LONG-TERM STABILITY OF MANDIBULAR ALIGNMENT AFTER ORTHODONTIC TREATMENT

A Dissertation

by

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ABSTRACT

The objectives of the present study were first, to synthesize the literature pertaining to post-treatment mandibular alignment changes, second to evaluate post-treatment mandibular growth and dentoalveolar changes, third to assess the relationship between mandibular incisor mesiodistal angulation and alignment changes, and finally, to evaluate treatment and post-treatment changes of mandibular anterior teeth rotation and curve of Spee leveling. The first study was a systematic review and meta-analysis that assessed the orthodontic literature pertaining to post-treatment mandibular alignment. The second study evaluated mandibular growth and dentoalveolar changes, using cephalometric radiographs of 100 orthodontic patients treated with four premolar extractions and followed-up an average of 19 years. The third study used panoramic radiographs and orthodontic models from the previously described sample to assess the relationship between mandibular incisors distal root tip and alignment changes. The fourth study used orthodontic models of the patients in the second study to assess post-treatment relapse of orthodontically rotated anterior teeth and curve of Spee leveling. The first study showed that post-treatment mandibular irregularity increases are limited, with slightly greater increases in patients treated with premolar extractions and in patients followed up over longer periods. The second study showed substantial amounts of post-treatment mandibular growth, which was greater in males than females, and in younger than older patients. It also showed that the dentoalveolar changes were affected by the retention method used and extraction patterns. The third study confirmed that post-treatment mandibular alignment changes were limited. It also showed that the mandibular incisors finished treatment with slight distal root tip, and exhibited minimal post-treatment changes. There was no relationship between mandibular incisors angulation at the end of treatment and mandibular alignment changes. The fourth study showed that there was post-treatment relapse of the rotational and COS changes that occur during treatment. The mandibular lateral incisors were most likely to relapse.

DEDICATION

This work is dedicated to my parents, wife, children, and siblings for their enduring love, support, and patience throughout my education journey.

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Statement of the Problem

Relapse and post-treatment instability of orthodontically moved teeth have been shown to occur time and time again after the removal of orthodontic appliance. Relapse is a reaction to orthodontic treatment; it usually occurs shortly after appliance removal either due to lack of adequate retention or violation of the biological boundaries. Post-treatment instability is due to contact slippage of teeth that result from factors other than treatment. Post-treatment stability is multi-factorial in nature. [1-3] Factors such as the memory force from transformed PDL fibers, [4] growth and continuous vertical eruption of teeth, [5, 6] have been found to be closely associated with orthodontic treatment instability, both in the short- and long-terms, respectively.

Mandibular incisors are less stable than their upper counterparts. Previous studies reported greater post-treatment malalignment in the lower than upper arches. [7, 8] This explains the focus of previous studies on the prevalence of mandibular malalignment, as well as the factors that thought to contribute to mandibular malalignment. Therefore, the present study focuses the investigation on the long-term stability of mandibular alignment after orthodontic treatment.

Despite the extensive studies that have evaluated post-treatment mandibular alignment, there is no previous systematically review of the literature that synthesizes what is known about long-term mandibular malalignment. Currently, there are only two review articles pertaining to post-treatment mandibular malalignment. One of them [2], focuses on the factors that might affect alignment changes (e.g. arch form, periodontal ligament and gingival fibers, mandibular incisors dimensions, third molars). The other provides a narrative review of long-term mandibular alignment changes [9]. The primary studies that have been published are mostly observational, with conflicting findings. Meta-analysis is needed to provide a reliable estimate of post-treatment alignment changes.

A better understanding of post-treatment craniofacial growth and associated dentoalveolar changes is also needed. Growth and associated tooth movements have been previously shown to affect the long-term stability of orthodontic treatment. [5, 6, 10] Compensatory tooth movements that occur after treatment also have the potential to negatively affect the long-term stability of orthodontic treatment. It is particularly important to understand post-treatment mandibular growth changes because it is the least mature craniofacial structure at the time when orthodontic treatment is typically completed. [11] On that basis, the present study will evaluate the long-term mandibular growth and dentoalveolar changes. The effects of demographic and clinical factors, including sex, malocclusion, extraction pattern, and retention method will also be assessed. Understanding these relationships should help orthodontists in planning proper treatment and retention protocols.

One treatment-related factor that has long been thought to determine long-term post-treatment stability is mandibular incisor angulation. However, it has not been previously investigated. Incisor crowns of untreated subjects with normal occlusion have been reported to be mesially angulated. [12] During orthodontic treatment, the mesiodistal angulation of the incisors are typically altered as the teeth are moved to their final positions. Changes in angulation can occur during the alignment phase, during retraction of teeth in extraction cases, or due to the tip and torque built into the bracket prescription. The tip built into the brackets differs widely from one system to another. For example, Roth and MBT prescriptions have no tip in the lower incisor brackets, while prescriptions such as Alexander, Andrews, and Damon have different degrees of distal tipping, ranging from 2-6 degrees. [13] To enhance long-term stability, it has been suggested that orthodontic treatment should be finished with a slight distal tip of the lower incisor roots, but the amount of tipping required to achieve stability was not specified. [14, 15] No previous study has investigated the association between lower incisor angulation and long-term mandibular alignment changes. Therefore, the present study will evaluate the relationship between end of treatment mandibular incisor angulation and long-term mandibular alignment changes.

