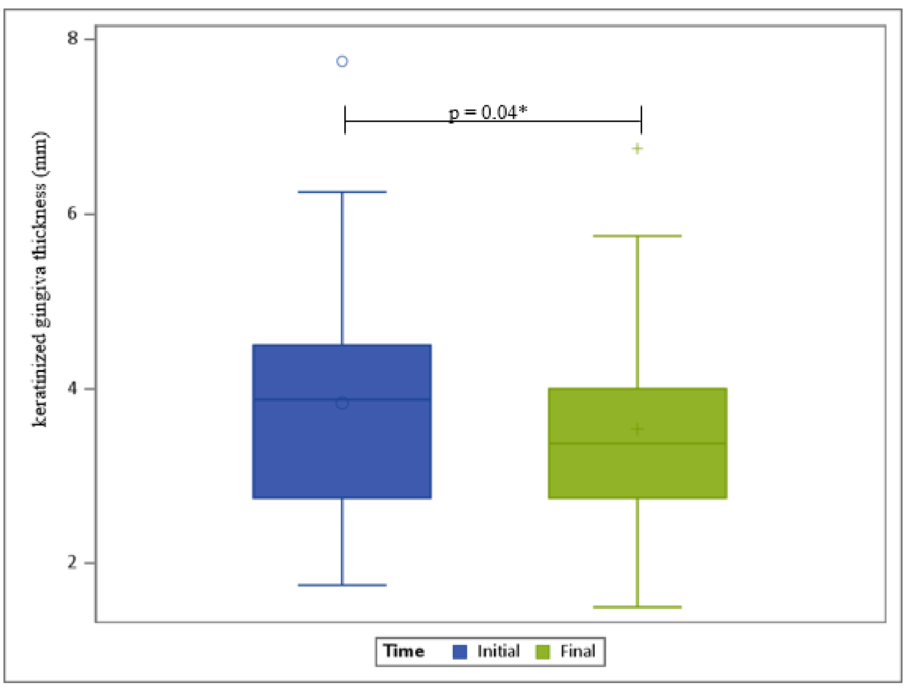


Figure 5.3.2: Initial and final keratinized gingival thickness in all appliances (n=26) (p = 0.04*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.



When comparing soft tissue changes between the appliance type (Forsus^{TM} vs. Herbst/MARA), both the initial probing depths and changes in probing depths were not significantly different (Table 5.3.2). However, there were significant differences between the two groups with regards to changes in keratinized gingiva during appliance therapy (Table 5.3.2).

Table 5.3.2: Soft tissue changes in Forsus^{TM} vs. Herbst/MARA

		Forsus^{TM} (n = 12)		**Herbst/MARA (n=14)**		**Difference Between Groups**		
		Mean	**Std Err**	**Mean**	**Std Err**	**Mean**	**Std Err**	**P-value**
Probe Depth	**Initial**	1.74	0.06	1.70	0.06	0.04	0.05	0.41
	Change (Final-Initial)	0.20	0.07	0.09	0.07	0.11	0.08	0.19
Keratinized Gingiva	**Initial**	4.33	0.39	3.40	0.36	0.93	0.52	0.09
	Change (Final-Initial)	0.15	0.17	-0.69	0.15	0.84	0.23	0.001*

Figure 5.3.3a: Differences in initial (p = 0.09) and final (p = 0.001*) values of keratinized gingiva width between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

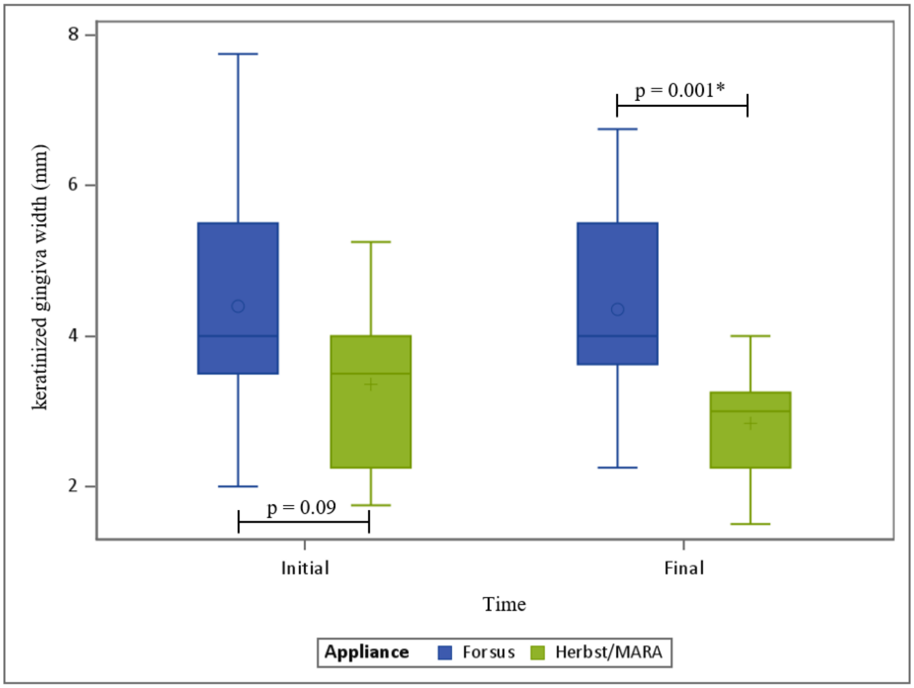
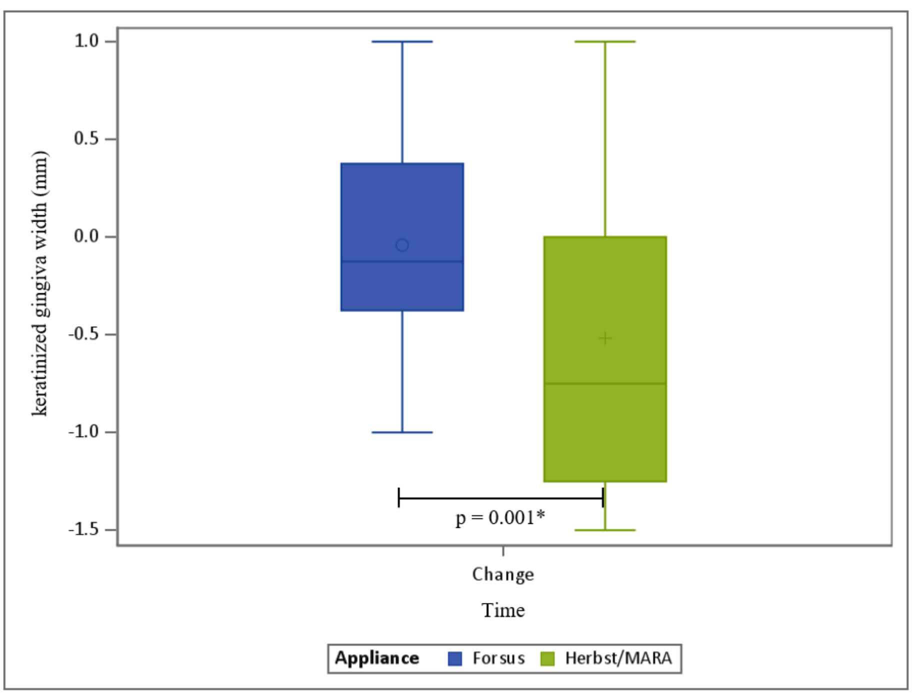


Figure 5.3.3b: Differences in change (p = 0.001*) of keratinized gingiva width between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outliers present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.



5.4. Hard Tissue Changes during Class II Correction

When all three appliances are combined together, there are significant changes to the teeth and alveolar housing during appliance therapy (Table 5.4.1). Horizontal bone thickness changes were measured at three different levels: 3 mm, 6 mm, and 9 mm apical to the CEJ on the buccal. There were no significant changes found in thickness at 3 mm apical to the CEJ (mean change = 0.00 mm, range: +0.6 to -0.8 mm, p = 0.8953). However, significant bone thickness was gained at 6 mm apical to the CEJ (mean change = +0.39 mm, range: +3.8 to -0.8, p = 0.0005) and 9 mm apical to the CEJ (mean change = +1.13 mm, range: +6.8 to -0.6, p = 0.0003) on the buccal of the incisors. The bone height on the buccal (CEJ to buccal) decreased 0.30 mm on average, but this change was not significant (range: +3.8 to -2.4 mm, p = 0.2622).

As it relates to the lingual bone, bone was significantly thicker at both 3 mm apical to the CEJ (mean change = +0.23 mm, range: +1.6 to -1.2 mm, p = 0.0031) and at 6 mm apical to the CEJ (mean change = +0.20 mm, range: +1.6 to -1.2, p = 0.0210) after therapy. Bone was thinner on the lingual at 9 mm apical to the CEJ, but this change was not significant (mean change = -0.06 mm, range: +1.8 to -1.4, p = 0.5929). The bone height on the lingual (CEJ to lingual) decreased on average 0.39 mm, but this change was not significant (range: +6.4 to -9.8 mm, p = 0.1145).

Changes in the teeth were also noted with Class II corrections. The buccal CEJ to lingual CEJ length decreased on average 0.05 mm during treatment, and this change was significant (range: +0.8 to -0.6 mm, p = 0.0071). The length of the root (CEJ to apex) also decreased on average 0.21 mm during treatment (range: +1.2 to -0.8, p = 0.0003). As was seen with the soft tissue measurements, most of the hard tissue changes during treatment were significantly related to their initial measurement magnitude (Table 5.4.1).

Table 5.4.1: Hard tissue changes in Forsus™ and functional appliances (n = 26)

	Initial Measurement		Final Measurement		Change in Measurement (Final - Initial)			
	Percentile or Mean	**Value**	**Mean**	**Std Error**	**Mean**	**Std Error**	**P-value**	**Initial associated with Change?**
CEJ to 3 mm buccal thickness	10%	0	0.04	0.02	0.04	0.02	0.1222	<0.0001*
	Mean	0.04	0.04	0.02	0.00	0.02	0.8953	
	99%*	0.8	0.06	0.06	-0.74	0.06	<0.0001*	
CEJ to 6 mm buccal thickness	10%	0	0.20	0.11	0.20	0.11	0.0814	0.0006*
	Mean	0.4	0.79	0.10	0.39	0.10	0.0005*	
	90%	1	1.67	0.13	0.67	0.13	<0.0001*	
CEJ to 9 mm buccal thickness	10%	0.6	1.35	0.29	0.75	0.29	0.0159*	0.0022*
	Mean	2	3.12	0.27	1.13	0.27	0.0003*	
	90%	3.6	5.16	0.30	1.56	0.30	<0.0001*	
CEJ to 3 mm lingual thickness	Mean	0.64	0.87	0.07	0.23	0.07	0.0031*	0.1036
CEJ to 6 mm lingual thickness	10%	0	0.50	0.10	0.50	0.10	<0.0001*	<0.0001*
	Mean	1.2	1.40	0.08	0.20	0.08	0.021*	
	90%	2.6	2.45	0.11	-0.15	0.11	0.175	
CEJ to 9 mm lingual thickness	10%	0.6	0.80	0.12	0.20	0.12	0.1198	0.0002*
	Mean	1.91	1.85	0.10	-0.06	0.10	0.5929	
	90%	3.6	3.21	0.13	-0.39	0.13	0.0077*	
CEJ to Buccal	10%	4.2	4.93	0.31	0.73	0.31	0.0268*	<0.0001*
	Mean	6.26	5.96	0.26	-0.30	0.26	0.2622	
	90%	8.8	7.24	0.33	-1.56	0.33	<0.0001*	
CEJ to Lingual	10%	0.8	0.87	0.30	0.07	0.30	0.8254	0.0161*
	Mean	3.41	3.02	0.24	-0.39	0.24	0.1145	
	90%	8.6	7.30	0.44	-1.30	0.44	0.0066*	
CEJ Width	10%	5.4	5.47	0.03	0.07	0.03	0.0392*	<0.0001*
	Mean	5.94	5.88	0.02	-0.05	0.02	0.0071*	
	90%	6.6	6.40	0.04	-0.20	0.04	<0.0001*	
Apex Length	10%	10.8	10.81	0.08	0.01	0.08	0.9109	0.0012*
	Mean	12.49	12.27	0.05	-0.21	0.05	0.0003*	
	90%	14.2	13.76	0.09	-0.44	0.09	<0.0001*	

Figure 5.4.1: Magnitude of changes that occurred in all appliances (n = 26) at (A) CEJ width, (B) CEJ to Apex length, (C) CEJ to Buccal Bone, and (D) CEJ to Lingual Bone

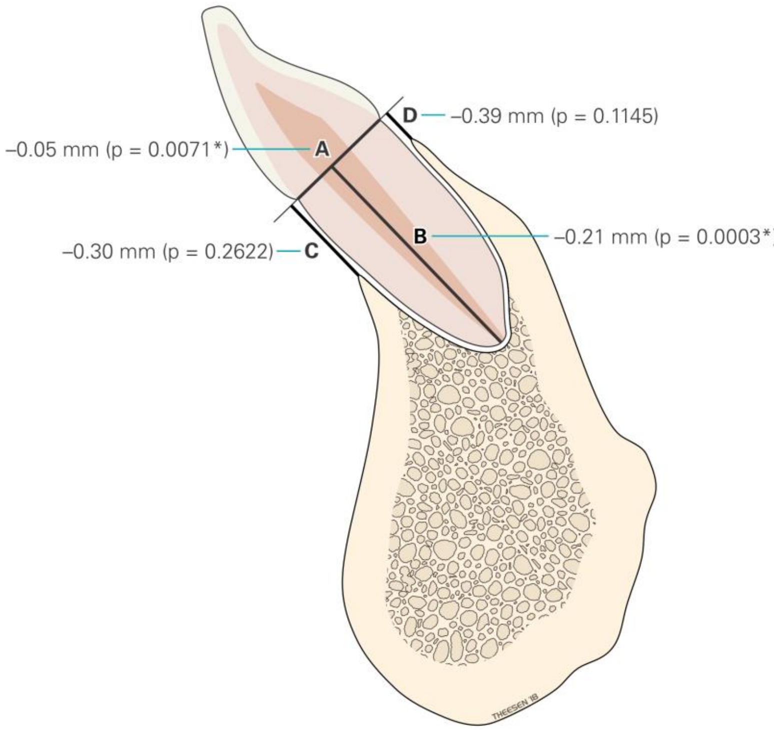


Figure 5.4.2: Magnitude of bone thickness changes that occurred in all appliances (n = 26) at 3 mm, 6 mm, and 9 mm apical to the CEJ on the buccal and lingual

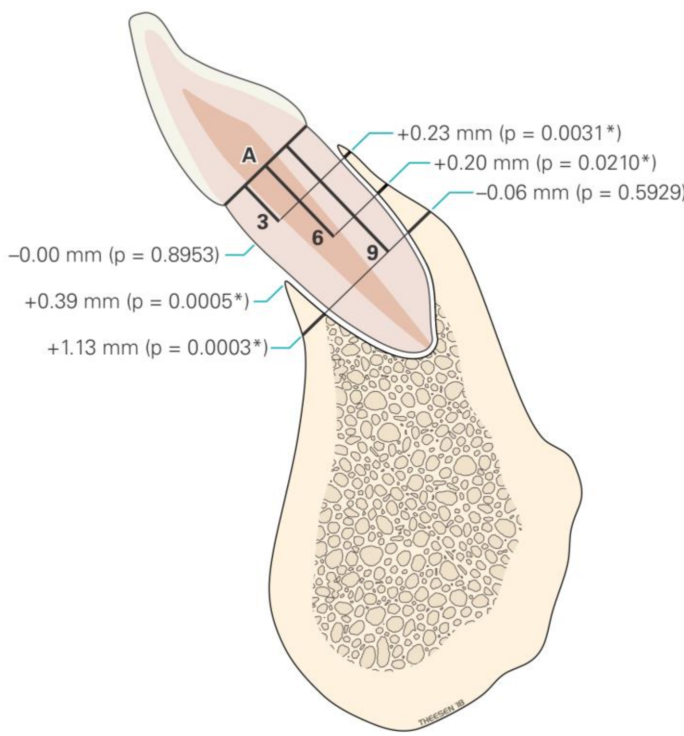


Figure 5.4.3: Initial and final buccal bone thickness measurements at 6 mm apical to the CEJ in all appliances (n = 26) (p = 0.0005*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

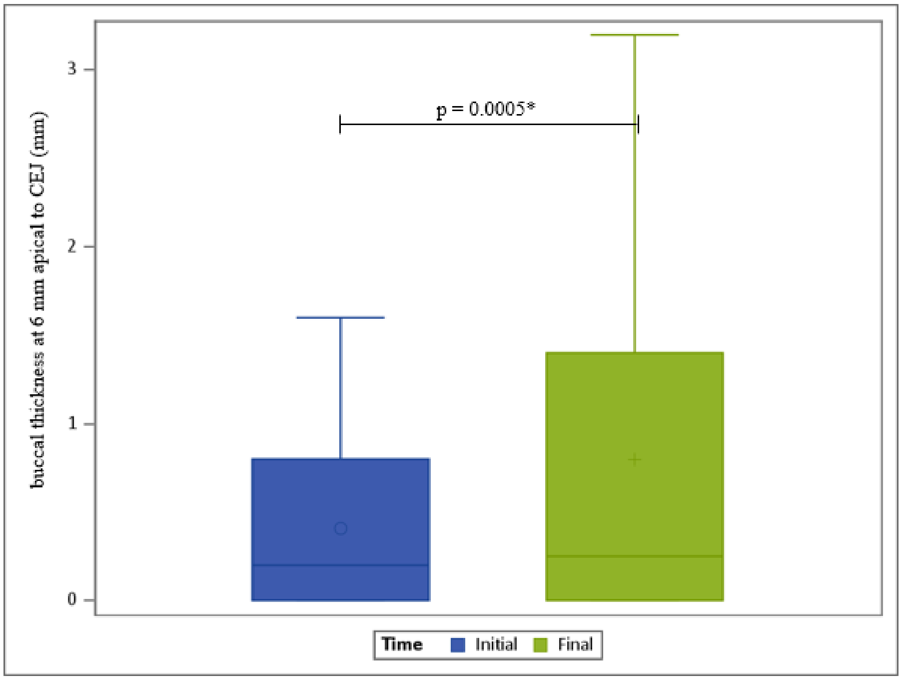


Figure 5.4.4: Initial and final buccal bone thickness measurements at 9 mm apical to the CEJ in all appliances (n = 26) (p = 0.0003*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

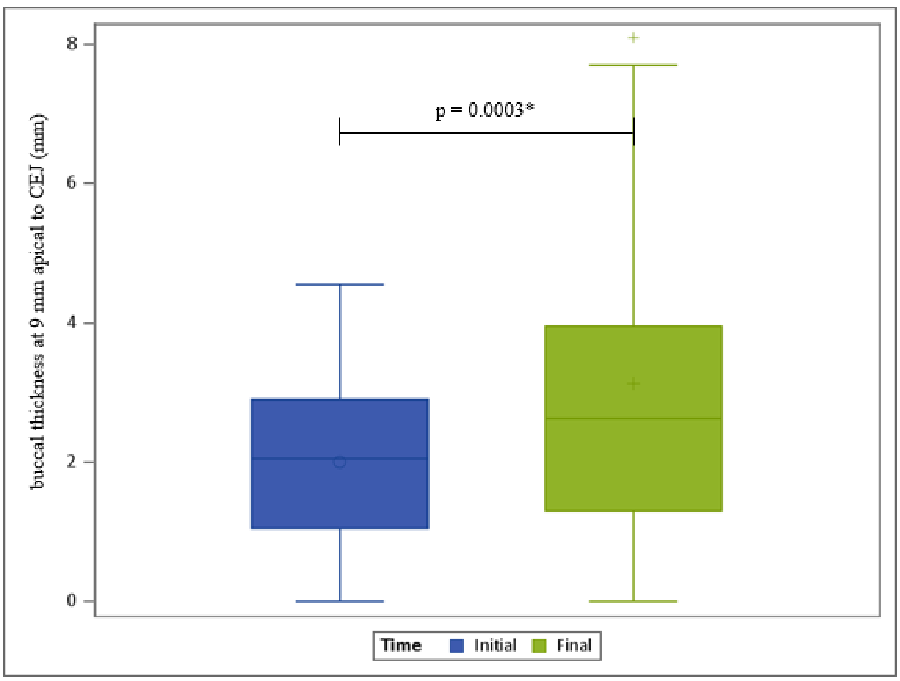


Figure 5.4.5: Initial and final lingual bone thickness measurements at 3 mm apical to the CEJ in all appliances (n = 26) (p = 0.0031*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