Post-treatment mandibular malalignment could also be due to rotation or labiolingual axial displacement. It has been suggested, without statistical support, that teeth rotated during treatment tend to relapse toward their pre-treatment position. [1, 4] Edward [16], who evaluated the effect of circumferential supracrestal fiberotomy (CSF) on incisor irregularity, showed that CSF was effective in alleviating relapse. Importantly, he did not associate the rotational changes that occurred before and after CSF, making it impossible to determine whether there is in fact a relationship between the treatment and post-treatment rotational changes. Previously, there have only been two studies that have evaluated treatment and post-treatment rotational changes. [17, 18] One study suggested the relationship without any quantification. The other study reported the frequency of teeth with varying degrees of rotational discrepancies before and after treatment, suggesting, again without quantification, that the amount of relapse that occurs may be related to the amount of correction required during treatment. To date, no study has quantified the relationship between the rotational changes that occur during and after treatment, which is necessary to differentiate stability and relapse.

The curve of Spee (COS) also appears to be important for the long-term stability of orthodontic treatment. The COS is one of six keys for normal occlusion and successful orthodontic treatment. [12] It tends to deepen after treatment, [19] due primarily to vertical changes of the anterior teeth. [20] To compensate for these expected changes, it had been suggested to finish orthodontic treatment with a flat or slightly reversed COS. [12] Previous studies have shown that the treatment changes of the COS are negatively correlated with the post-treatment COS changes, [20, 21] indicating post-treatment relapse. However, one of the studies had a short follow-up [20] and the other did not clearly specify the mechanotherapy used to level the COS. [21] The mechanotherapy is important because leveling of the COS depends on the mechanotherapy that is used. [22] On that basis, the present study will assess the treatment and post-treatment changes of the COS in a large homogenous sample that has been followed-up over an average of 19 years post-treatment.

Despite the extensive research that had been performed, our understanding of long-term stability after orthodontic treatment remains uncertain. This reflects the complexity of the issue and indicates the necessity for further investigations. It is especially important to evaluate the various factors involved because long-term stability of incisors is multifactorial.

Specific Aims

The present study will address the following aims:

Aim 1: To synthesize the literature pertaining to post-treatment mandibular alignment changes.

Aim 2: To evaluate post-treatment mandibular growth and dentoalveolar changes.

Aim 3: To assess the relationship between mandibular incisor mesiodistal angulation and alignment changes.

Aim 4: To evaluate treatment and post-treatment changes of mandibular anterior teeth rotation and curve of Spee leveling.

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CHAPTER II

MANDIBULAR ALIGNMENT CHANGES AFTER FULL-FIXED ORTHODONTIC TREATMENT: A SYSTEMATIC REVIEW AND META-ANALYSIS*

Synopsis

While post-treatment mandibular alignment has been extensively investigated, the findings remain controversial. The objective was to assess mandibular alignment changes, as measured by the irregularity index, of patients who underwent full-fixed orthodontic treatment and were followed-up at least one year after retention. MEDLINE, EMBASE, and Cochrane library, in addition, the reference lists of included studies were screened. The search was conducted up to April 2018. The study designs included both interventional and observational studies of orthodontic patients who received either extraction or non-extraction treatment. The interventional studies were assessed using the Cochrane Collaboration's risk of bias assessment tool. The quality of the observational studies was evaluated using National Institution of Health (NIH) quality assessment tools. The first two authors independently applied the eligibility criteria, extracted the data, and assessed the risk of bias. Any conflicts were resolved with consensus discussion with the third author. The search retrieved 11,326 articles, 170 of which were assessed for eligibility. There were 44 studies included in the qualitative

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assessments and 30 in the meta-analyses. The studies included 1 RCT and 43 observational studies. The RCT was judged to have a high risk of bias and all of the observational studies had either fair or poor quality. The meta-analysis was based on studies judged to be of fair quality, included a total of 1,859 patients. All meta-analyses were performed using random effect models. The standardized mean difference (SMD) between post-treatment and post-retention irregularity was 1.22 (95% CI, 1.04-1.40) and 0.85 (95% CI, 0.63-1.07) after extraction and non-extraction treatments, respectively. There was a substantial heterogeneity for the extraction (I2 = 75.2%) and non-extraction (I2 = 70.1 %) studies. The follow-up duration (1-10 years vs. 10-20 years) explained 33% of the heterogeneity, with longer follow-up studies showing more irregularity. The quality of evidence provided by the studies was low. There was a risk of publication bias, and the search was limited to English language. Mandibular irregularity post-treatment increases are limited. Irregularity increases are slightly greater in patients treated with mandibular premolars extractions, and in patients followed-up over longer periods of time. The study protocol was not registered.

Introduction

Rationale

The maintenance of mandibular anterior alignment after orthodontic treatment is a major concern of orthodontists and patients. Clinicians want to maintain the quality of results they achieved during treatment and patients want their teeth to remain aligned after removal of the orthodontic appliances. Because mandibular teeth are less stable than their upper counterparts [1, 2], the focus has been on the maintenance of anterior mandibular alignment.

Several factors are thought to play a role in the development of post-treatment mandibular alignment changes [3]. Including retention methods [4], type of malocclusion [5], teeth extraction [6], craniofacial growth pattern [7], patients age during treatment [8], and various cephalometric and dental cast measurements. To date, none have systematically evaluated these factors in patient out of retention.

Currently, there are only two review articles pertaining to post-treatment mandibular malalignment [3, 9]. One of them [3], focuses on the factors that might affect alignment changes (e.g. arch form, PDL & gingival fibers, mandibular incisors dimensions, third molars, etc.). The other provides a narrative review of long-term mandibular alignment changes [9].The primary studies that have been published are mostly observational, with conflicting findings. There are no systematic reviews evaluating the long-term post-treatment malalignment of mandibular anterior teeth. Meta-analyses are needed to provide a reliable estimates of post-treatment alignment changes.

The type of study designs included in systematic reviews are usually based on the focus of the investigation [10]. The purpose of the present systematic review was to synthesize the literature describing post-retention changes in mandibular alignment, which is a prognostic rather than treatment effectiveness question. For these types of questions randomized trials or prospective cohort studies would be too costly and time consuming. As such, the majority of studies are observational, usually retrospective longitudinal, in nature. Observational studies often have better external validity, and are considered more representative of the target population [11].

Objectives

The purpose of this systematic review was to evaluate the changes in the anterior alignment of mandibular teeth after orthodontic treatment. The primary objective was to compare post-treatment irregularity changes of orthodontic patients who underwent either extraction or non-extraction treatment. The secondary objectives were to assess the effects of follow-up duration, adjunctive procedures use, retention protocol, clinical setting, and pre-treatment irregularity on mandibular alignment changes after orthodontic treatment.

Material and Methods

Protocol and registration

This systematic review was conducted in accordance with the guidelines of the preferred reporting items for systematic review and meta-analysis (PRISMA) statement [12]. The protocol of the review was not registered.

Eligibility criteria

The following selection criteria were used to identify potential studies:

1. Either interventional or observational study designs.
2. Case reports, review articles, and techniques description studies were excluded.
3. Orthognathic surgical treatments and craniofacial deformities were excluded.

4. The study must have evaluated mandibular incisor irregularity changes in orthodontic patients who received full fixed appliance therapy and were at least one year out of retention.
5. The assessment of mandibular anterior teeth alignment had to be based on Little's irregularity index [13], measured in mm, and reported separately for extraction and non-extraction groups.
6. Post-treatment (T1) and post-retention (T2) irregularity, or the irregularity changes that occurred over time, had to have been reported.

Information sources, search strategy, and study selection

A comprehensive search of the literature was conducted to identify studies published on or before April 1st, 2018. The search was restricted to studies published in English. The following databases were searched: MEDLINE (through PubMed), Cochrane library including CENTRAL, CDSR, DARE, and EMBASE database via OVID. Table 1 provides the search strategy used for the MEDLINE (PubMed) database. Cochrane and EMBASE searches were conducted excluding the Medline results. Hand searches of the studies' reference lists were assessed to identify other primary studies. The first two authors (A.J.S. & A.V.G.) applied the eligibility criteria, extracted the data, and assessed the risk of bias independently, and in duplicate. Disagreements between reviewers were resolved by consensus discussions and consultations with the third author (P.H.B.)

Data collection process and data items

A data extraction form was used to record the study design (observational or interventional), sample size and source, age of the patients at T1 and T2, male/female ratio, treatment approach (extraction or non-extraction), adjunctive procedures used (inter-proximal enamel reduction, supra-crestal fiberotomy, or both), retention protocol (fixed or removable retainers) used, post-retention follow-up duration, and the pre-treatment (T0), post-treatment (T1), and post-retention (T2) irregularity indices. In case of missing or incomplete data, an effort was made to contact the corresponding authors via emails. Duplicate publications were eliminated after full text article reviews. To improve the homogeneity and comparability of the studies, only studies with mandibular premolar extractions were included in the extraction group.