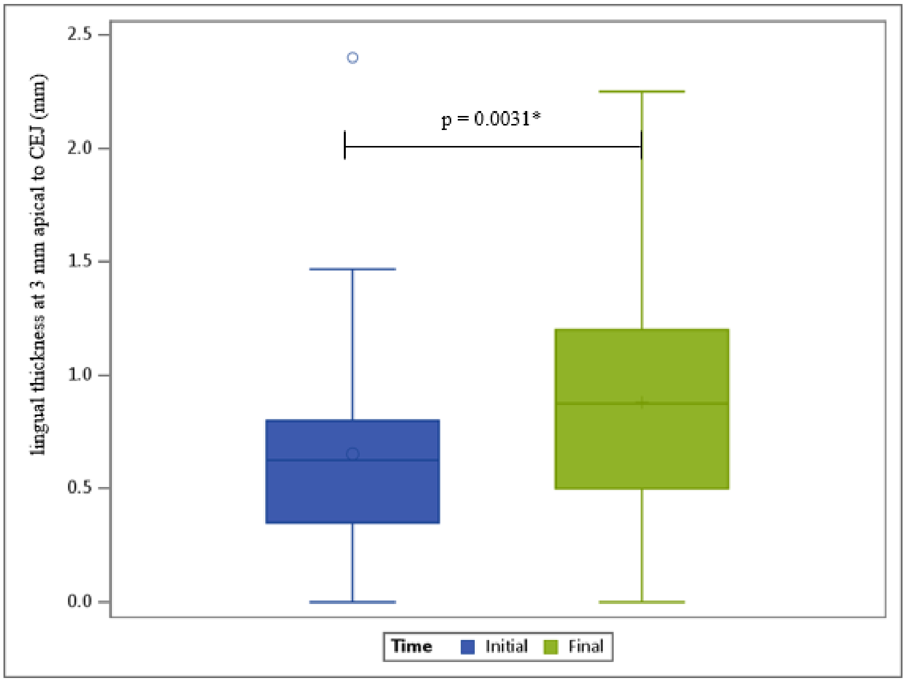


Figure 5.4.6: Initial and final lingual bone thickness measurements at 6 mm apical to the CEJ in all appliances (n = 26) (p = 0.021*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

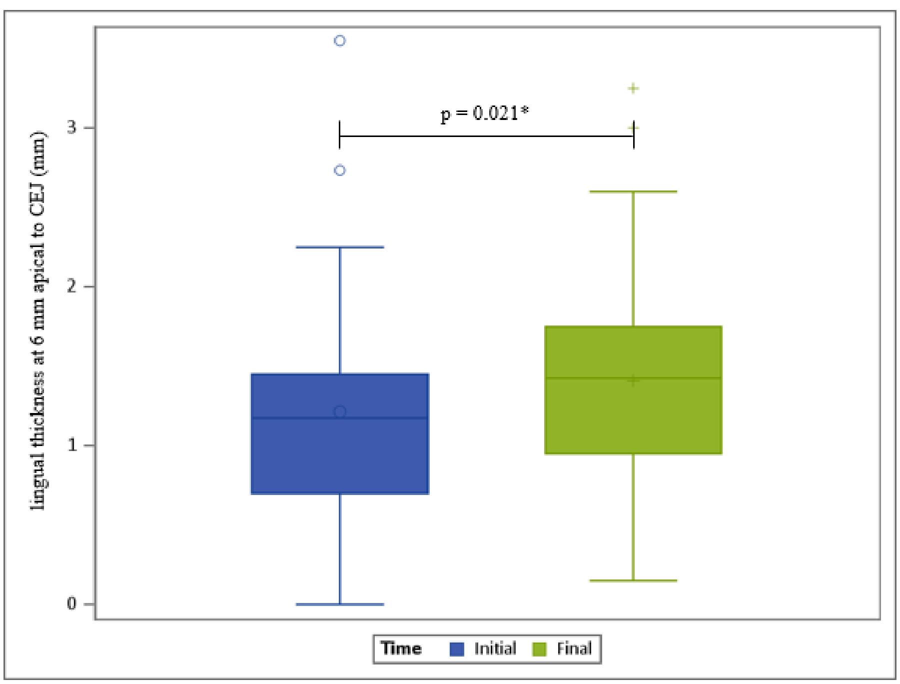


Figure 5.4.7: Initial and final tooth width measurements at the CEJ (mm) in all appliances (n= 26) (p = 0.0071*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

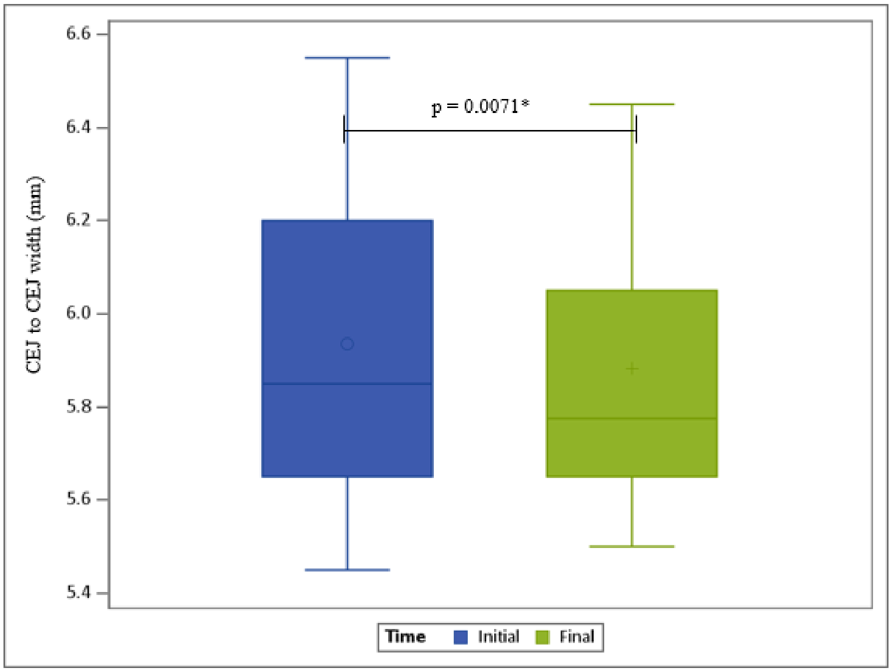
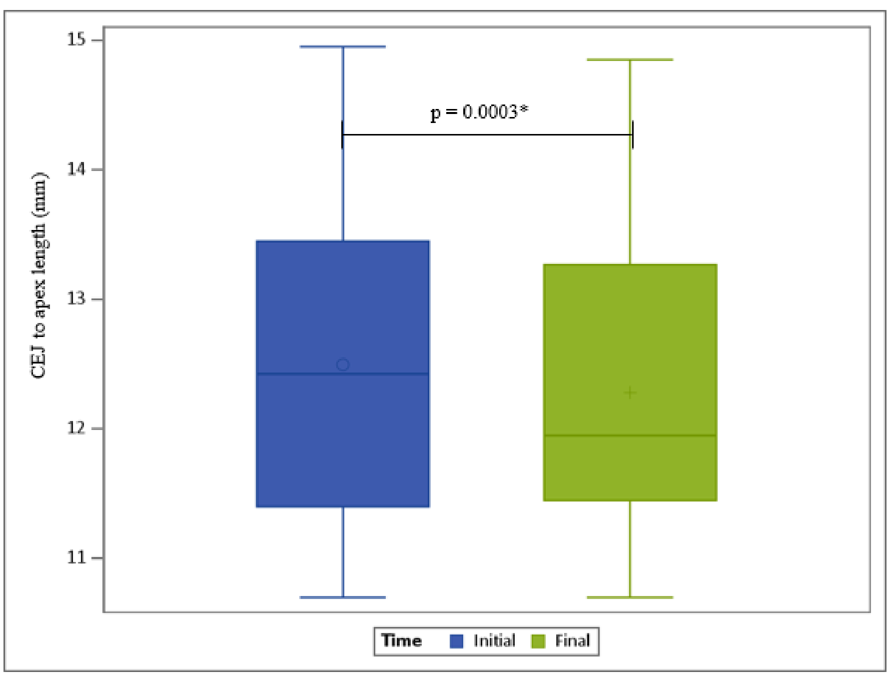


Figure 5.4.8: Initial and final tooth length measurements from the CEJ to the apex (mm) in all appliances (n =26) (p = 0.0003*). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.



When bony changes that occurred during treatment were compared between the Forsus™ group (n = 12) and the Herbst/MARA group (n = 14), there were no significant differences (Table 5.4.2). The initial bone thickness at 3 mm apical to the CEJ was significantly thinner pre-treatment in the Forsus™ group (mean difference = -0.45 mm, p = 0.02) (Figure 5.4.10). Likewise, the initial bone thickness at 9 mm apical to the CEJ was significantly thinner pre-treatment in the Forsus™ group (mean difference = -0.91 mm, p = 0.02) (Figure 5.4.11). Finally, the vertical distance from the CEJ to lingual alveolar crest was significantly increased before treatment initially in the Forsus™ group compared to the functional appliance group (mean difference = 2.46 mm, p = 0.02) (Figure 5.4.9). However, any mean changes that occurred during treatment did not significantly differ between the two appliance groups at any location (all p-values were > 0.05) (Table 5.4.2).

Table 5.4.2.: Hard tissue changes in Forsus™ vs. Herbst/MARA

		Forsus™ (n = 12)		Herbst and MARA (n = 14)		Difference		
		Mean	Std Err	Mean	Std Err	Mean	Std Err	P-value
CEJ to 3 mm buccal thickness	**Initial**	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Change (Final-Initial)	0.01	0.03	0.00	0.03	0.02	0.02	0.42
CEJ to 6 mm buccal thickness	**Initial**	0.35	0.14	0.46	0.13	-0.11	0.19	0.57
	Change (Final-Initial)	0.53	0.14	0.26	0.13	0.27	0.19	0.18
CEJ to 9 mm buccal thickness	**Initial**	1.76	0.31	2.21	0.29	-0.45	0.37	0.24
	Change (Final-Initial)	1.32	0.32	0.97	0.31	0.35	0.32	0.28
CEJ to 3 mm lingual thickness	**Initial**	0.41	0.14	0.86	0.13	-0.45	0.19	0.02*
	Change (Final-Initial)	0.20	0.11	0.25	0.10	-0.04	0.15	0.77
CEJ to 6 mm lingual thickness	**Initial**	0.89	0.21	1.49	0.20	-0.59	0.29	0.05
	Change (Final-Initial)	0.18	0.12	0.21	0.11	-0.03	0.17	0.88
CEJ to 9 mm lingual thickness	**Initial**	1.44	0.27	2.35	0.25	-0.91	0.37	0.02*
	Change (Final-Initial)	-0.07	0.16	-0.05	0.15	-0.02	0.22	0.92
CEJ to Buccal	**Initial**	6.58	0.51	5.94	0.48	0.63	0.70	0.38
	Change (Final-Initial)	-0.15	0.39	-0.43	0.36	0.28	0.54	0.61
CEJ to Lingual	**Initial**	4.71	0.72	2.26	0.66	2.46	0.98	0.02*
	Change (Final-Initial)	-0.31	0.37	-0.46	0.34	0.15	0.52	0.77
CEJ Width	**Initial**	5.83	0.09	6.02	0.09	-0.19	0.13	0.15
	Change (Final-Initial)	-0.08	0.03	-0.03	0.02	-0.05	0.04	0.19
Apex Length	**Initial**	12.27	0.34	12.68	0.32	-0.41	0.47	0.39
	Change (Final-Initial)	-0.31	0.07	-0.13	0.07	-0.18	0.10	0.09

Figure 5.4.9a: Differences in initial (p = 0.02*) and final (p = 0.77) values of lingual bone height (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

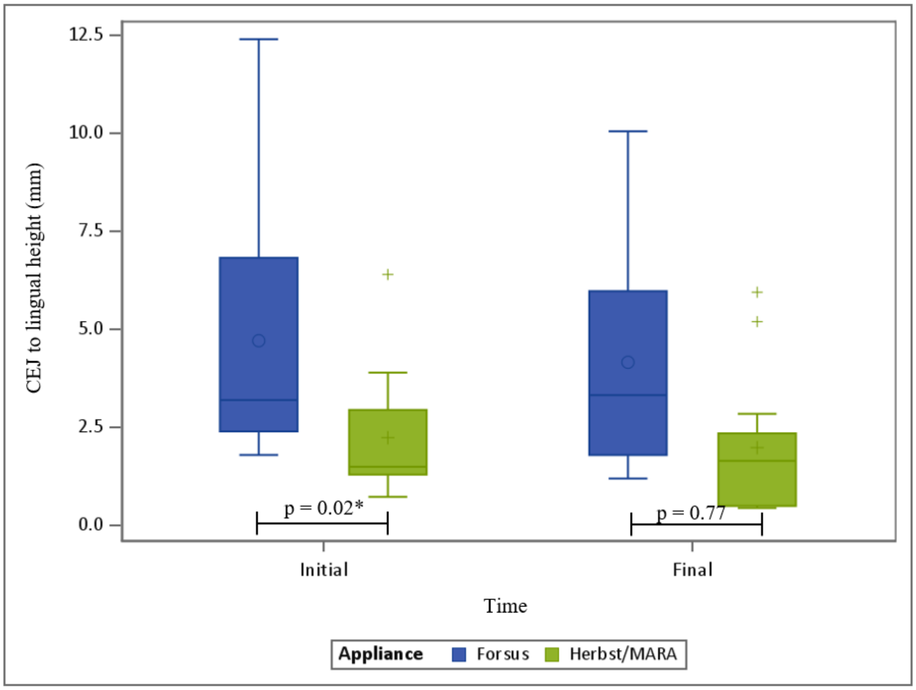


Figure 5.4.9b: Differences in changes (p = 0.77) of lingual bone height (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

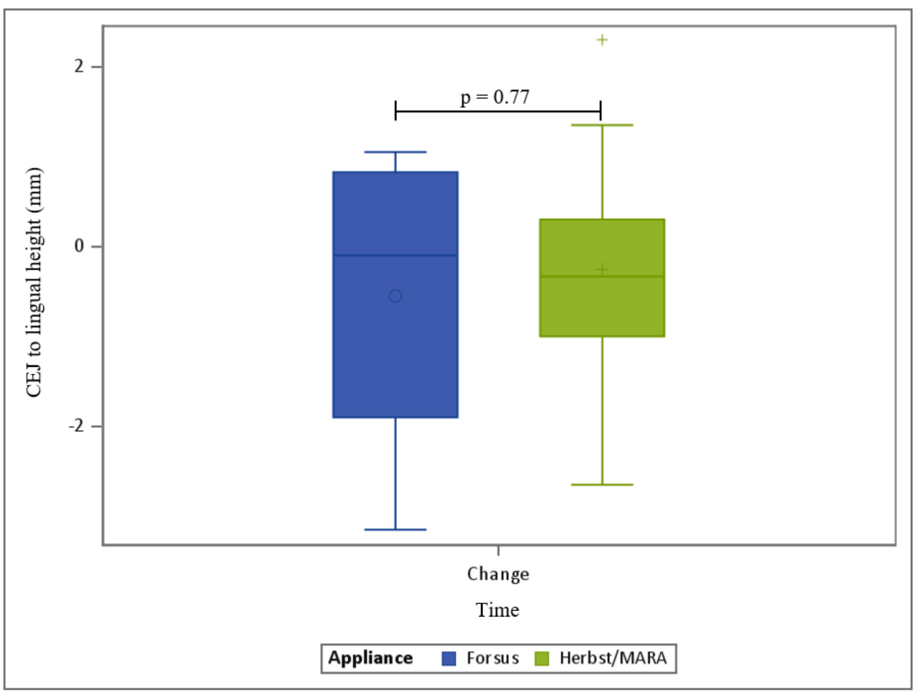


Figure 5.4.10a: Differences in initial (p = 0.02*) and final (p = 0.77) values of lingual bone thickness at 3 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

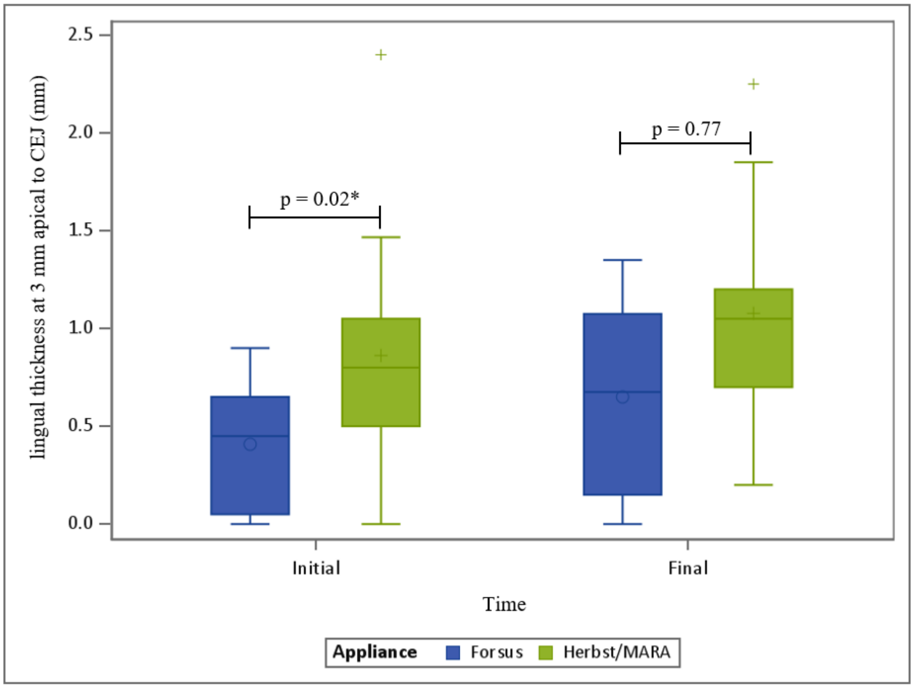


Figure 5.4.10b: Differences in final (p = 0.77) values of lingual bone thickness at 3 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