Risk of bias in individual studies

The Cochrane collaboration's risk of bias assessment tool [14] was used to assess the randomized clinical trials. The following source of biases were evaluated: selection bias, detection bias, attrition bias, reporting bias, and other biases. They were judged as low, unclear, or high.

NIH quality assessment tools were used to evaluate the observational studies [15]. The number of questions in each tool depended on the study design, with a specific tool for each study design. The questions were answered either "yes," "no," or "cannot determine/not reported/not applicable". Each study was judged to be either good, fair, or poor quality. Poor quality studies were not included in the meta-analysis.

Summary measures and synthesis of results

The primary outcome measure (i.e. summary effect measure) used in this study was the standardized mean difference (SMD) between T1 and T2 incisor irregularity ($II_{T2} – II_{T1}$/ pooled SD); along with the 95% confidence intervals. The estimates were combined using the Hedge's random effect model. Forest plots were used to graphically present the summary effect measures of the studies.

Heterogeneity and risk of bias across studies assessments

The heterogeneity of the studies was determined by analyzing the treatment protocols, patients' characteristics, studies' methodologies and any other relevant sources of heterogeneity. It was assessed statistically by visual appraisal of the summary effect forest plot, Q-statistics, Tau-squared, and the I^2 index. I^2 indices of < 25%, 50%, and 75% indicated low, moderate, and high heterogeneity, respectively [16]. Publication bias was assessed by visual inspection of funnel plot symmetry, along with statistical tests (i.e. Begg and Mazumdar rank correlation method [17], and Egger weighted regression method) [18].

Meta-regression and subgroup analyses

Random-effect model meta-regression was performed to evaluate the effects of follow-up duration, study design, adjunctive procedures used, pre-treatment irregularity, clinical setting, type of retainer used, and treatment protocol (extraction vs. non-extraction) on the primary outcome measure. The subgroup analyses included comparisons of the SMD estimates based on study designs (i.e. interventional vs. observational studies), and follow-up duration (1-10 y vs 10-20 y) after orthodontic treatment. These durations were chosen to ensure that there were roughly equal numbers of primary studies in each category. All the statistical analyses in this meta-analysis were performed using the STATA® 14.2 software package (StataCorp, College Station, TX).

Results

Study selection

A total of 10,759 articles were identified in the MEDLINE database, and another 567 were identified using the other resources (Embase, Cochrane, and hand search of reference lists) (Figure 1). After duplicates were removed, there were 11,326 articles, of which 11,164 were excluded after title and/or abstract screening. Of the 170 articles that were fully assessed for eligibility, 126 were excluded (Table 2). A total of 44 studies were included in the qualitative assessment; 14 of which were excluded from the meta-analysis (Table 3).

Study characteristics

One randomized controlled trial [4] and 43 longitudinal (pre-post) observational studies were included in this systematic review [1, 2, 5-8, 19-55]. The randomized trial [4], which was conducted in a private practice, included 49 patients treated with four premolars extractions, and followed up 5-9 years out of retention. The study had 3 subgroups based on different retention protocols; lower 3-3 fixed retainer, lower inter-proximal reduction, or pre-fabricated positioners.

The 43 observational studies were conducted in academic clinics [1, 5, 6, 21, 24, 29, 34, 36, 38, 45, 47, 51, 54, 55], private practices [2, 7, 19, 22, 26, 27, 30, 32, 33, 39, 41-44, 46, 53], or both [8, 20, 25, 35, 37, 48-50, 52]. Settings were not reported for some studies [23, 28, 31, 40]. There were 16 studies that reported mandibular premolars extraction treatment [2, 4, 8, 7, 19, 20, 22, 24, 25, 29, 32, 35, 37, 38, 41, 48] , 15 that reported non-extraction treatment [5, 23, 26, 27, 30, 39, 42, 44-47, 49-51, 53], and 11 that reported subgroups of extraction and non-extraction treatments [1, 6, 21, 28, 31, 33, 34, 36, 40, 54, 55]. There were 2 studies that reported mandibular incisors extraction treatment protocol [43, 52].

The follow-up duration after orthodontic treatment and retention ranged from 1-31.8 years. Adjunctive procedures were used in 7 studies [4, 22, 26, 27, 46, 53, 55], 35 studies reported no adjunctive procedures [1, 2, 5-8, 19-21, 23-25, 28-30, 32-35, 37-45, 47-52, 54]. Two studies did not state whether adjunctive procedures were used [31, 36].

There were 15 studies that used fixed lower 3-3 retainers, 9 used removable retainers [28, 32, 33, 38, 44, 45, 52, 54, 55] and 6 used either fixed or removable retainers [2, 4, 41, 46, 47, 51]. Fourteen studies did not report the type of retention protocol used [1, 6, 20, 21, 23, 30, 31, 35, 36, 40, 43, 48-50]. Characteristics of studies included in the meta-analysis are provided in Table 4. Table 5 provides the characteristics of studies excluded from the meta-analysis.

Risk of bias within studies

The randomized control trial [4] was judged to have a high risk of bias (Table 6), due to 34 % of the sample having been lost to follow-up. In addition, compliance with the retention protocol was unclear. Of the 42 longitudinal observational studies, the quality of 31 [1, 2, 5-8, 19-42, 52] was judged to be fair and 12 [43-51, 53-55] were judged to be poor (Table 7).

Risk of bias across studies

There was a significant risk of publication bias among the studies. The funnel plot (Figure 2) showed an asymmetrical distribution of studies, which was confirmed by the Begg's (P = 0.006) and Egger's (P = 0.024) tests.

Results of individual studies, meta-analyses, and additional analyses

A total of 30 studies were included in the meta-analysis, including a total of 1859 orthodontic patients [1, 2, 4, 5, 7, 8, 19-42]. The studies that reported sub-groups of extraction and non-extraction treatment were analyzed separately. There were 30 (66.6 %) extraction studies or subgroups, and 15 (33.3 %) non-extraction studies or subgroups (Figure 3). The SMD between T1 and T2 irregularity for the extraction group was 1.22; (95% CI, 1.04-1.40), compared to 0.85; (95% CI, 0.63-1.07) for the non-extraction group. There was a statistically significant (P <0.001) difference between extraction and non-extraction groups.

The heterogeneity was substantial for both the extraction (Q-test = $116.7_{df\ 29}$, P < 0.001, $Tau^2 = 0.18$, $I^2 = 75.2\%$) and non-extraction (Q-test = $46.9_{df\ 14}$, P < 0.001, $Tau^2 = 0.13$, $I^2 = 70.1\ \%$) studies (Figure 3). Due to the high heterogeneity, meta-regression analysis was conducted to determine how the study characteristics influenced effect size, and to evaluate their contributions (Table 8). Approximately 33 % of the between-study variance (heterogeneity) was explained by follow-up duration (1-10 y vs. 10-20 y). Treatment protocol (extraction vs. non-extraction) explained 9.9 % of the heterogeneity, and study design (interventional vs. observational studies) explained 9.2 % of the heterogeneity. The type of retention used, the adjunctive procedures used, pre-treatment irregularity, and clinical setting did not significantly influence the estimated alignment changes.

Subgroup analyses have shown a significant influence of follow-up duration (1-10 y vs. 10-20 y) and study design (interventional vs. observational studies) on the irregularity changes. The SMD of the 1-10 year follow-up group was 0.89 (95% CI, 0.73- 1.05), compared to 1.39 (95% CI, 1.18- 1.60) for the 10-20 year follow-up group (Figure 4).The SMD was 1.90 (95% CI, 1.13- 2.67) and 1.05 (95% CI, 0.91-1.19) for the interventional and observational studies, respectively (Figure 5).

Discussion

Summary of evidence

Both standardized and unstandardized mean differences (UMDs) of post-treatment irregularity are important and need to be reported. The SMDs, which were reported in the results, provide better control of the outcome variable's variance, resulting in smaller confidence intervals. For example, the 95% C.I. of the SMDs in the present study ranged from 0.95-1.23, compared to 1.39-1.86 for the UMDs (Table 9). The UMDs are necessary because they maintain the measurement's unit (e.g. mm) and make the results of this meta-analysis more easily understood and interpreted [56, 57]. Table 9 summarizes the long-term irregularity estimate, along with the 95% confidence intervals, in different clinical comparisons.

Importantly, post-treatment changes of mandibular irregularity are less than commonly thought. The average overall post-treatment irregularity change in this meta-analysis was 1.63 mm. Based on the estimated confidence interval (95% CI, 1.39 - 1.86 mm), irregularity changes greater than 2 mm are unlikely to occur. Approximately 93% of the studies in this review reported changes less than 3 mm. The difference in the amount of irregularity reported in this study and previous studies might be related to statistical power. This meta-analysis was based on 1859 patients, whereas previous reports typically used small samples, which can bias estimates of variation. Large sample size enhances statistical power, limits the influence of outliers, and provides a more representative estimate of the target population. In addition, this meta-analysis used post-treatment changes (T2-T1) in irregularity rather than post-retention (T2) irregularity, which often includes irregularities that remain after treatment. Assuming little or no post-treatment irregularity, the changes estimated are not clinically significant, being less than the 3.5 mm suggested as minimally acceptable [20].

The limited irregularity changes that occur post-treatment are probably not treatment-related because similar changes have been previously reported for untreated individuals [19, 58, 59]. In this review the average age at the end of treatment (T2) was 15.8 years, and the average age at follow-up was 27 years. Crowding of untreated individuals has been shown to increase maximally during the teen years, with rates decreasing thereafter through the twenties [58]. The average irregularity change reported in this review is slightly less than changes reported over comparable time periods for untreated individuals [19, 59], suggesting greater stability in orthodontic patients than in untreated individuals. Orthodontic patients might be expected to be more stable because they were treated and retained throughout the critical growth ages, when the greatest irregularity changes normally occur.