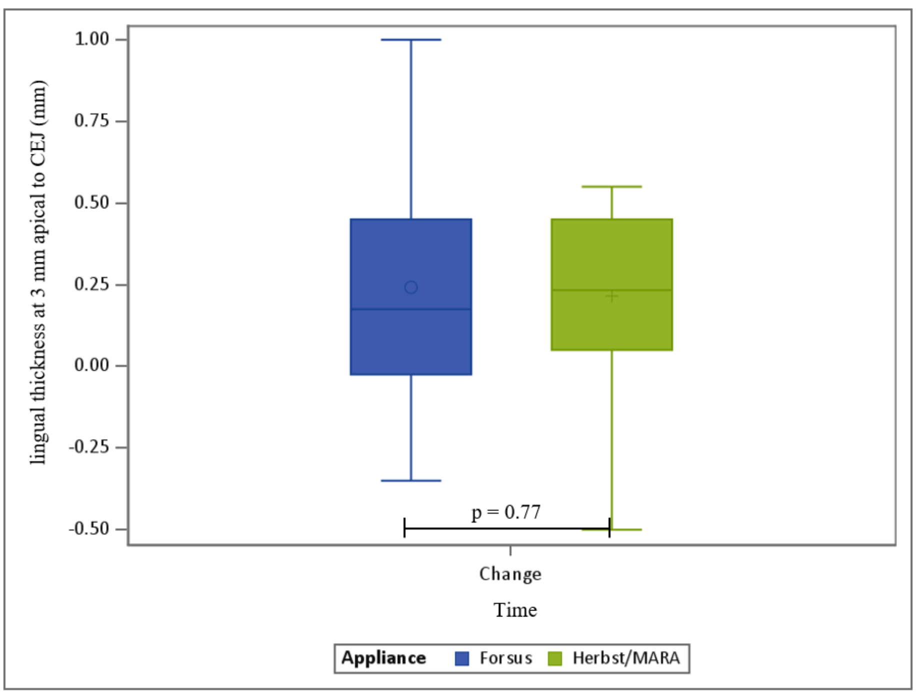


Figure 5.4.11a: Differences in initial (p = 0.02*) and final (p = 0.92) values of lingual bone thickness at 9 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

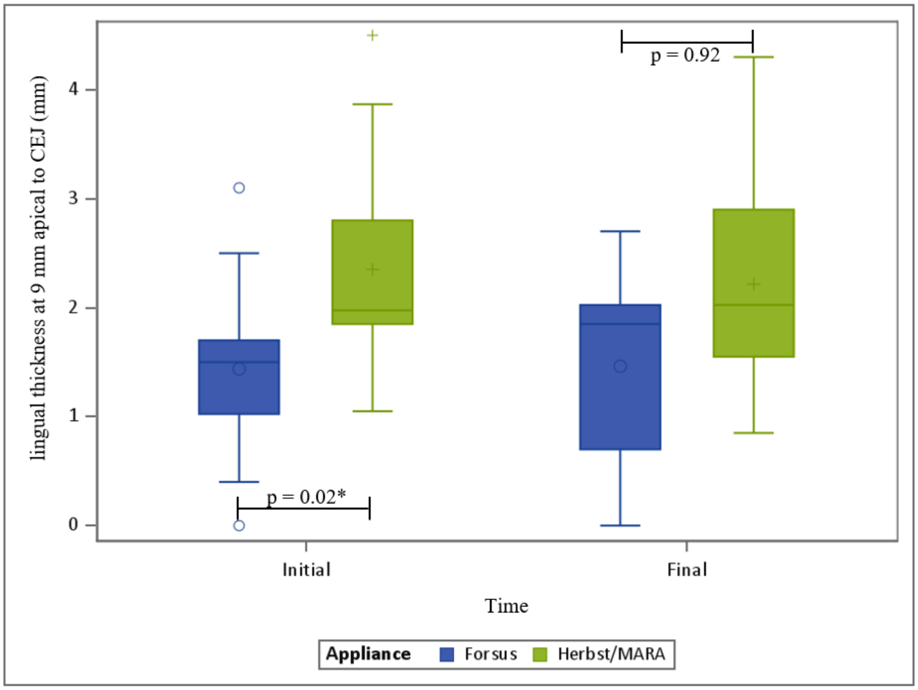
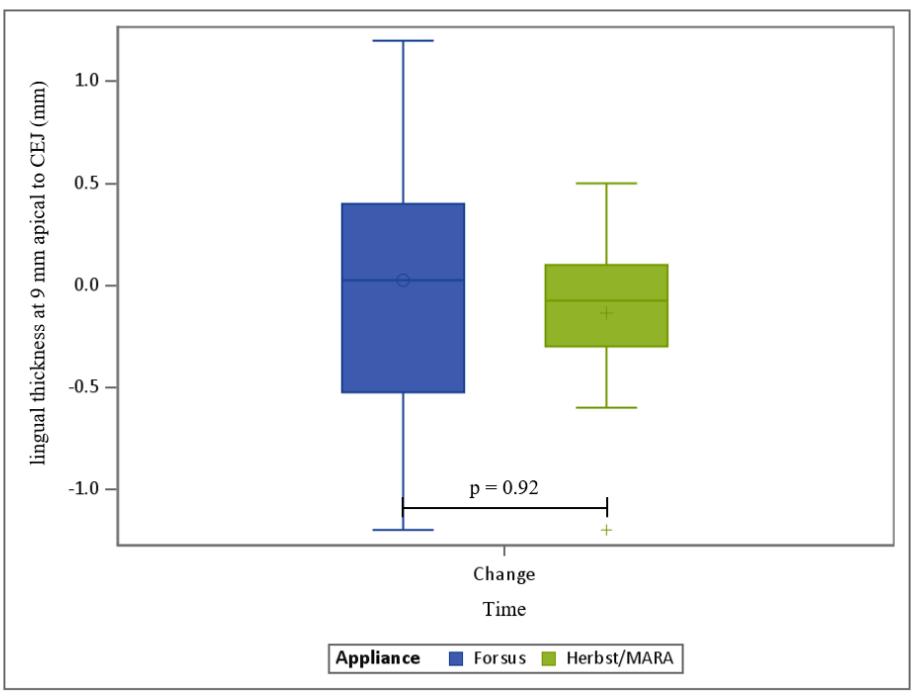


Figure 5.4.11b: Differences in changes (p = 0.92) of lingual bone thickness at 9 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.



To determine whether tooth length was changed relative to vertical bone support during therapy, pre-treatment and post-treatment ratios of the CEJ to lingual bone and CEJ to apex were analyzed. The ratios of bone height to tooth length did not significantly change during therapy (p = 0.1828) (Table 5.4.3).

Table 5.4.3: Ratios of CEJ to lingual bone to CEJ to apex pre- and post-treatment

	Pre-treatment mean ratio	Post-treatment mean ratio	P-value
(CEJ to lingual)/(CEJ to apex)	0.271	0.245	0.1828

5.5. Correlations to IMPA Changes and Initial Gingival Biotype

Correlations between IMPA (degrees) and therapeutic changes in all hard tissue measurements were investigated (Table 5.5.1). Only four associations were found to be statistically significant. Changes in the buccal bone height (CEJ to Buccal) were found to be negatively related to IMPA changes (-0.163 mm per 1 degree of IMPA change, p = 0.010). In other words, for every one degree of proclination, the distance between the CEJ and buccal plate of lower incisors decreased by 0.163 mm. Changes in buccal bone thickness at 6 mm apical to the CEJ and 9 mm apical to the CEJ were also found to be statistically related to changes in IMPA. Bone at 6 mm from the CEJ on the buccal increased by 0.075 mm in thickness for every degree of proclination (p = 0.001), whereas buccal bone at 9 mm from the CEJ increased by 0.104 mm in thickness for every degree of proclination (p = 0.010) (Table 5.5.1). Only one measurement on the lingual of the mandibular incisors was related to IMPA change. At 9 mm from the CEJ on the lingual, bone decreased in thickness by 0.064 mm for every degree of proclination (p = 0.014).

Table 5.5.1.: Associations between IMPA changes and hard tissue measurement changes in millimeters (adjusted for initial measurement of variable and tooth)

	Adjusted Estimate for 1° Change in IMPA	Adjusted SE	P-value
CEJ to 3 mm buccal thickness	0.005	0.002	0.057
CEJ to 6 mm buccal thickness	0.075	0.020	0.001*
CEJ to 9 mm buccal thickness	0.104	0.037	0.010*
CEJ to 3 mm lingual thickness	0.018	0.018	0.317
CEJ to 6 mm lingual thickness	-0.017	0.021	0.408
CEJ to 9 mm lingual thickness	-0.064	0.024	0.014*
CEJ to Buccal	-0.163	0.059	0.010*
CEJ to Lingual	-0.028	0.062	0.654
CEJ to CEJ	0.001	0.005	0.819
CEJ to Apex	-0.017	0.014	0.251
Keratinized Gingiva width	0.008	0.034	0.815

Figure 5.5.1: Correlation between changes in IMPA (degrees) and changes in buccal bone thickness 6 mm apical to the CEJ in all appliances (n=26) (p = 0.001*)

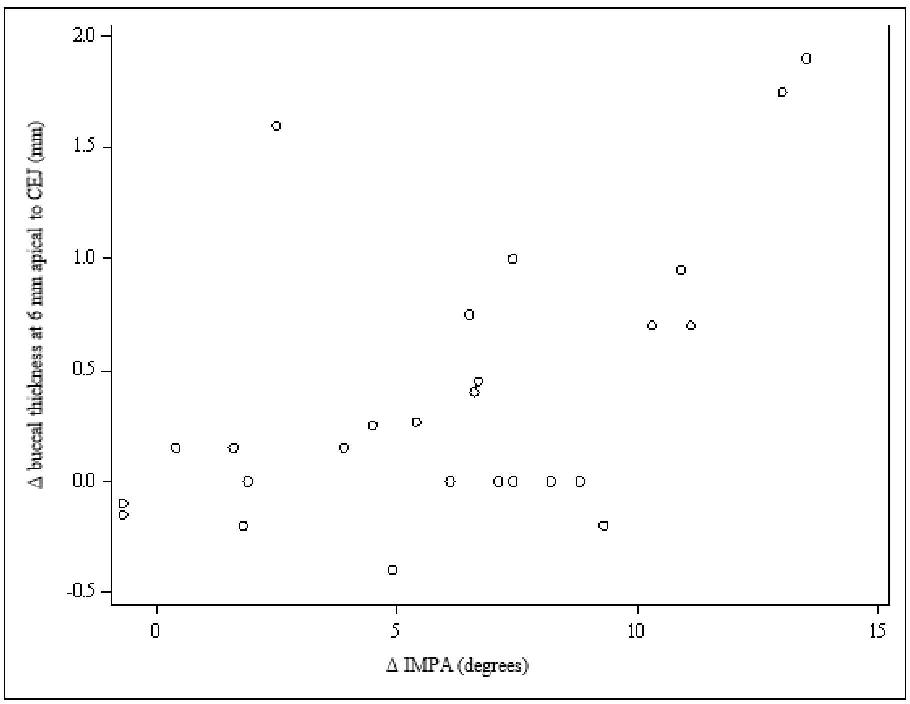


Figure 5.5.2: Correlation between changes in IMPA (degrees) and changes in buccal bone thickness 9 mm apical to the CEJ in all appliances (n=26) (p = 0.010*)

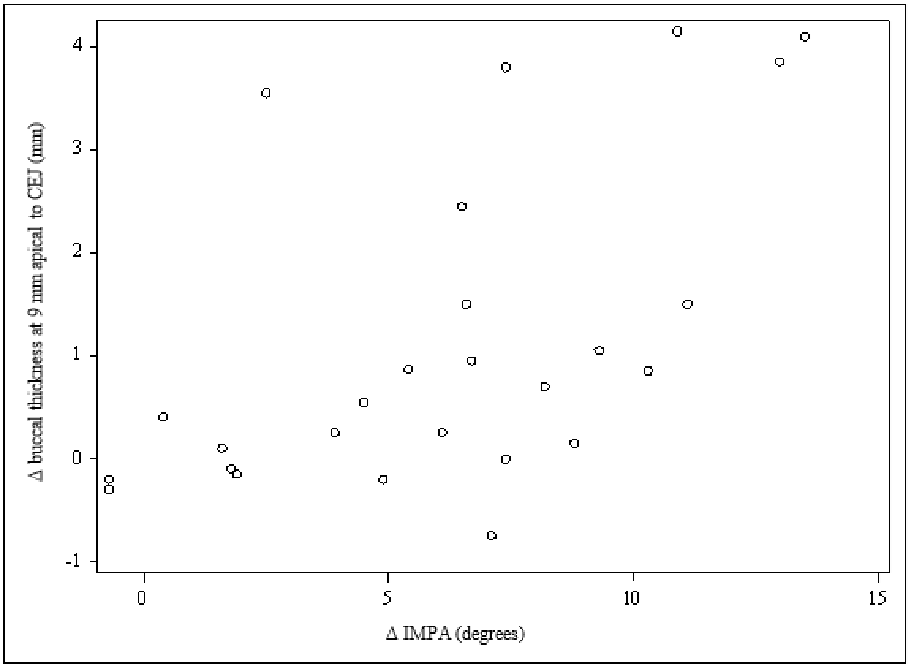


Figure 5.5.3: Correlation between changes in IMPA (degrees) and changes in lingual bone thickness 9 mm apical to the CEJ in all appliances (n=26) (p = 0.014*)

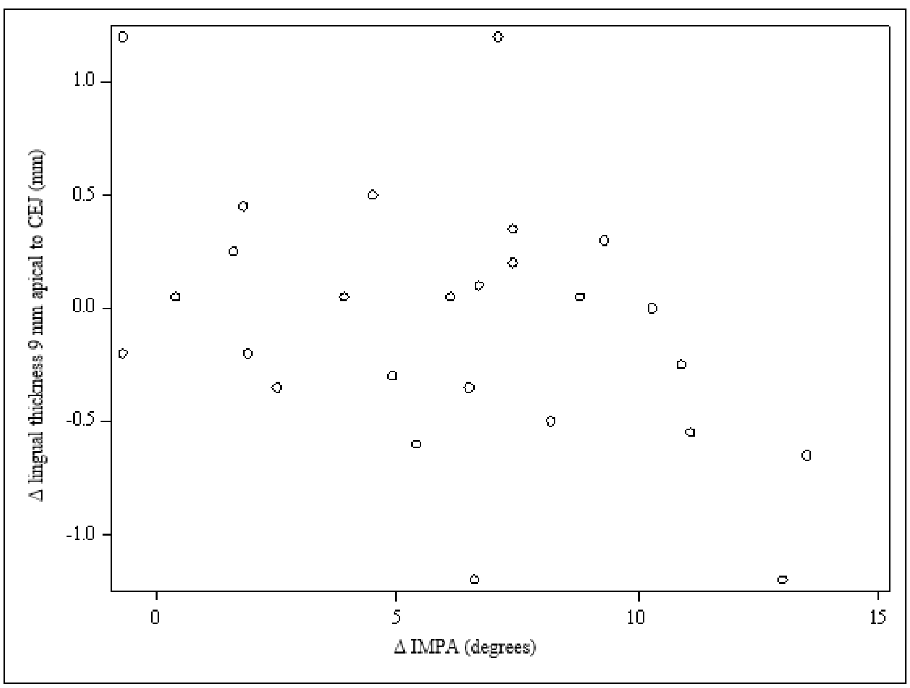
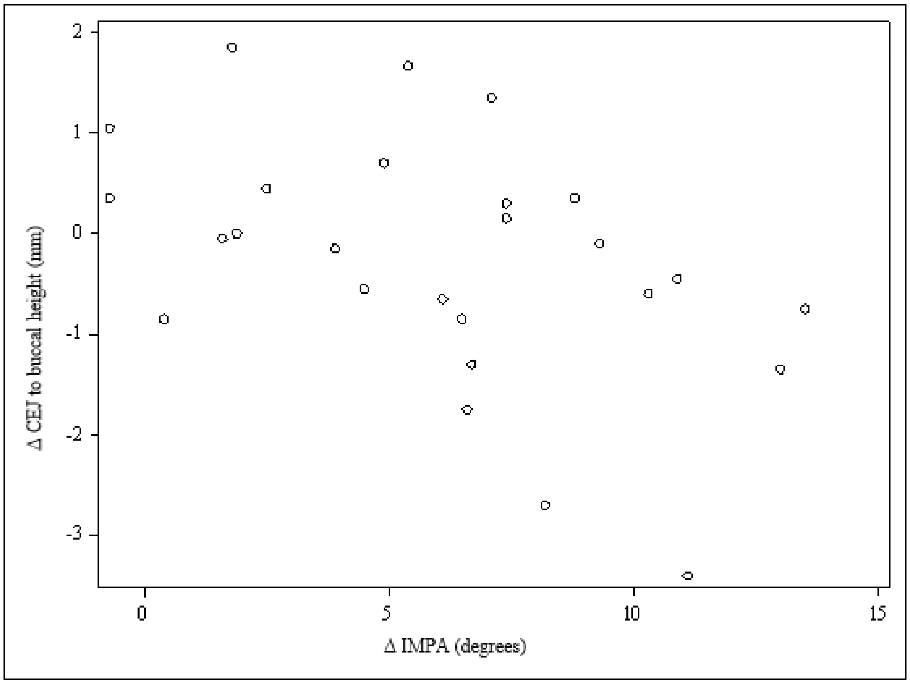


Figure 5.5.4: Correlation between changes in IMPA (degrees) and changes in vertical buccal bone height in all appliances (n=26) (p = 0.010*)



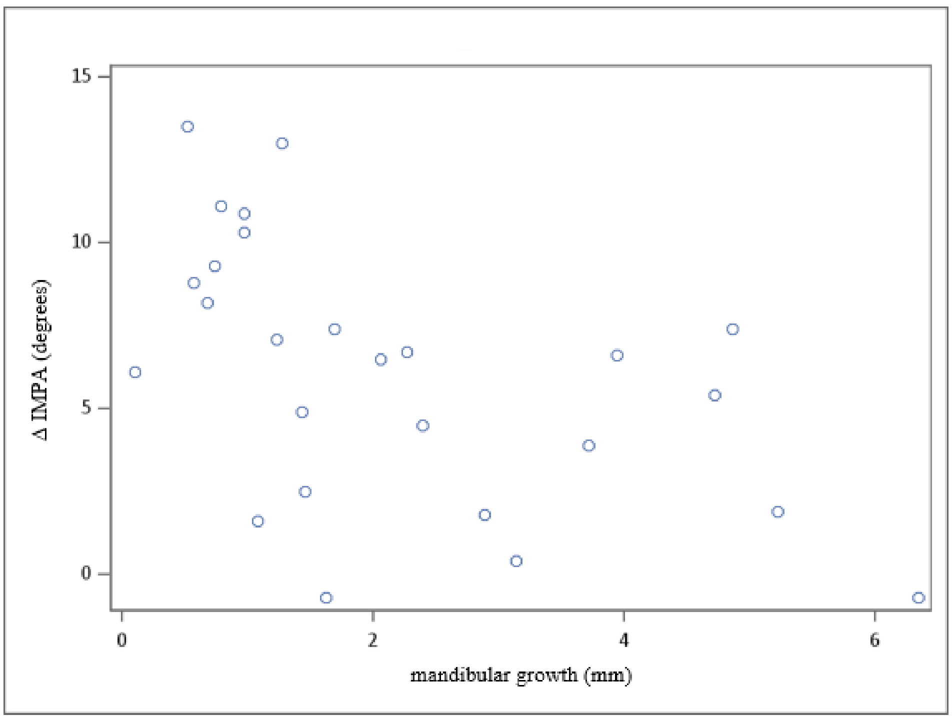
Mandibular growth and its correlation to lower incisor proclination was also assessed. Both mandibular growth and mandibular growth rate were found to be negatively correlated to proclination and changes in IMPA; however, only magnitude of growth was found to be correlated in a manner that was statistically significant (Table 5.5.2). This means that for every 1 mm of mandibular ramal growth during treatment, proclination of the mandibular incisors decreased 1.12 degrees during treatment (p = 0.02*). A correlation between IMPA change and mandibular growth rate was not found to be statistically significant (p = 0.08).

Table 5.5.2: Associations between mandibular growth (1 mm) and growth rate (1 mm/month) and IMPA change (while adjusting for IMPA initial) (linear model)

	Adjusted Estimate for Change in Mandibular Growth (1 mm)	Adjusted SE	P-value
IMPA (degrees)	-1.12	0.43	0.02*

	Adjusted Estimate for Change in Mandibular Growth Rate (1 mm/month)	Adjusted SE	P-value
IMPA (degrees)	-4.56	2.51	0.08

Figure 5.5.5: Correlation between changes in mandibular growth (mm) and changes in IMPA (degrees) in all appliances (n=26) (p = 0.02*)



The final correlations assessed were between biotype and incisor proclination changes, biotype and soft tissue changes, and biotype and hard tissue changes. In all three situations, there were no significant correlations found (Tables 5.5.3 and 5.5.4). Biotype was not associated with changes in IMPA (p = 0.141). Nor was it found to be correlated with changes in soft tissue (keratinized gingiva, p = 0.575) or hard tissue (CEJ to buccal, p = 0.252). These data suggest that the patient's pre-treatment biotype marker that we used was not related to measurable clinical or radiographic changes.

Table 5.5.3: Associations between biotype and measurement changes (adjusted for initial measurement of variable and tooth) (linear mixed model)

	Adjusted P-value for Biotype
CEJ to Buccal (post-pre)	0.252
Keratinized Gingiva (post-pre)	0.575

Table 5.5.4: Associations between biotype and IMPA change (linear model)

	Adjusted P-value for Biotype
IMPA (post-pre)	0.141

For brevity, only statistically significant correlations or graphical representations are shown. All additional graphical representations showing non-significant correlations or comparisons are available in the Addendum.

5.6. Intra-examiner Reliability

Method errors ranged from 0.094 to 0.129 (Table 5.6.2) Intraclass correlations ranged from 0.917 to 0.993 (Table 5.6.1). Intra-examiner reliability was acceptable, as any intraclass correlations between 0.75 and 1.00 are considered excellent (Cicchetti, 1994).

Table 5.6.1: Intra-examiner reliability measurements (Intraclass Correlations)

Area:	**Intraclass Correlations**
Tooth Horizontal (CEJ to CEJ)	0.917
Tooth Height (CEJ to apex)	0.977
Bone Horizontal (buccal thickness at 6 mm from CEJ)	0.993
Bone Vertical (CEJ to buccal height)	0.988

Table 5.6.2: Intra-examiner reliability measurements (Method Error)

Area:	**Method Error**
Tooth Horizontal (CEJ to CEJ)	0.111
Tooth Height (CEJ to apex)	0.129
Bone Horizontal (buccal thickness at 6 mm from CEJ)	0.094
Bone Vertical (CEJ to buccal height)	0.115

CHAPTER 6: DISCUSSION

6.1. Power Analysis

Sample size and power analysis were calculated from data provided in a recently published article from Garlock et al. (Garlock et al., 2016). The sample size was based on our primary question for comparing pre- and post-treatment results of bony changes that occur on the mid-root, buccal surface of a mandibular incisor (noted as "CEJ to 6 mm buccal thickness" in this paper, "MLFB" in Garlock et al.). A sample size of 23 was estimated to be adequate to identify a change of 0.29 mm during appliance treatment at a significance of 0.05 (alpha) and a power of 82%.

6.2. Proclination of Mandibular Incisors and Growth during Class II Correction

From our results, all three measurements of proclination showed significant changes (Table 5.2.1). Average overall IMPA (degrees) change in all appliances combined was 6.09 degrees (Table 5.2.1). When looking at the appliance groups separately, the Forsus™ produced 7.41 degrees of proclination during therapy, whereas the functional appliance group's mean proclination change was 4.96 degrees (Table 5.2.2). Previous studies reported that proclination of lower incisors during functional appliance therapy increased by about 5 to 7 degrees (Pancherz & Bjerklin, 2014, Rodrigues de Almeida et al., 2005, Wigal et al., 2011). The amount of lower incisor proclination in Forsus™ patients in the present study is similar to what has been reported by others (Franchi et al., 2011, Jones et al., 2008). Mean change in ii/OLp for functional appliances in the present study was 3.03 mm. That is similar in magnitude to what had been previously reported (Pancherz, 1982).

With regards to time in treatment and skeletal growth, we would expect there to be a significant difference between time in active treatment and growth between the Forsus™ and Herbst/MARA cohorts for two reasons (Table 5.2.4). First, the Forsus™ protocol usually involves both non-growing and growing patients, whereas the functional appliance group by definition should have significant growth potential as predicted by CVMS. Second, the functional appliance group is usually in treatment on average 2-3 times longer than the Forsus™ sample (Table 5.2.4). This means that not only did the functional appliance group have patients that were actively growing in the sample, but we had them in the regimen for a longer period of time, which ultimately gave them a relatively larger window for growth to occur. These values should be expected, as they were innately tied to the inclusion criteria and methodology laid out in the experimental design.

6.3. Soft Tissue Changes during Class II Correction

Probing depth measurements showed that during appliance therapy, there was an increase in probing depths of 0.14 mm (p = 0.03) (Table 5.3.1). While this was statistically significant, the clinical ramifications are minimal and well within measurement error (+/- 1.0 mm) (Osborn et al., 1992, Corraini et al., 2013). Furthermore, this “increase” in pocket depth may not be directly related to the appliance therapy. Poor oral hygiene associated with orthodontic appliances is known to cause gingival hyperplasia and pseudo-pocketing (Krishnan et al., 2007). Therefore, any increase in probing depths could be due oral hygiene issues rather than a true decrease in periodontal attachment. To make this situation even more complicated, the changes in probing depths were related to their pre-treatment standing (Table 5.3.1). In sites with shallower initial probing depths, there was a greater increase in probing depths. Conversely, in sites with deeper probing depths pre-treatment, there was an actual decrease in probing depth during therapy and a statistical reversion to the mean. Thus, with all available information and taking into account the magnitude of changes that occurs, it appears like there are negligible clinical changes in probing depths during treatment.

Much like the data regarding probing depths, information pertaining to changes with keratinized gingiva should be taken with some perspective. Overall, the mean keratinized gingiva width decreased 0.30 mm during treatment ($p = 0.0407$) (Table 5.3.1). While this change was statistically significant, an average change of this magnitude may not be very clinically relevant and within measurement error (+/- 0.43 mm) (Trentini et al., 1995). Again, much like probing depths, the data demonstrates that the change in keratinized gingival widths were largely depended on the pre-treatment width (Table 5.3.1). For example, those patients with the thinnest keratinized gingiva pre-treatment actually averaged a net positive gain in width. Conversely, those with the most amount of width pre-treatment averaged a more significant loss in width compared to the mean. It is probable that these trends signify a statistical reversion to the mean. This obviously further complicates the picture of what occurs at the soft tissue level during treatment, and calls into question the ability to determine how proclination affects these parameters.

With regards to differences in soft tissue changes due to different appliances, there were no statistically significant differences with regards to probing depths (Table 5.3.2). When looking at changes in keratinized gingiva though, there were statistically significant differences noted during treatment (Table 5.3.2). Yet, when looking at the magnitude of change, and taking into consideration that those values may not be readily measurable using a standard periodontal probe, it may be reasonable to suggest that these findings are again clinically not significant.

The ambiguity associated with what happens to soft tissues during orthodontic therapy is far from a novel finding. Numerous studies show that orthodontic treatment and functional appliances cause recession and soft tissue changes (Yared et al., 2006, Renkema et al., 2013, Slutzkey & Levin, 2008). Conversely, data from other studies (sometimes over many decades) have refuted these claims (Ruf et al., 1998, Hansen, 2003, Djeu et al., 2002). Overall, it currently is not clear as to why some patients may be predisposed to intraoral soft tissue changes during orthodontic therapy, and why others may not. In this study, we intended to identify how gingival biotype may predispose certain patients to periodontal side effects. However, it was not possible to isolate the effects of only the appliances on the soft tissues. More comprehensive and thorough investigation in this field must be performed before we can understand what predisposes patients to soft tissue loss during treatment, and what can be done prior to treatment to prevent negative sequelae.

6.4. Hard Tissue Changes during Class II Correction

When assessing the hard tissue changes that occur during treatment, a general trend that occurs in bony changes observed on both the buccal and lingual is indicative of uncontrolled tipping of the mandibular incisors. The increases in thickness that we see from our data in the buccal bone near the apex (6 to 9 mm apical to the CEJ) and in the lingual bone near the CEJ (3 to 6 mm apical to the CEJ) are in line with what we would expect from uncontrolled tipping (Wehrbein et al., 1994) (Table 5.4.1, Figure 5.4.1, and Figure 5.4.2). If true uncontrolled tipping occurred, one would expect bone loss on the buccal near the CEJ, and on the lingual near the apex (opposite of where bone thickness increases) (Figure 6.4.1). Yet, two parts of our data cannot confirm this expectation. The lack of data of pre-treatment bone 3 mm apical to the CEJ on the buccal cannot confirm this movement. Furthermore, a non-significant decrease in thickness in the lingual near the apex might not strengthen this theory.

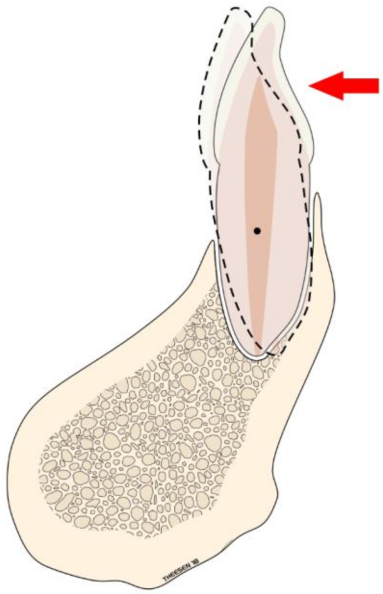
Concerning vertical bone height changes during treatment, there was a mean loss in the vertical heights of the buccal and lingual plates over time, yet both were not statistically significant (Table 5.4.1). However, this finding is very important from another perspective. If only the tooth moved in the housing due to tipping or translation, then we would expect to not only see the bone thicknesses change (which we do), but we would also expect to see the vertical heights change (which we do not). This would suggest that uncontrolled tooth tipping is not the only anatomical change that is occurring. In order for the vertical heights to be maintained during tipping, some other compensation must be concurrently occurring. One potential phenomenon could be the presence of bone bending. Bone bending is one of the commonly proposed theories to explain how teeth move orthodontically (Baumrind, 1969). This theory suggests that when a force is placed on a tooth, all entities intimately related to the tooth, such as the PDL and bone, will actively respond (Baumrind, 1969). In other words, this theory suggests that when force is placed on a tooth, the tooth is not moving independent or free of other surrounding anatomical units. The PDL and surrounding alveolar bone react to the forces they feel, and consequently react through bone modeling and remodeling (Baumrind, 1969). This theory fits well with what our data is conveying. If teeth in our study were in a static alveolar environment, it would not be expected that alveolar bone heights (relative to the tooth CEJ) would be statistically the same before and after treatment. Overall, the hard tissue changes seen in this data set appear to suggest that lower incisor proclination occurs locally through a combination of uncontrolled tipping and alveolar bending.

Concerning changes that occurred on the teeth during therapy, there were unexpected statistically significant changes in both the tooth widths (at the CEJ) and tooth lengths (from the CEJ to apex) (Table 5.4.1). However, when the data is analyzed, both of these statistically significant findings may be called into question. The changes in tooth thickness should remain the same during treatment and no changes should occur. In reality, the mean decrease was only 0.05 mm – a change that is well below that voxel size and resolution of the imaging software. With this in mind, and recognizing that 0.05 mm is not clinically relevant, we are confident that this aspect of the study is a reasonable finding. As it relates to changes in tooth length, we can again call into question whether or not there is clinical relevance from the descriptive statistics. On average, the teeth decreased in length 0.21 mm during therapy. Even though the magnitude of change is again questionable relative to the imaging software's spatial resolution, perhaps a better explanation for changes could be due to anatomical variables. Measuring the apices could be reasonably difficult, as root deviations and dilacerations are difficult to control for in measurements. Furthermore, we know that mandibular incisor apices do not completely close until roughly 3 years after eruption (Proffit et al., 2013). Due to the population studied in this protocol, there is a definite possibility that apical closure and modeling was occurring during therapy, and could directly play a role in skewing measurements. Both of these explanations do not mean that apical root resorption does not occur during Class II correction with these appliances; however, previously reported reliable data suggests that indicators such as significant time in treatment, significant changes in apical movement, and genetics may be more causative factors (Sameshima & Sinclair, 2001, Segal et al., 2004, Weltman et al., 2010). Time in treatment and apical movements would have been relatively minimal in this protocol.

To assess whether or not changes in root length were significant relative to bone height, pre-treatment and post-treatment ratios of CEJ to lingual bone to CEJ to apex length were compared. Statistical analysis suggests that there was no difference between the ratios from pre- to post-treatment ($p = 0.1828$) (Table 5.4.3). This further conveys that any statistical change in root length may not be significant relative to other hard tissue changes.

Finally, findings if the present study indicate that there were no statistically significant changes in hard tissue during treatment that could be dependent on the type of appliance used. Although there were some significant differences in bone thickness in the study subjects before therapy, there were no significant differences that occurred at any location during treatment (Table 5.4.2). This implies that hard tissue changes were not associated with the appliance used to correct the malocclusion.

Figure 6.4.1: Uncontrolled tipping of a mandibular incisor



6.5. Correlations to IMPA Changes and Initial Gingival Biotype

Statistical correlation between changes in incisor proclination, IMPA (degrees), and hard tissue changes confirm some previously discussed results. As the mandibular incisors flare forward, buccal bone thickness increased at 6 mm apical to the CEJ (p = 0.0001) and 9 mm apical to the CEJ (p = 0.010). Conversely, bone decreased in thickness at 9 mm apical to the CEJ on the lingual (p = 0.014) and vertical height decreased on the buccal of the teeth in accordance to proclination (p = 0.010). The rest of the hard tissue correlations were not found to be statistically related to changes in IMPA (Table 5.5.1**)**. These associations reiterate the possibility of uncontrolled tipping, as any increases in IMPA and concurrent statistically significant correlations help to depict the aforementioned changes in bone thicknesses.

Mandibular growth was also found to be significantly associated with IMPA change (p = 0.02) (Table 5.5.2). This negative correlation suggests that patients undergoing active mandibular growth and skeletal change during Class II correction may have milder dentoalveolar compensations in the form of mandibular incisor proclination. Our data supports previous findings that suggests that treatment during peak pubertal growth be a factor that helps to facilitate more skeletal effects than dental effects (proclination) (Pancherz & Bjerklin, 2014). However, many other intra-treatment influences, such as anchorage loss, vertical growth pattern, and initial overjet discrepancy, may play just as large of roles in the ratio of skeletal to dentoalveolar changes (Pancherz & Bjerklin, 2014). Overall, our study indicated that the use of a functional appliance during maximum growth is advisable, as aiming to minimize the amount of incisor proclination and dental compensations should be the ultimate goal. A negative correlation between mandibular growth rate and IMPA was also found, but it was not quite significant ($p = 0.08$) (Table 5.5.2).

When assessing relationships to a patient's gingival biotype, no statistically significant correlations were found with changes in IMPA, keratinized gingiva, or vertical bone height (CEJ to Buccal) (Tables 5.5.3 and 5.5.4). For example, we did not find a relationship that would depict a situation where patients with a thinner biotype would have a stronger correlation to increased proclination, increased loss of keratinized gingiva, or decreased vertical bone height. With that being said, two major confounding factors must be considered. First, our biotype indicators come from maxillary central incisors. The only published, non-invasive, clinical methodology we could find to assess gingival biotype was using maxillary incisors (De Rouck et al., 2009). This obviously causes issues for many reasons, with the most notable issue being the reliability to correlate a maxillary biotype and mandibular biotype. The second issue is that poor hygiene could affect biotype assessment. Some patients had brackets on their maxillary incisors, and orthodontic related gingival hypertrophy or hyperplasia could affect biotype indication. This could also negatively skew our results. The data regarding gingival biotype and its correlations is weak at best, with the core issue being the clinical determination and accuracy.

There is ample literature suggesting that patients with a thin biotype are at risk for recession (Olsson & Lindhe, 1991). However, there does not seem to be a definitive agreement what constitutes different categories of gingival biotypes. Furthermore, most of the literature related to biotype determination is either limited to evaluating the maxillary incisors, is related to prosthetic and esthetic concerns, or categorizes based on a clinically invasive procedure (Cook et al., 2011, Lee et al., 2011, De Rouck et al., 2009). None of these factors are truly relevant to our study, or to any practitioner who is concerned about the dentoalveolar support in the anterior mandible during Class II corrective therapy. Thus, a more comprehensive and non-invasive methodology of categorizing mandibular incisor biotypes is needed.

6.6. Limitations of the Study

6.6.1. Radiographic Limitations

Perhaps the first limitation of the study that should be noted relates to CBCT imaging. It is well documented that CBCT is a reliable tool for research and orthodontic treatment (Kapila et al., 2011). However, some issues arise when attempting to accurately measure the most delicate hard tissue samples, such as those seen on the buccal of mandibular incisors (Molen, 2010). The technology we used offers a diagnostic value of 0.2 mm voxels. In theory, this means we could measure up to 0.2 mm reliably. However, research shows that the actual spatial resolution is worse than the true voxel size, as factors such as artifacts and noise negatively affect the image quality (Molen, 2010). Our spatial resolution is not entirely known, but past studies of older CBCTs correlated a 0.2 mm voxel size to a spatial resolution closer to 0.4 mm (Ballrick et al., 2008). Our unit is much newer than those studied, and advances in technology over the past decade probably have diminished the discrepancy between voxel size and true spatial resolution, but this inconsistency must not be overlooked. This information makes it important to not rely entirely on the p-values and statistical significance when looking at CBCT data. Rather, it is important to also look at the actual magnitudes of change and assess if they realistically can be measured or assessed based off the voxel size, or more importantly, the true spatial resolution.

Radiographic limitations of lateral cephalometric radiographs should also be noted. A common limitation of data garnered from lateral cephalometric radiographs is related to landmark identification (Major et al., 1994). We attempted to minimize any potential issues with this by having two clinicians agree upon the necessary landmarks. However, it can be very difficult to perfectly measure landmarks, which would directly affect all cephalometric data.

6.6.2. Clinical Limitations

There are a few clinical limitations to this study that may have affected data collection and statistical outcomes. The first and most significant clinical limitation deals with patient hygiene. Hygiene is very hard to control for, and it is well known that poor hygiene during orthodontic treatment can cause gingival hyperplasia (Krishnan et al., 2007)**.** In our study, changes in probing depths could be overestimated as poor hygiene could cause pseudo-pocketing. Intra-examiner reliability for soft tissue measurements would be difficult to assess as well.

Another clinical limitation is the inability to accurately diagnose biotypes for mandibular incisors. Our study utilized the De Rouck protocol for measuring biotype; however, this clinical indicator is using maxillary central incisors, not mandibular incisors (De Rouck et al., 2009). Much more research needs to be completed to provide a methodology that allows for clinicians to reliably and non-invasively diagnose the biotype of the mandibular incisors.

A final clinical limitation is that we were not able to randomize the appliance use between the three types. Ideally, we would have been able to randomly assign the appliances, especially between the Herbst and MARA subsets. Due to the nature of assignments of patients at our clinic, pure randomization was not possible.