Mandibular anterior teeth exhibit greater post-treatment irregularity in patients whose premolars were extracted than in patients whose premolars were not extracted. The long-term changes in irregularity were 1.74 mm (95% CI, 1.46 - 2.02) after extraction treatments and 1.40 mm (95% CI, 0.96 - 1.85) after non-extraction treatments (Table 9). Primary studies comparing extraction and non-extraction treatments have also reported greater post-treatment malalignment after extraction than non-extraction treatments, with differences ranging from 0.2 - 0.8 mm [6, 21, 40, 60]. Higher dental crowding has been reported in individuals with narrower arches [61, 62], suggesting that the difference between two treatments approaches might be related to the shape of dental arch rather than the type of treatment. The difference could also be related to the major tooth movements that are usually required during extraction treatment. Regardless, differences in long-term irregularity changes between the extraction and non-extraction treatment were small, 0.34 mm, and clinically negligible.

The longer the post-treatment follow-up, the greater the irregularity, with most of the irregularity changes occurring during the earlier years. The irregularity index was 1.22 mm for studies reporting up to 10-year follow-up and 2.25 mm for studies reporting up to 20-year follow-up (Table 9). A similar pattern of change has been reported for patients evaluated longitudinally after orthodontic treatment [48, 63]. Untreated individuals also exhibit the same pattern [64, 65]. These findings support the notion that the factors that cause irregularity, especially growth and the anterior component of force, have a major impact on mandibular alignment after orthodontic treatment. This emphasizes how important it is for orthodontic patients and clinicians to understand these effects and to maintain their retention protocol indefinitely. Informing the patients of possible minor irregularity changes after retention should help motivate them to use their retainers long-term and increase their awareness of possible corrections later.

Even though the study design showed a significant effect, the design itself probably plays no role in explaining the difference. In the present study there were two main designs, with greater irregularities in the interventional than observational studies (Table 9). The greater irregularity changes identified in the interventional study was probably related to the use of positioners, which required patient compliance [66].

Whether the patients are given fixed or removable retainers has no effect on post-treatment alignment changes that occur. In the present study, the irregularity changes were 1.42 mm with fixed and 1.48 mm with removable retention. Currently, there is no consensus among orthodontists concerning the best retention protocol to use. Retention depends on multiple factors, including the type of malocclusion, periodontal status of patients, amount of subsequent growth, patient compliance, and patient preference [67]. Several types of retainers were included in each category, which makes the comparison less accurate. In addition, compliance with removable retainers use, operators' skills, and failure rates with fixed retainers could have increased the variation and made differences difficult to detect.

The amount of pre-treatment irregularity was also unrelated to the long-term changes in alignment that occurred. The meta-regression showed that amount of pre-treatment irregularity explained an insignificant 4% of the variability in the long-term irregularity changes that occur. This agrees with previous studies that found no association between pre-treatment irregularity and long-term irregularity changes of mandibular anterior teeth [20, 37]. No relation between the pre-treatment irregularity and post-retention malalignment should be expected. The teeth do not have any preordained positions to which they return if properly treated and retained.

While no significant effect was shown in the present study, the ability of adjunctive procedures (i.e. the use of supra-crestal fiberotomy, inter-proximal enamel reduction, or both) performed at the end of orthodontic treatment or retention to enhance long-term mandibular alignment cannot be ruled out. In this review, the irregularity changed 1.06 mm for the studies using adjunctive procedures and 1.65 mm for those not using adjunctive procedures (Table 9). The lack of significant difference could have been due to insufficient power, since only a small number of studies used adjunctive procedures. Similar amounts of irregularity change have been reported for patients who had IPR during treatment and evaluated up to 9 years out of retention [68]. The difference in irregularity is probably related to the broader contacts that could prevent mandibular incisors contact slippage [69].

The clinical setting of orthodontic treatment probably does not affect post-treatment alignment changes (Table 9). The 0.6 mm difference in irregularity change reported in the present study might be related to follow-up durations, with almost 50 % of the university studies reporting individuals followed 10-20 years, compared to only 12 % of private practice studies. As shown in the present study, follow-up duration has a significant effect on post-treatment alignment changes. While no previous study has evaluated long-term alignment changes in different clinical settings, it has been shown that both produce similar quality of treatment outcome [70-72]. Clinical setting might affect the duration of treatment, but it plays a limited or no role in long-term mandibular alignment.

Finally, mandibular alignment changes following lower incisors extraction had been evaluated in two studies [43, 52]. An exploratory meta-analysis showed that irregularity change was limited, with irregularity increasing 0.74 mm (95% CI, -0.05, 1.52) (Figure 6). Importantly, irregularity changes were based on changes of four rather than five contacts.