6.6.3. Relapse of Proclination

There is some data that shows that proclination will relapse or rebound after Class II correction has finished (Rodrigues de Almeida et al., 2005, Pancherz, 1991, Pancherz & Bjerklin, 2014). To ideally evaluate this parameter, we would have CBCTs and lateral cephalometric data at the initial date of activation, the date of deactivation, and then some period of time after therapy has ended. As we tried to minimize radiation exposure, we realized it was not feasible to take three CBCTs. Thus, we settled on taking scans at the initial activation time point and then again at the deactivation date, as this is where the most amount of proclination would occur. Furthermore, any continuous fixed appliance therapy after the appliances studied were removed would affect the outcome of incisor proclination. Thus, limiting the study to just the period of time when the only change in treatment was the addition of either a Forsus™, Herbst, or MARA allowed for us to determine that any changes were solely due to these appliances.

6.6.4. Long-Term Follow Up

One of the commonly held beliefs as it relates to orthodontic proclination is that the periodontal effects and ramifications may not occur immediately; rather, some suggest that the repercussions may only become apparent later on in life (Slutzkey & Levin, 2008). Other groups dispute those claims and provide results that show long-term periodontal health and stability (Ruf et al., 1998). There is limited data on the long-term effects of these appliances. Due to the nature of this study, we are unfortunately not able to provide any long-term data that is needed in this field.

6.7. Conclusions

The data collected suggests that Class II correctors and functional appliances significantly procline the mandibular incisors during treatment. Corresponding hard and soft tissue changes occur in a statistically significant manner, but these changes may be small in magnitude and may not be clinically measurable or noteworthy. Presence and absence of hard tissue changes at specific locations suggest that mandibular incisor proclination occurs in a manner that includes a combination of both uncontrolled tipping and alveolar bending. Therefore, hard tissue changes and damage that could result from uncontrolled tipping may be minimized by bone bending. Correlations between incisor angulation changes and hard and soft tissue changes confirm these dimensional findings.

Overall, these outcomes suggest that Forsus™ appliances, Herbst appliances, and MARAs effectively correct Class II malocclusions without negative, short-term periodontal outcomes. However, these appliances should still be used judiciously in those patients with pre-treatment periodontal concerns and/or with mandibular incisors that are already significantly proclined before orthodontic care.

6.8. Future research

Future research in this field could address some limitations of this current study. First and foremost, we must improve upon the already excellent imaging that CBCT data provides us. It should be a priority to find a way to more accurately image the most precious and notable site for potential bone loss: anywhere from 0 to 6 mm apical from the CEJ on the buccal surface of teeth. Better spatial resolution is needed to efficiently measure these areas, but this currently comes with larger radiation doses. We should work more effectively at increasing image resolution while concurrently lowering radiation doses.

Another radiographic limitation that should be more thoroughly addressed is the discrepancy between what bone measurements are seen in the patient clinically, and how that bony architecture is displayed radiographically. Some research has been done in this arena previously, and it suggests that CBCT underestimates the bony support that is truly present

(Patcas et al., 2012). However, as we improve technology, we should be able to provide a better depiction of what is exactly occurring clinically.

A final point of emphasis for future studies revolves around the need for more robust long-term data in this area of research. It currently appears that these treatment modalities do not affect the dentoalveolar support of the mandibular incisors in the short-term, but we still lack sufficient data to suggest what may occur many decades after therapy. There is conflicting evidence on this issue, but ultimately it is the most important question that must be answered in the coming years.

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ADDENDUM

Figure a5.2.6a: Differences in initial (p = 0.188) and final (p = 0.121) values of IMPA (degrees) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

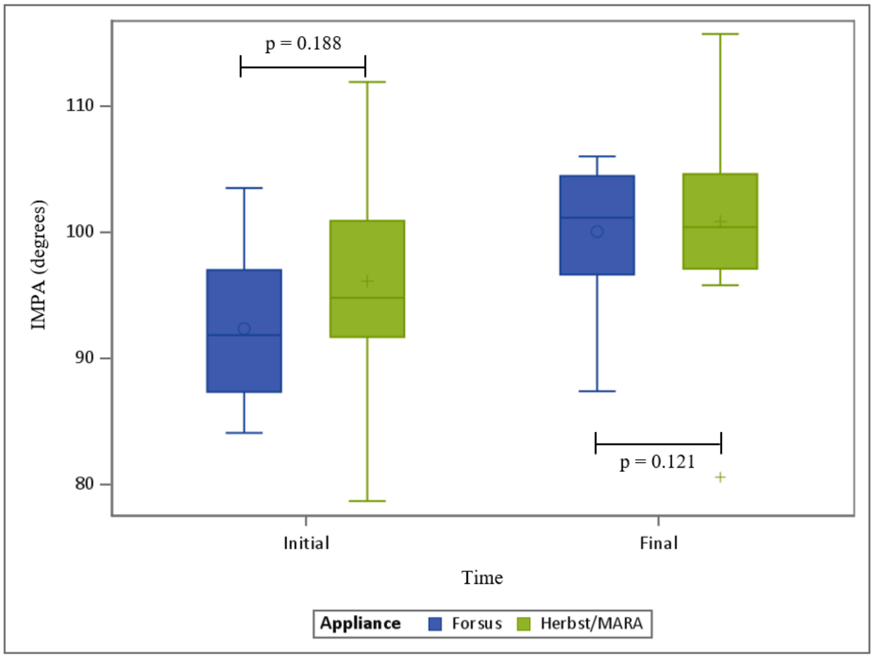

Figure a5.2.6b: Differences in change (p = 0.121) of IMPA (degrees) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

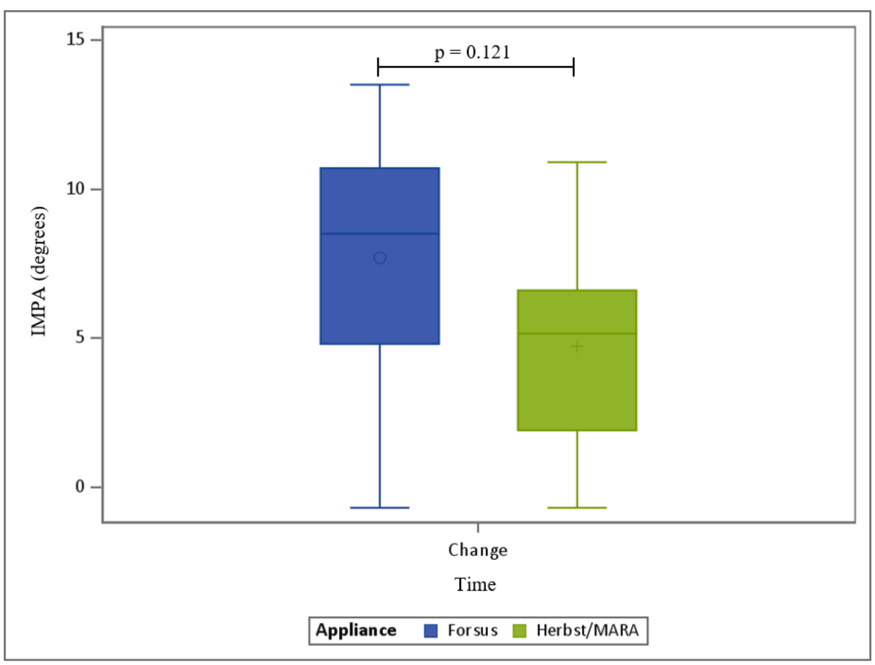

Figure a5.2.7a: Differences in initial (p = 0.984) and final (p = 0.284) values of Lower Incisor to A-Po (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

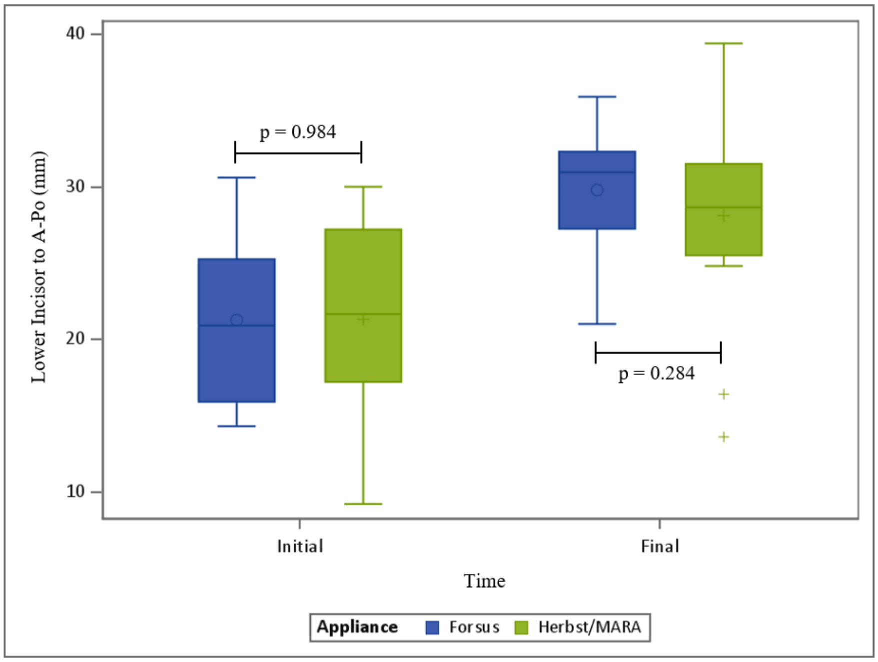

Figure a5.2.7b: Differences in change (p = 0.284) of Lower Incisor to A-Po (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

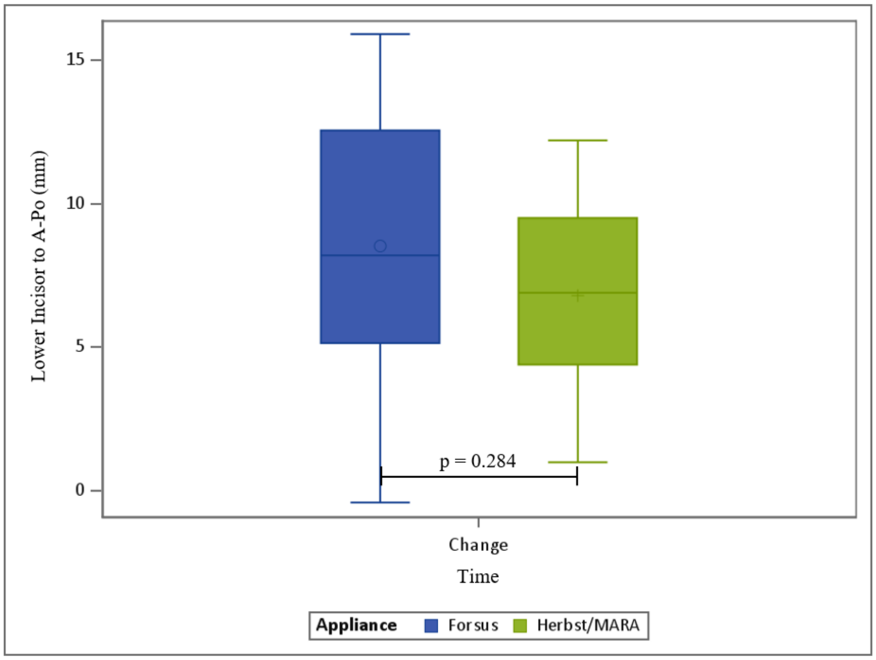

Figure a5.2.8a: Differences in initial (p = 0.134) and final (p = 0.095) values of ii/OLp (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

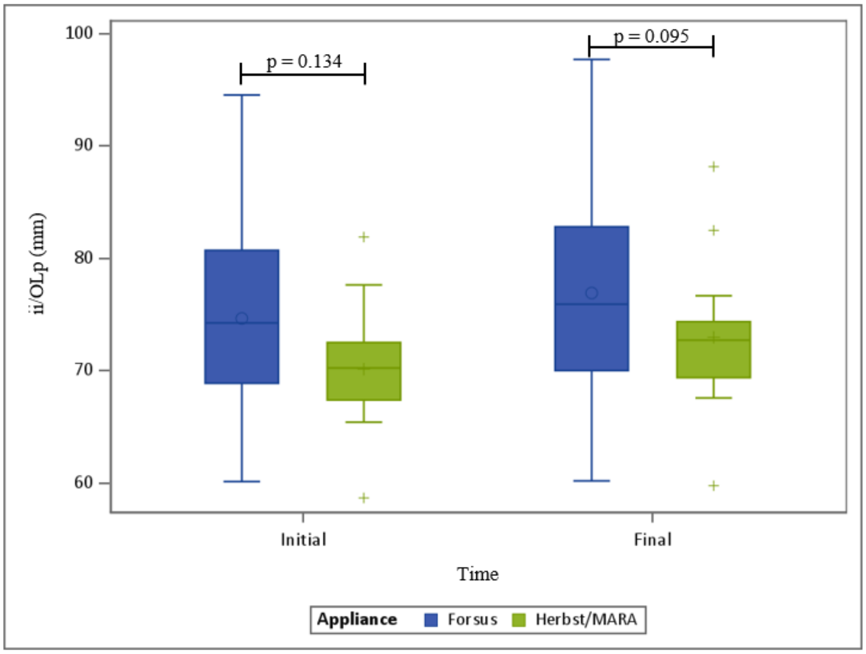

Figure a5.2.8b: Differences in change (p = 0.095) of ii/OLp (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

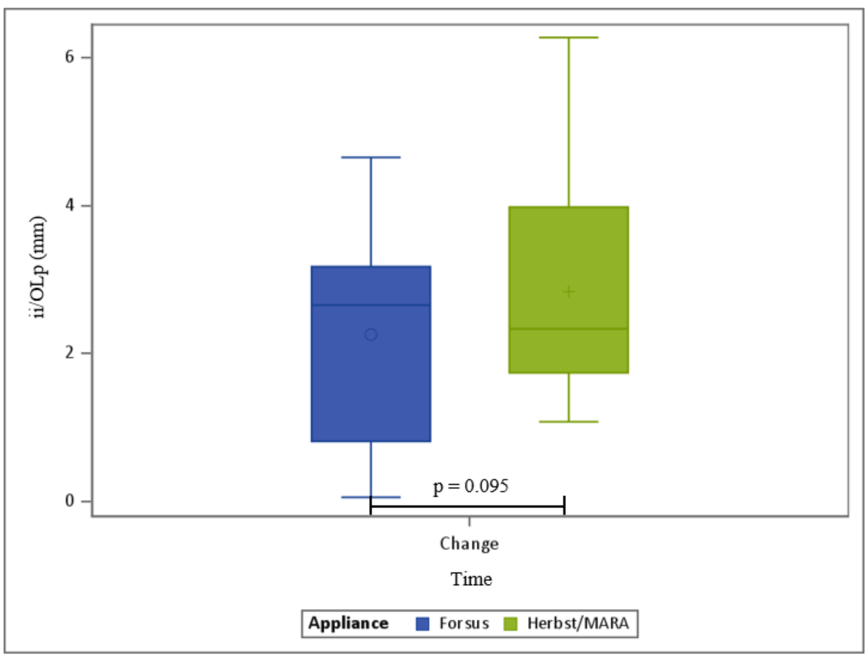

Figure a5.3.4a: Differences in initial (p = 0.41) and final (p = 0.19) values of probing depths (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

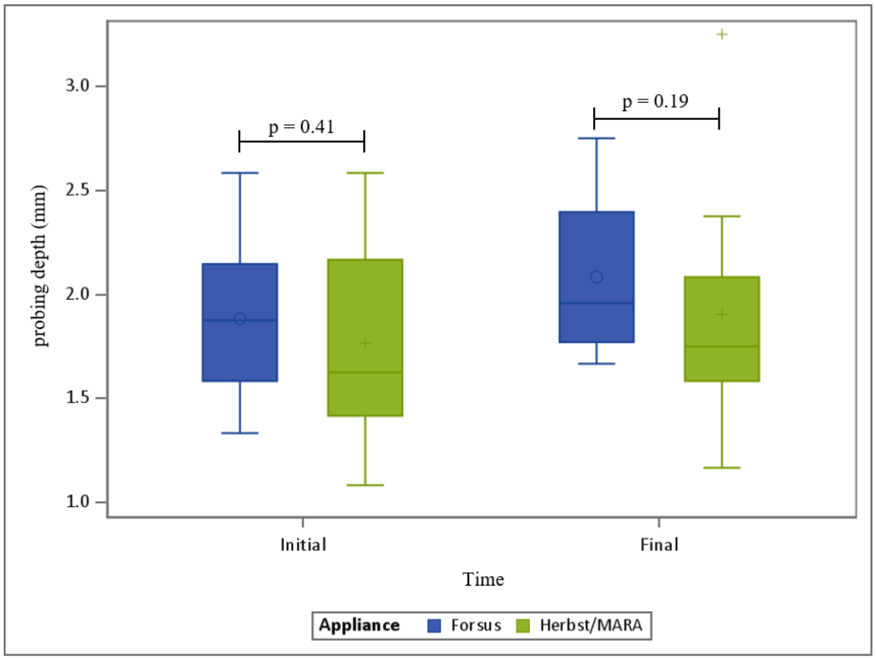

Figure a5.3.4b: Differences in change (p = 0.19) of probing depths (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

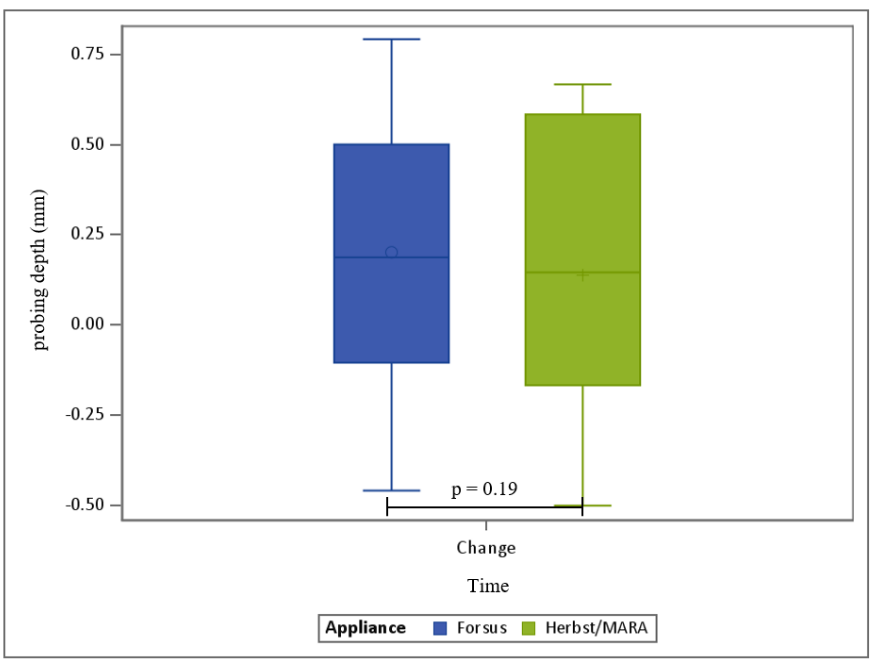

Figure a5.4.12: Initial and final buccal bone thickness measurements at 3 mm apical to the CEJ in all appliances (n = 26) (p = 0.8953). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

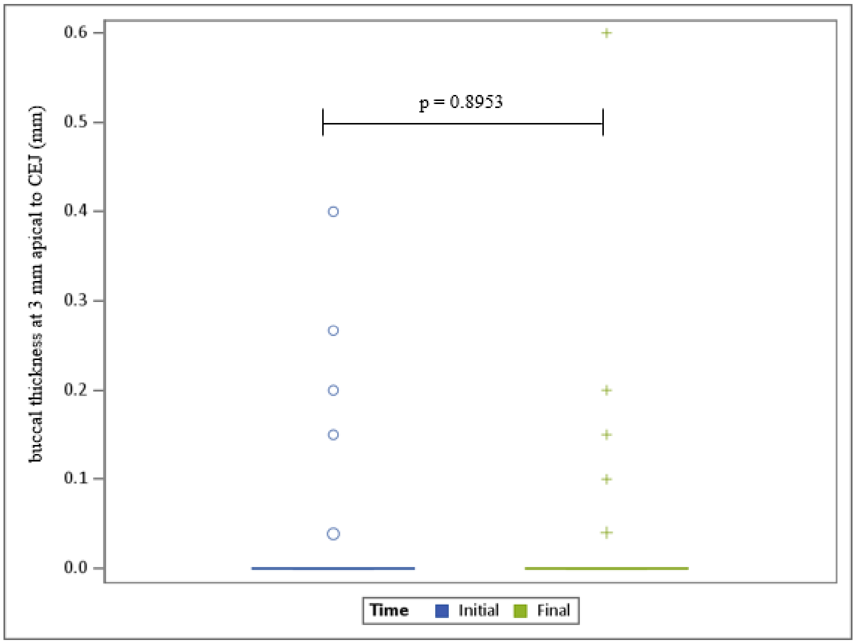

Figure a5.4.13: Initial and final lingual bone thickness measurements at 9 mm apical to the CEJ in all appliances (n = 26) (p = 0.5929). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

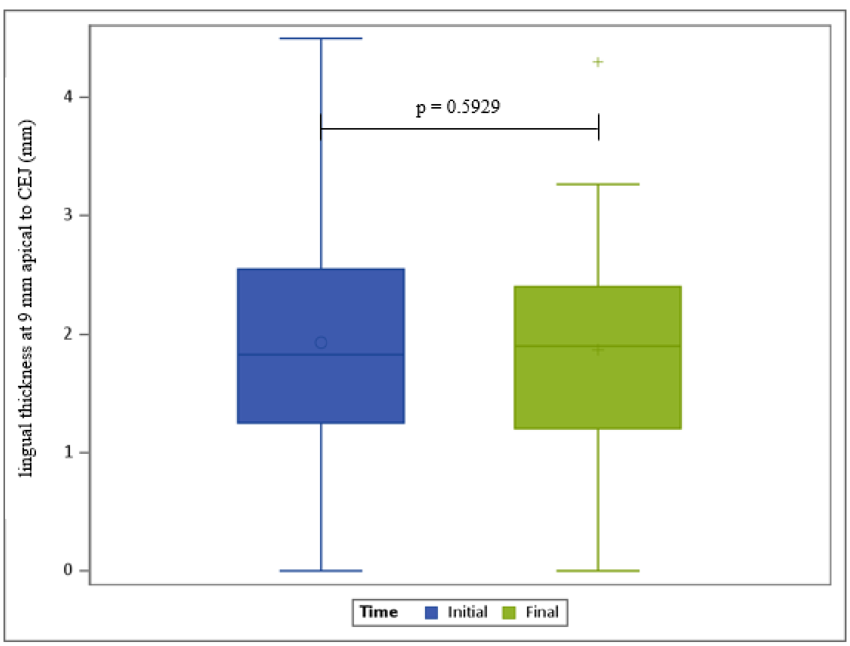

Figure a5.4.14: Initial and final buccal bone heights in all appliances (n = 26) (p = 0.2622). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

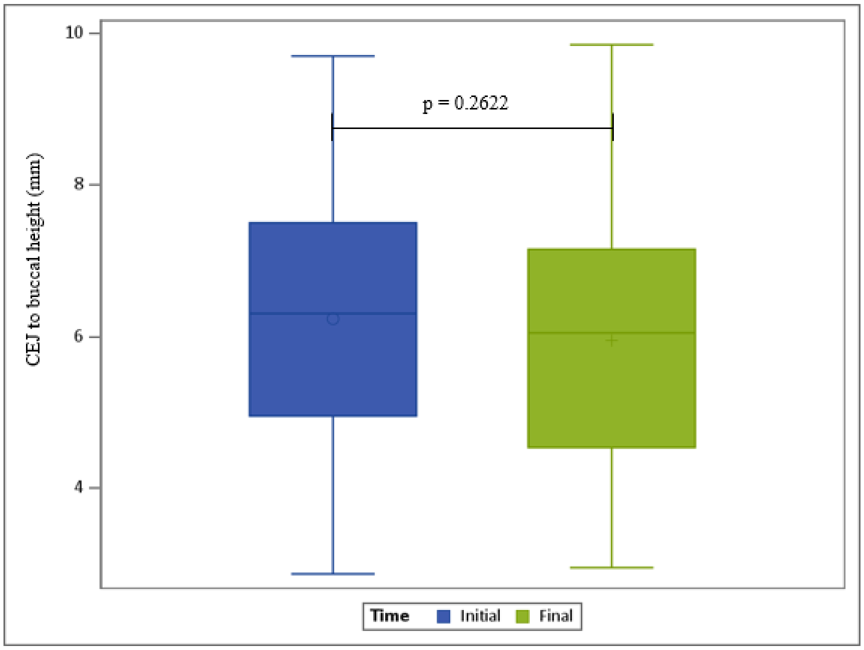

Figure a5.4.15: Initial and final lingual bone heights in all appliances (n = 26) (p = 0.1145). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

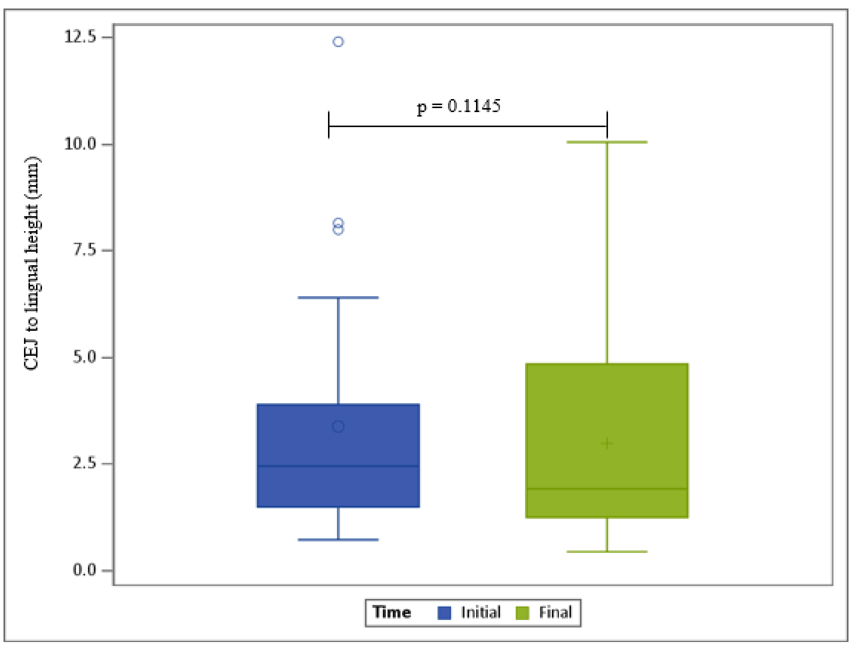

Figure a5.4.16a: Differences in initial (p is N/A) and final (p = 0.42) values of buccal bone thickness at 3 mm apical to the CEJ (mm) between Forsus^{TM} (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

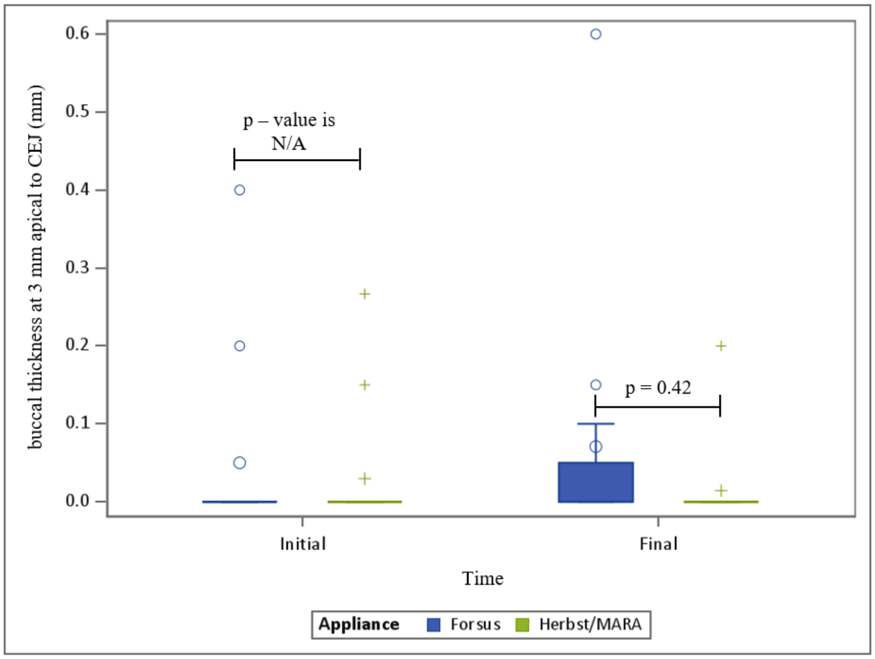

Figure a5.4.16b: Differences change (p = 0.42) of buccal bone thickness at 3 mm apical to the CEJ (mm) between Forsus^{TM} (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

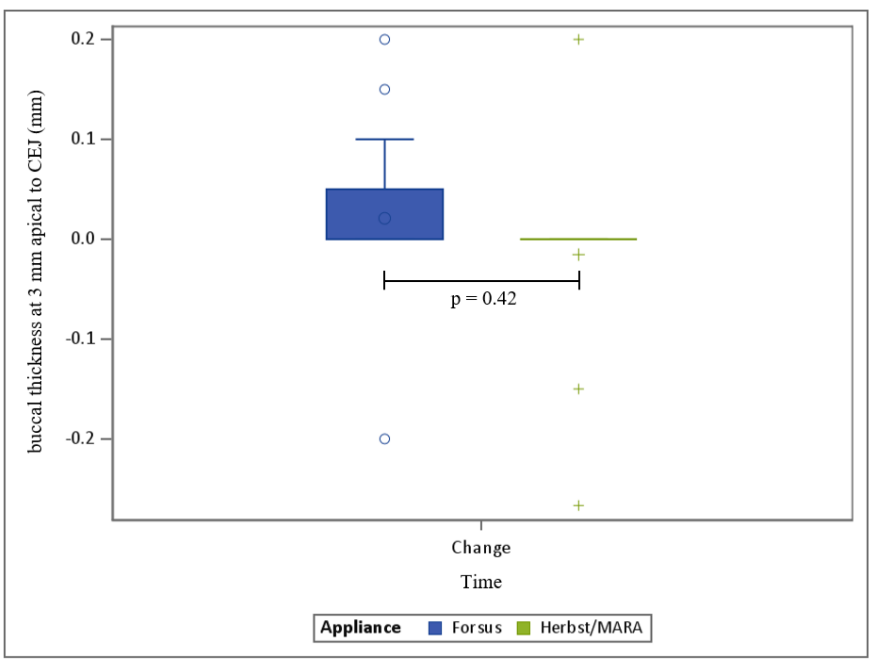

Figure a5.4.17a: Differences in initial (p = 0.57) and final (p = 0.18) values of buccal bone thickness at 6 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

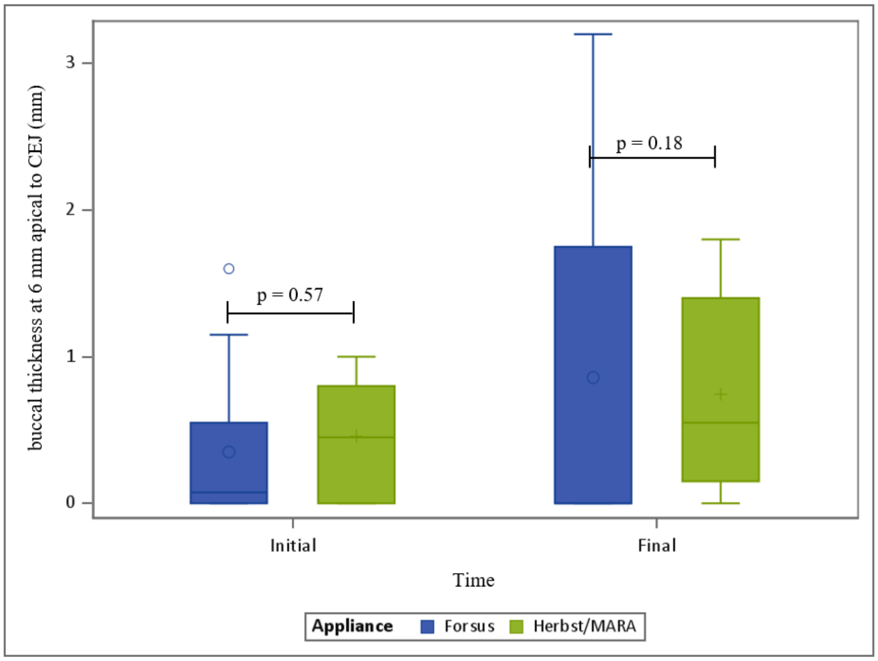

Figure a5.4.17b: Differences in change (p = 0.18) of buccal bone thickness at 6 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

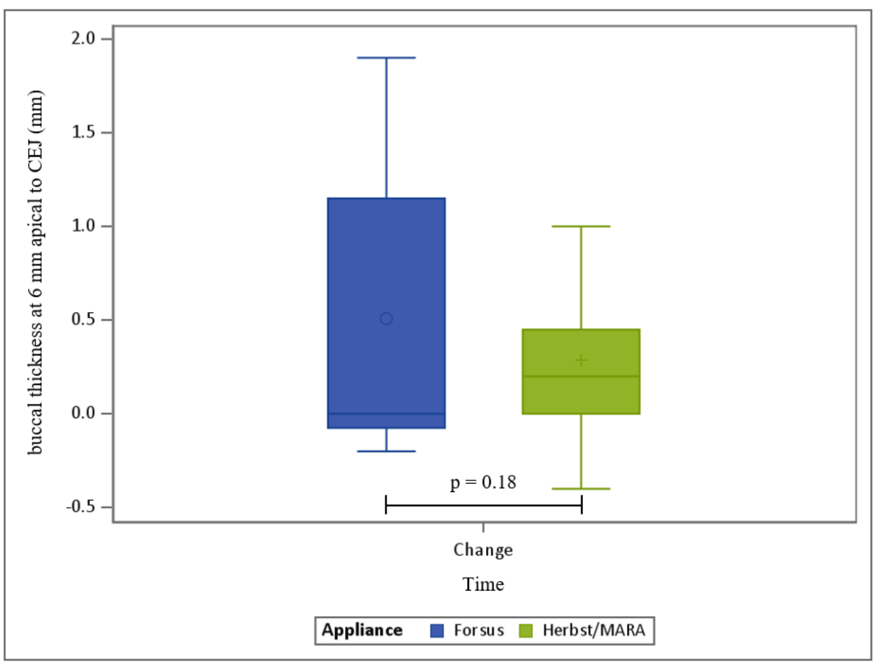

Figure a5.4.18a: Differences in initial (p = 0.24) and final (p = 0.28) values of buccal bone thickness at 9 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

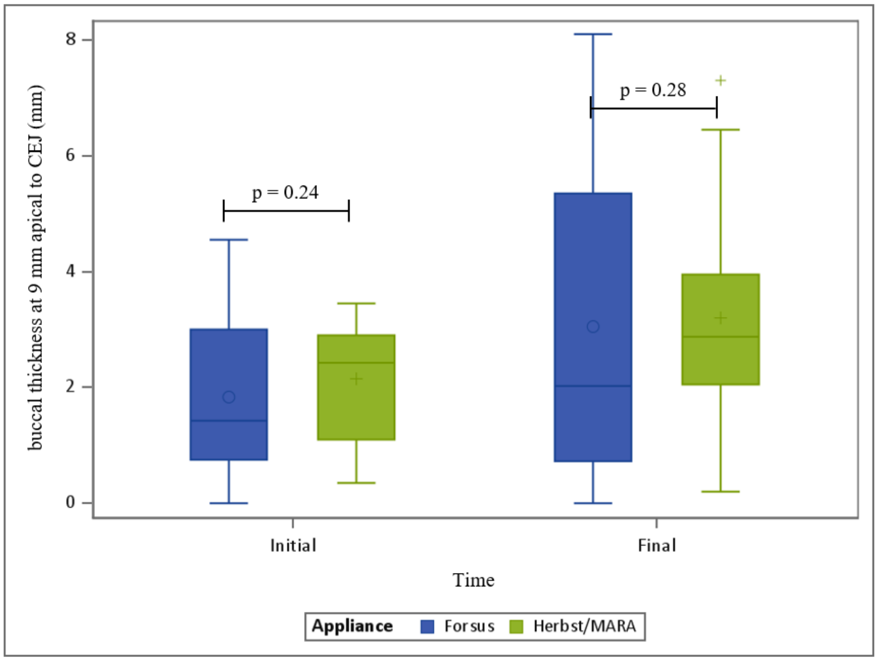

Figure a5.4.18b: Differences in change (p = 0.28) of buccal bone thickness at 9 mm apical to the CEJ (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

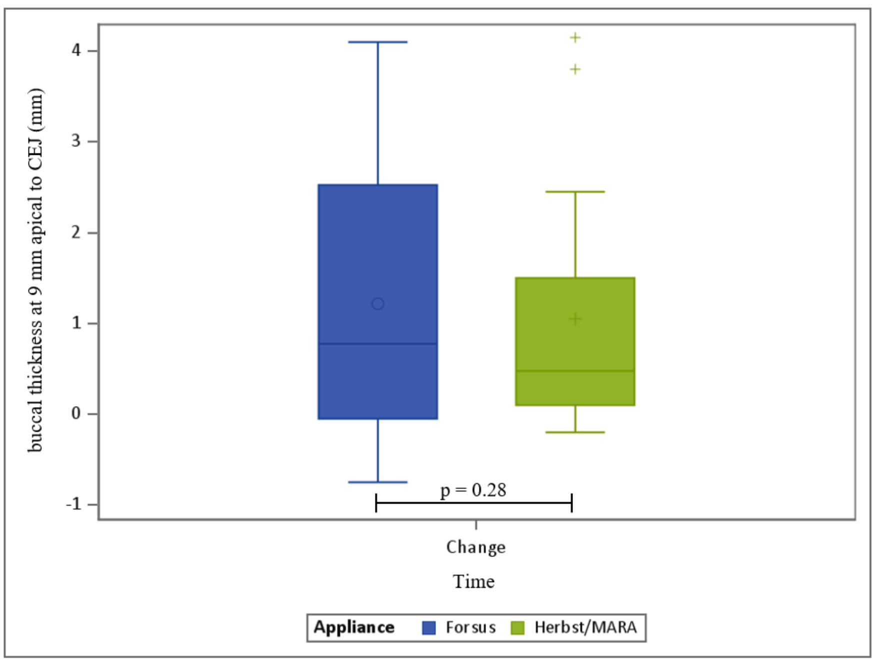

Figure a5.4.19a: Differences in initial (p = 0.05) and final (p = 0.88) values of lingual bone thickness at 6 mm apical to the CEJ (mm) between Forsus^{TM} (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