Strengths and limitations

This review was able to identify a large number of studies that were systematically reviewed and investigated. It is the first review of long-term mandibular alignment changes. The major limitation of this review pertains to the quality of evidence provided by the studies. The majority of studies were longitudinal and retrospective, which are known to have inherited design issues, and prone to high risk of bias. Because the quality of evidence in this review was low to moderate, the findings should be interpreted carefully. Higher quality studies of mandibular alignment changes after orthodontic treatment are needed to substantiate these finding. The lack of high quality evidence is probably related to the nature of the phenomenon being investigated. Long-term alignment of mandibular anterior teeth could be affected by multiple factors and designing prospective studies requires time and resources that many might consider impractical. Another limitation of this review is the lack of protocol registration.

There was a significant risk of publication bias (Figure 2). It is likely that only studies with larger sample size and significant findings were published. There might be unpublished studies that could have affected the irregularity estimates reported in this review.

In addition, it is crucial to understand that there are various clinical factors (e.g. arch width manipulation, amount of incisors proclination, the number and experience of treated practitioners and outcome assessors, and possibly the treatment philosophy) that could have affected post-treatment irregularity change, but were not feasible to assess in this paper because they are not commonly reported. Therefore, the findings of this review should be interpreted cautiously, and the importance of semi-permanent or permanent retention should not be neglected. This is especially important for patients completing their orthodontic treatment during the critical growth ages (late teens).

Conclusions

On the basis of 30 studies involving 1859 patients, the following conclusions relating to post-treatment mandibular alignment changes can be drawn:

1. There are only limited amounts of irregularity change after orthodontic treatment. It increases only 1.6 mm, over an average of 9.3 post-treatment years.
2. There is a statistically significant difference in post-treatment irregularity changes between mandibular premolars extraction and non-extraction treatments.

3. There are greater irregularity changes in orthodontic patients who are followed up for longer periods of time.
4. Meta-regression analysis showed that pre-treatment irregularity, the clinical setting, the type of retention, and adjunctive procedures have no significant effects on post-treatment irregularity changes.

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CHAPTER III

LONG-TERM MANDIBULAR SKELETAL AND DENTOALVEOLAR CHANGES AFTER EXTRACTION ORTHODONTIC TREATMENT

Synopsis

The present study assessed long-term mandibular growth changes in patients treated with four premolar extractions and followed-up an average of 19.2 years post-treatment. The sample consists of 100 orthodontic patients (19 men, 81 women) who were treated using the Tweed philosophy. The average post-treatment and follow-up ages were 15.9 ± 3.3 years and 35.2 ± 7.4 years, respectively. 56% of the patients had four first premolars extracted, 29% had upper first and lower second premolars extracted, and 15% had four second premolars extracted. Rigid banded fixed retainers were used in 57 cases, and removable acrylic retainers were used in 43 cases. The radiographs were scanned using a 480-dpi preset. All the cephalometric measurements were performed using Dolphin ® software. Post-treatment (T1), and follow-up (T2) cephalograms were used to assess mandibular skeletal and dentoalveolar changes. All the variables showed statistically significant post-retention changes for both sexes over time. Ramus height, corpus length, and lower anterior facial height increased 1.5, 1.9, and 0.9 mm, respectively. The gonial angle decreased by 1 degree, and the mandibular plane angle decreased by 0.5 degrees. The lower incisors erupted 1.4 mm, the interincisal angle increased 2.8 degrees, the upper and lower incisors retroclined 1 degree, the first molars tipped mesially 5.4 degrees, and the functional occlusal plane decreased 1.2 degrees. Males showed greater ramal height growth ($P < 0.001$) and more counterclockwise rotation of the functional occlusal plane ($P = 0.002$) than females. The mandibular incisors erupted more after rigid fixed than acrylic removable retainers ($P < 0.001$). Mandibular incisors inclination decreased substantially with second than first premolars extraction. There is a substantial amount of post-treatment mandibular growth, which is greater in males than females, and in younger than older patients. The dentoalveolar changes were affected by the retention method used and extraction patterns.

Introduction

Post-treatment craniofacial growth and associated dentoalveolar changes are important in determining the long-term stability of orthodontic treatment. [1] Growth and associated tooth movements have been previously shown to affect the long-term stability of orthodontic treatment. [2, 3, 4] Compensatory tooth movements that occur after treatment also have the potential to negatively affect the long-term stability of orthodontic treatment. It is particularly important to understand post-treatment mandibular growth changes because it is the least mature craniofacial structure at the time when orthodontic treatment is typically completed [5], and mandibular incisors undergo greater alignment changes than their maxillary counterparts. [6, 7]