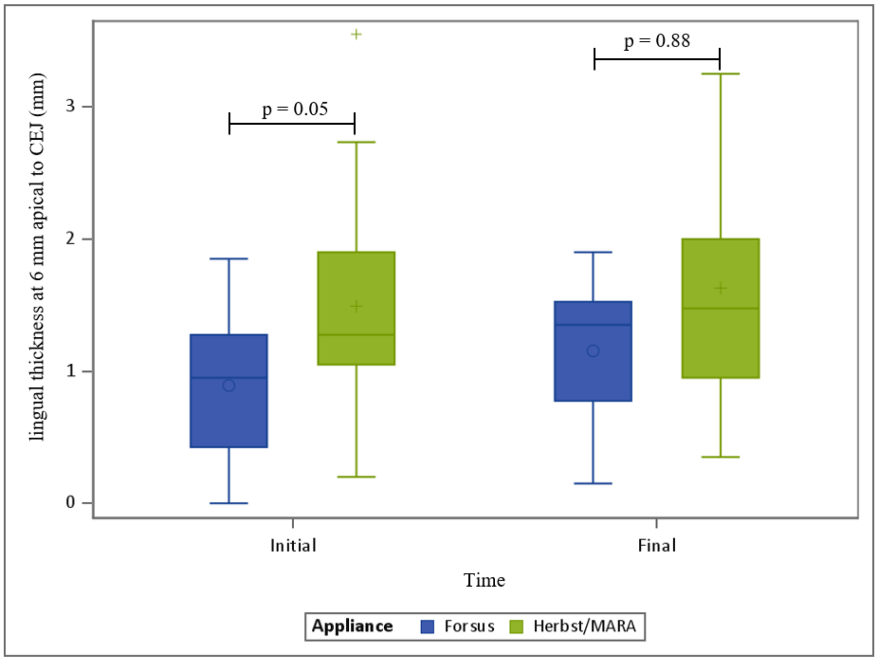

Figure a5.4.19b: Differences in change (p = 0.88) of lingual bone thickness at 6 mm apical to the CEJ (mm) between Forsus^{TM} (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

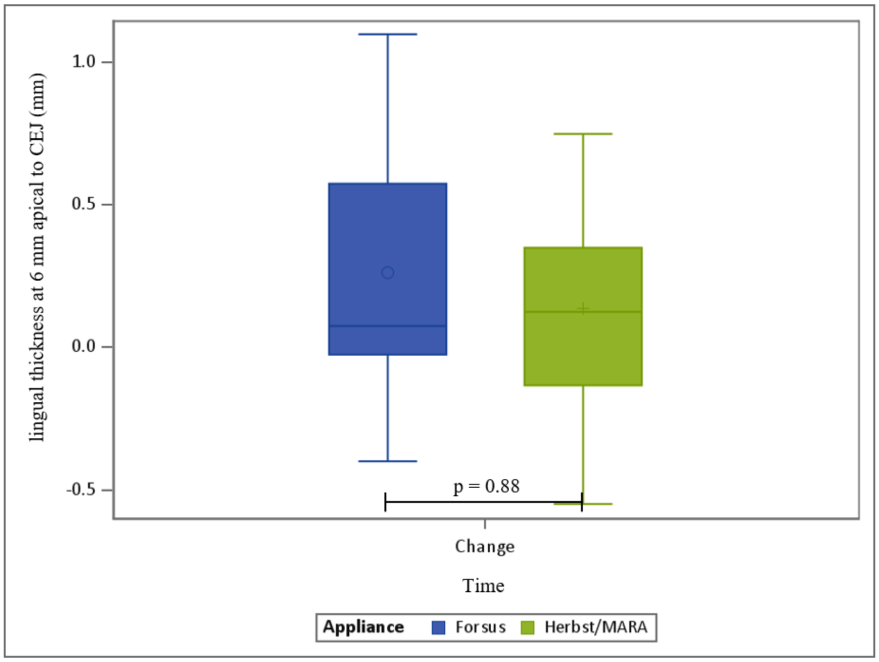

Figure a5.4.20a: Differences in initial (p = 0.38) and final (p = 0.61) values of CEJ to buccal bone height (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

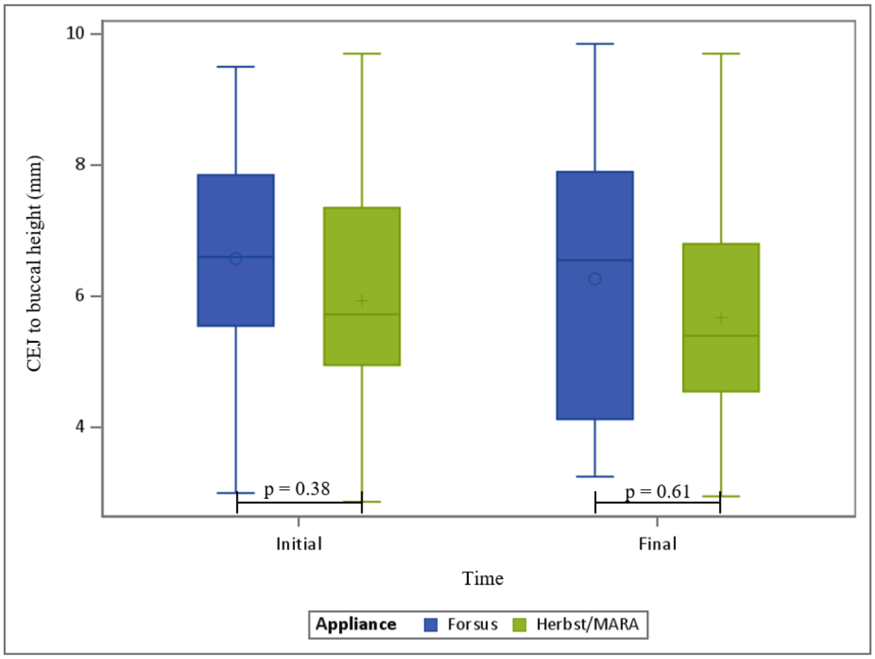

Figure a5.4.20b: Differences in change (p = 0.61) of CEJ to buccal bone height (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

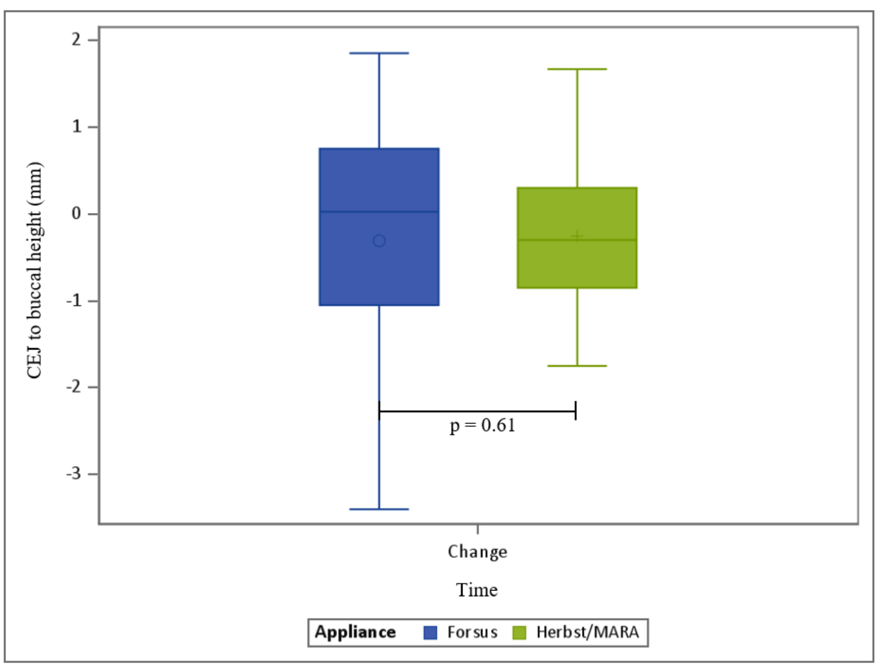

Figure a5.4.21a: Differences in initial ($p = 0.15$) and final ($p = 0.19$) values of CEJ to CEJ width (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

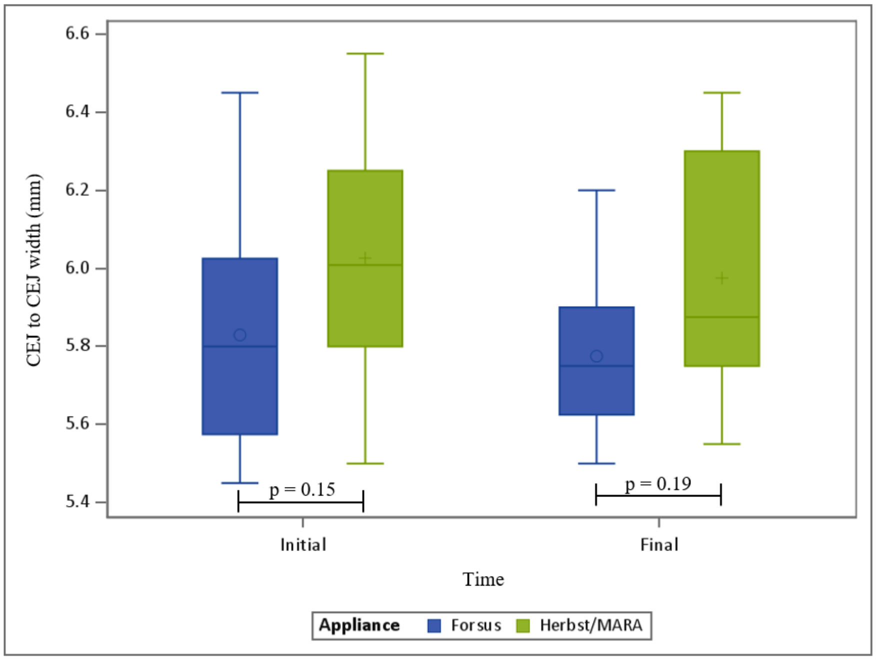

Figure a5.4.21b: Differences in change ($p = 0.19$) of CEJ to CEJ width (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

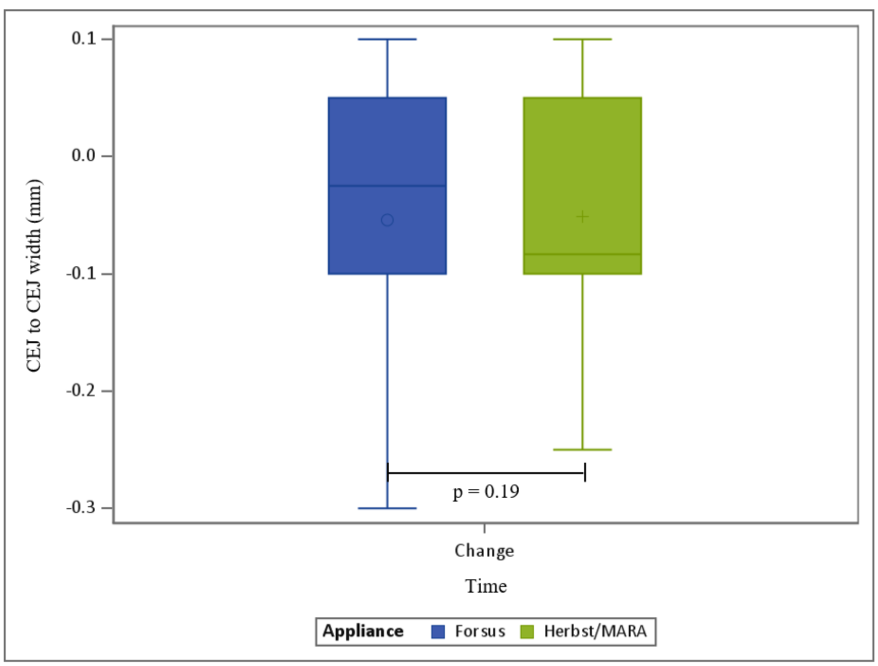

Figure a5.4.22a: Differences in initial (p = 0.39) and final (p = 0.09) values of CEJ to apex length (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

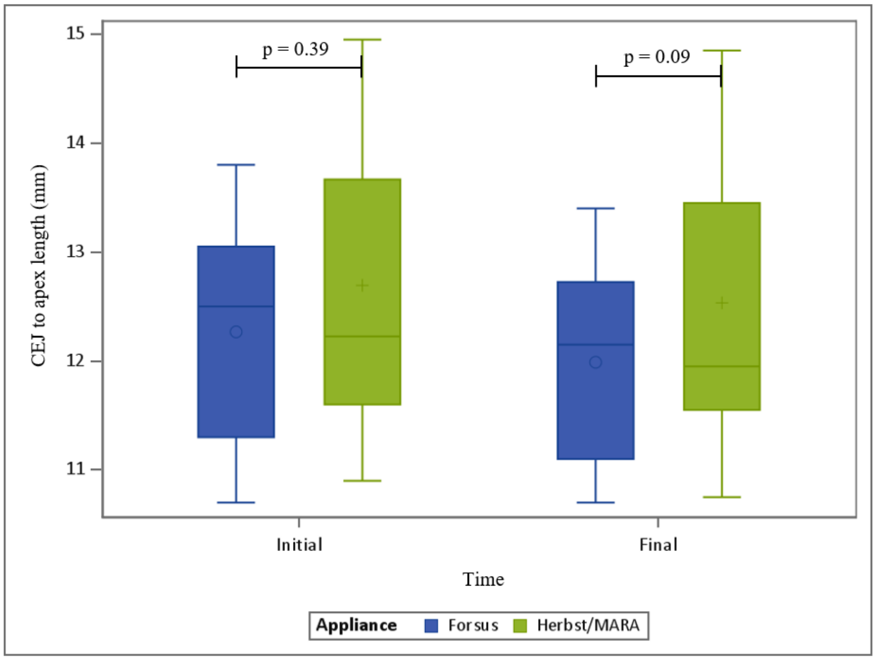

Figure a5.4.22b: Differences in change (p = 0.09) of CEJ to apex length (mm) between Forsus™ (n=12) and Herbst/MARA (n=14) groups. Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

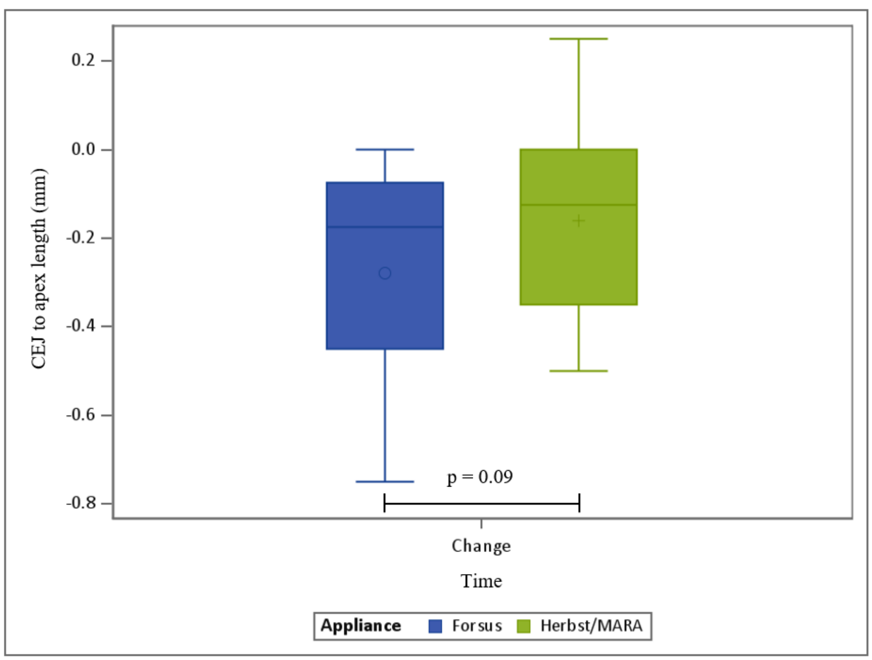

Figure a5.5.6: Correlation between changes in IMPA (degrees) and changes in buccal bone thickness 3 mm apical to the CEJ in all appliances (n=26) (p = 0.057)

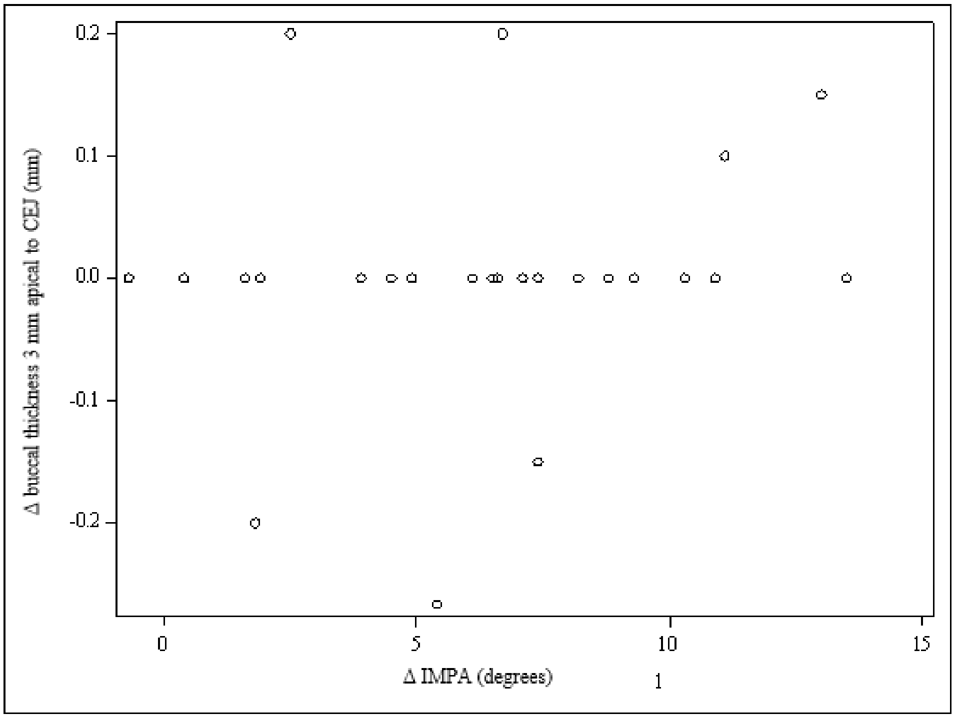

Figure a5.5.7: Correlation between changes in IMPA (degrees) and changes in lingual bone thickness 3 mm apical to the CEJ in all appliances (n=26) (p = 0.317)

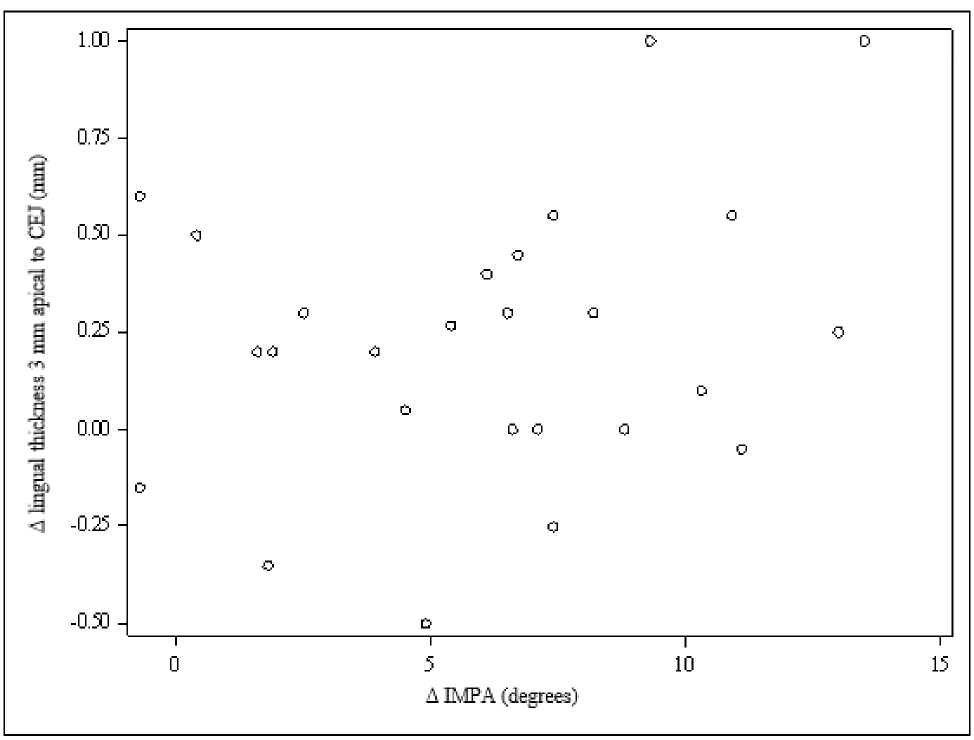

Figure a5.5.8: Correlation between changes in IMPA (degrees) and changes in lingual bone thickness 6 mm apical to the CEJ in all appliances (n=26) (p = 0.408)

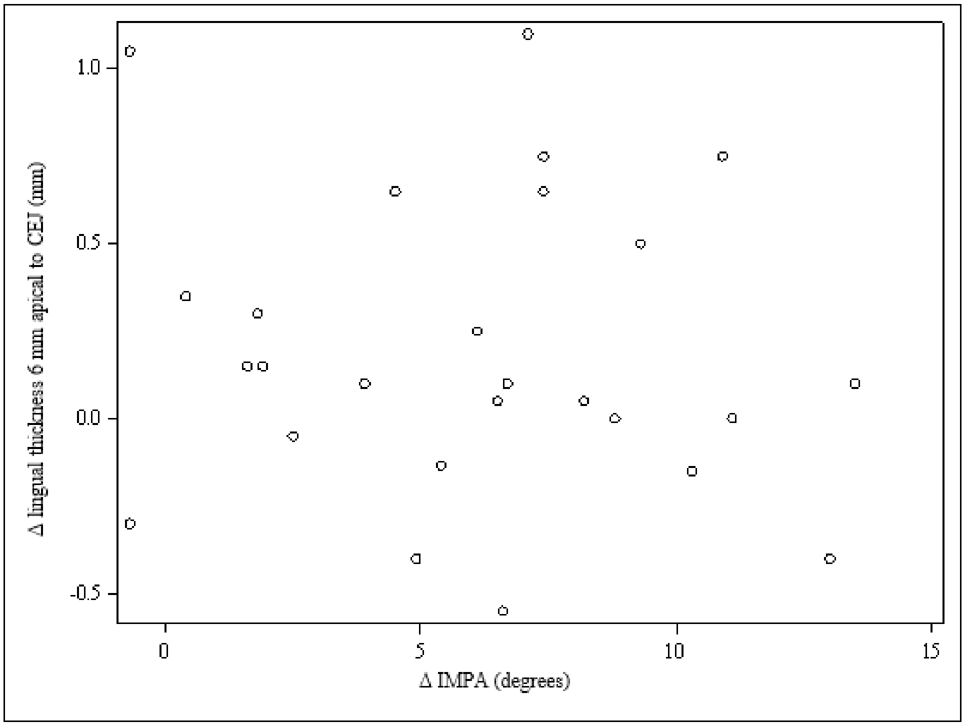

Figure a5.5.9: Correlation between changes in IMPA (degrees) and changes in CEJ to lingual bone height in all appliances (n=26) (p = 0.654)

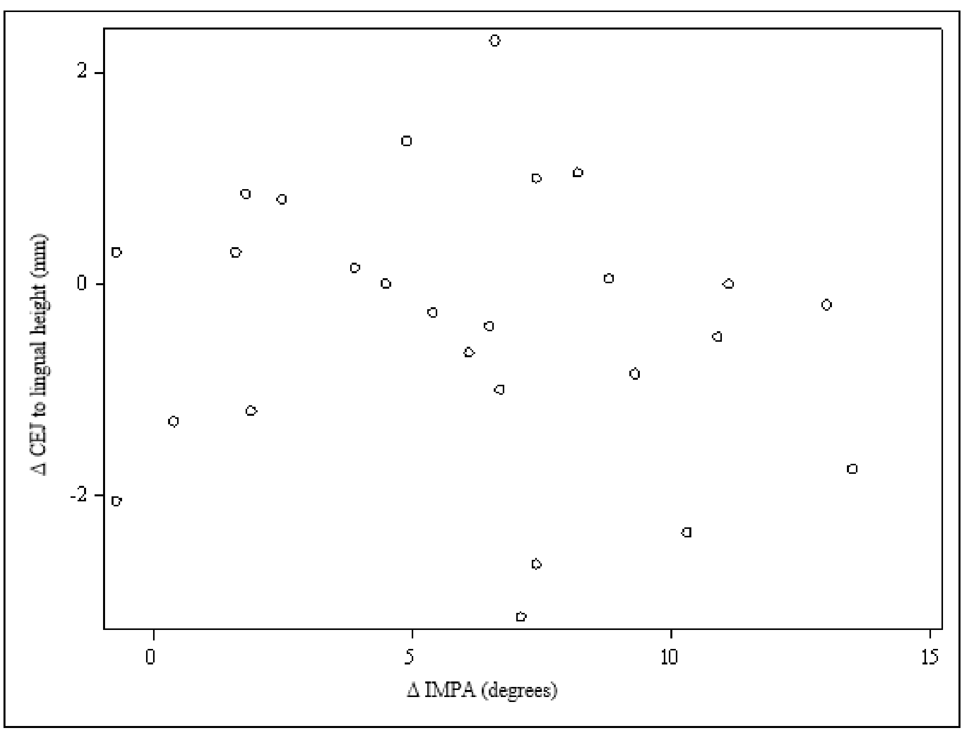

Figure a5.5.10: Correlation between changes in IMPA (degrees) and changes in CEJ to CEJ width in all appliances (n=26) (p = 0.819)

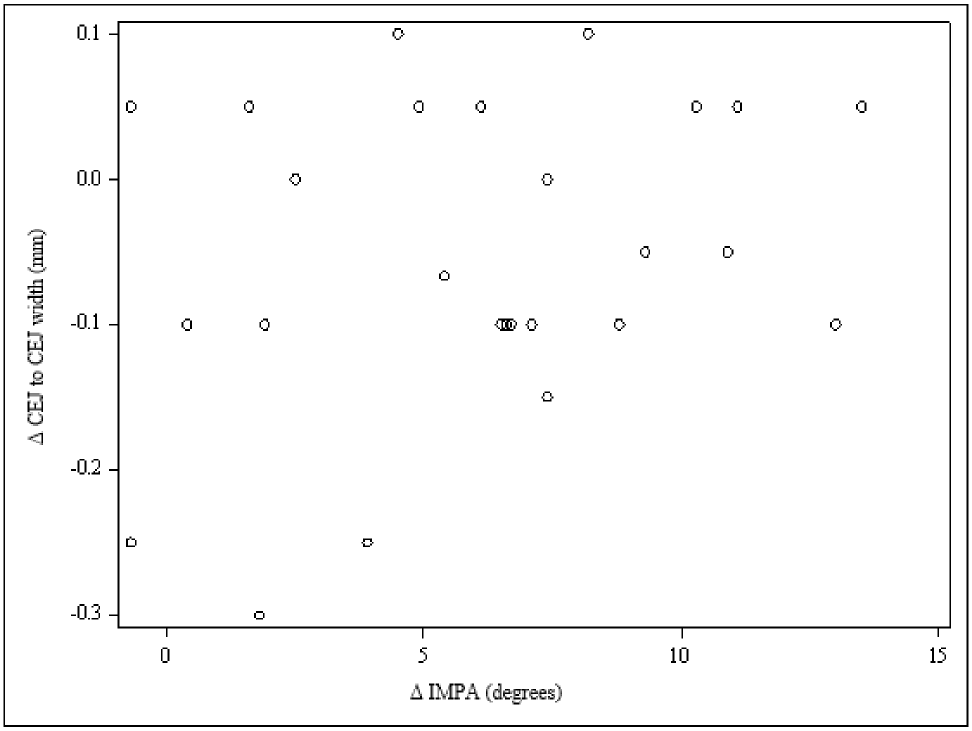

Figure a5.5.11: Correlation between changes in IMPA (degrees) and changes in CEJ to apex length in all appliances (n=26) (p = 0.251)

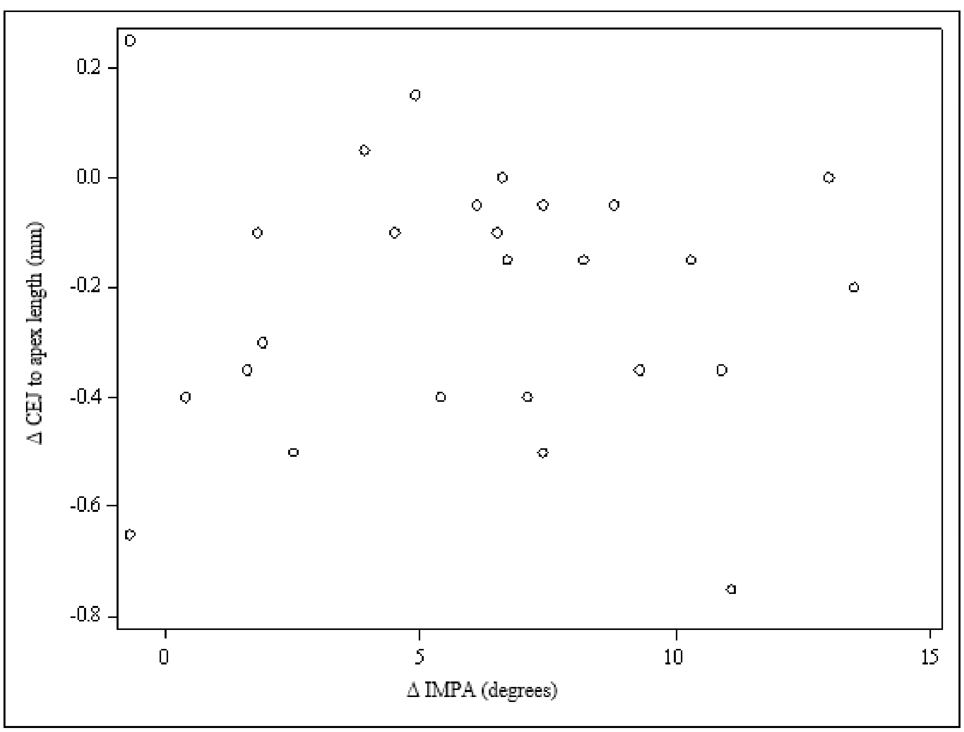

Figure a5.5.12: Correlation between changes in IMPA (degrees) and changes in keratinized gingiva thickness in all appliances (n=26) (p = 0.815)

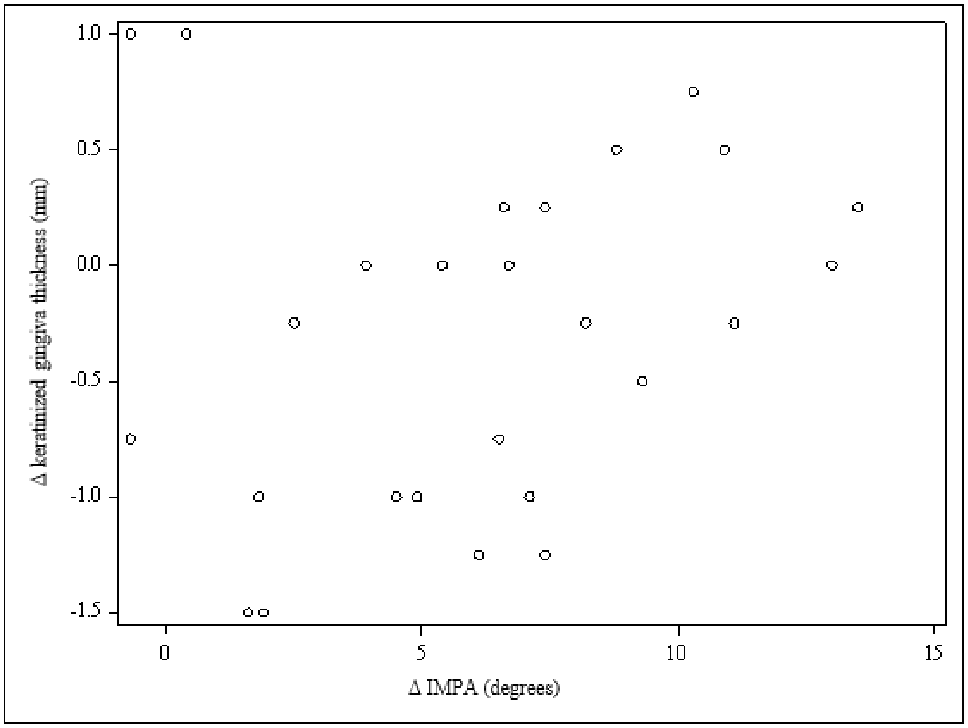

Figure a5.5.13: Correlation between changes in mandibular growth rate (mm/month) and changes in IMPA (degrees) and in all appliances (n=26) (p = 0.08)

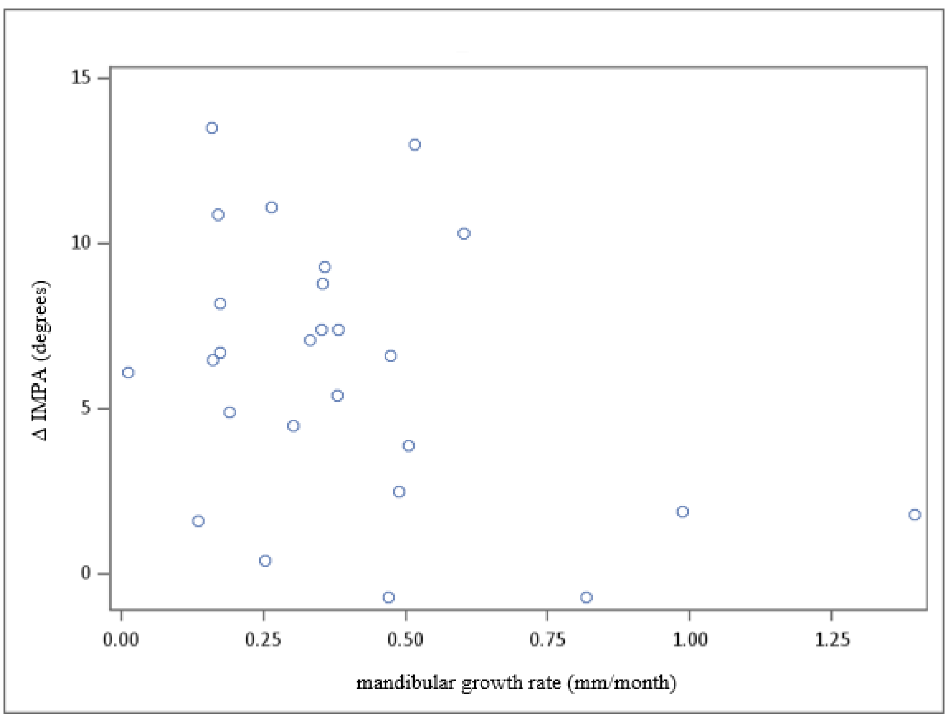

Figure a5.5.14: Correlation between biotype and changes in IMPA (degrees) and in all appliances (n=26) (p = 0.141). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

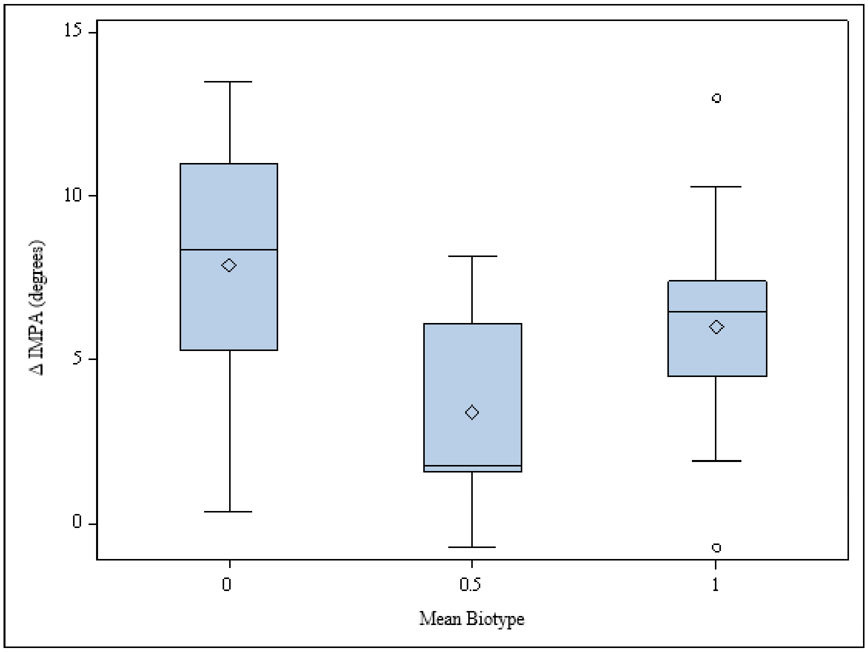

Figure a5.5.15: Correlation between biotype and changes in CEJ to buccal bone height (mm) and in all appliances (n=26) (p = 0.252). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.

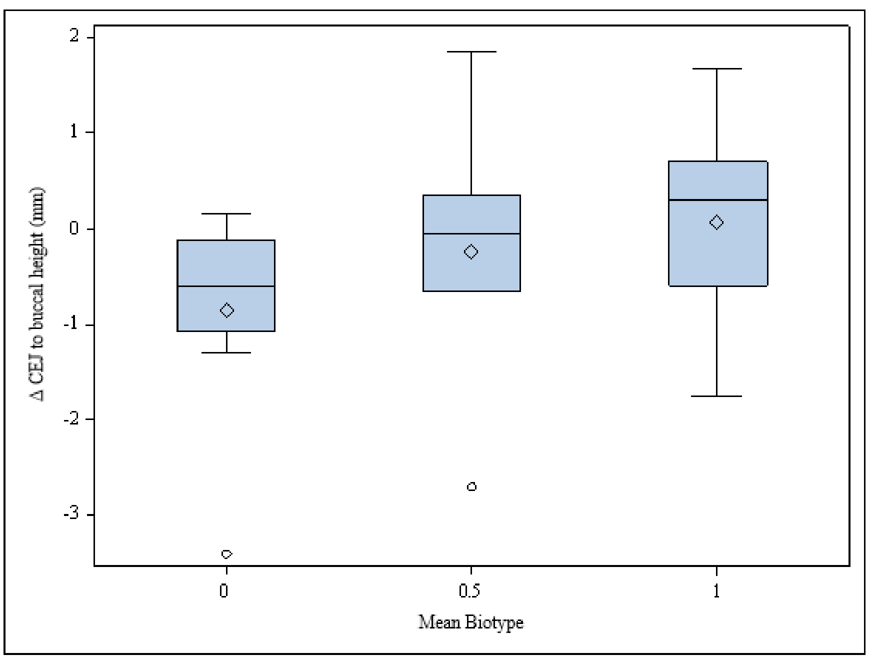

Figure a5.5.16: Correlation between biotype and changes in keratinized gingiva thickness (mm) and in all appliances (n=26) (p = 0.575). Bars define minimum and maximum values unless outlier is present. 25th and 75th quartiles are defined by boxes. Means and medians are defined by dots and lines, respectively.