Only a few studies have evaluated post-treatment mandibular growth changes, and most of these have limitations. While the reports are consistent in showing that the mandible continues to grow in size after treatment, [1, 8] they are inconsistent in terms of dentoalveolar changes that occur. [9, 10] Studies reporting post-treatment mandibular growth changes either had small sample sizes, [8, 11] short follow-up durations [12] or reported different patterns of post-treatment growth. [13] As a result, their statistical power was limited and the post-treatment pattern of mandibular growth could have been obscured. Importantly, it may not be possible to apply estimates of growth and dentoalveolar changes of untreated subjects to treated subjects. Treated and untreated individuals exhibit distinct differences in the dentoalveolar changes that occur. [2] For example, changes in incisor inclination were three times greater in treated than untreated individuals. More long-term studies with larger sample sizes are needed to fully understand post-treatment growth and dentoalveolar changes.

Demographic and clinical factors also must be considered when planning long-term stability after orthodontic treatment. While sex differences have been demonstrated for mandibular growth, [14-17] they have not been clearly established for post-treatment dentoalveolar changes. [12, 18] The effect of aging on craniofacial growth has also been demonstrated, with greater post-treatment changes occurring in younger than older patients. [8, 14] Pre-treatment malocclusion has also been shown to have a significant effect on the post-treatment horizontal growth of the mandible, with three times greater increase in corpus length reported in class II than class I patients. [1] However, other clinical factors, such as the retention protocol and extraction patterns, which might be expected to have an effect on post-treatment dentoalveolar changes, have not previously been investigated.

The aim of the present study was to investigate the long-term mandibular growth and dentoalveolar changes. The effects of demographic and clinical factors, including sex, malocclusion, extraction pattern, and retention method, will also be assessed. Understanding these relationships should help orthodontists in planning proper retention protocols.

Materials and Methods

The participants' records were obtained from two private orthodontic practices, which mainly used the Tweed orthodontic treatment technique. The tweed technique concepts include sequential appliance placement, sequential tooth movement, sequential mandibular anchorage preparation, directional forces, and prescribed treatment timing. It also includes using J-hook high-pull headgear and anterior vertical elastics to control the vertical dimension during treatment. The cases are usually finished with the lower incisors upright over basal bone and the curve of Spee over-corrected. This longitudinal observational study was approved by the institutional research board of Texas A&M University (IRB ID: 2017-0305-CD-EXP). To be considered for this study, the patients had to meet the following criteria:

1. Orthodontic patients five or more years out of retention.
2. Treatment plan that included four premolar extractions.
3. A full set of good quality orthodontic records, including post-treatment (T1) and long-term follow up (T2) cephalometrics x-rays.
4. No orthognathic surgery as part of their treatment plan.
5. No cases with Class III malocclusion.
6. No missing or heavy restorations of the lower first molars and incisors.

The sample included 100 orthodontic patients who were treated with four premolar extractions and full fixed appliance. 56% of the subjects were treated with four first premolar extractions, 29% had upper first and lower second premolars extracted, and 15% had four second premolars extracted (Figure 7). The sample included 19 males and 81 females; 38 had class I and 62 had class II malocclusions pre-treatment. The average retention time was 1.5 years for the cases treated by the first orthodontist and 3.5 years for the second orthodontist. Fixed retainers were used in 57 cases and removable retainers were used in 43 cases (Table 10). The mean post-treatment age was 15.9 years, the post-retention age was 35.2 years, and they were followed-up on an average of 19.2 years (Table 11).

The cephalometric radiographs were scanned using an Epson Expression 11000XL® digital scanner and Silver Fast v8® software, with a 480-dpi preset. After scanning, the images were imported to Dolphin 11.90 ® software. All the cephalometric measurements were performed using Dolphin ® software. Post-treatment (T1) and post-retention (T2) status, as well as the changes that occurred between T1 and T2, were assessed. Sixteen landmarks were identified (Table 12) and digitized. Cephalometric measurements included seven angular and five linear measurements (Figure 8) (Figure 9). In addition, the effects of sex, pre-treatment malocclusion, extraction pattern, and retention method were evaluated relative to the mandibular growth changes. All the measurements were performed by one operator (A.J.S.).

Statistical analysis

Statistical package IBM SPSS 25 ® was used for the analyses. Measurement errors were assessed based on 22 replicates. The systematic error was assessed using the paired t-test. The random error was quantified using Dahlberg's method errors and intraclass correlations. The normality of the distributions was statistically demonstrated using the skewness and kurtosis statistics, as well as the Shapiro Wilk's test.

The data were described with means and standard deviations. Paired t-tests were used to evaluate the changes from the end of treatment (T1) to long-term follow up (T2). The interaction of clinical factors with mandibular growth changes was evaluated using four-factor ANOVA, controlling for the follow-up duration and the variables' T1 values. Since the present study evaluated several parameters of mandibular growth and dentoalveolar changes, the sample size was calculated based on the ability to identify 0.5 mm and 1 degree of linear and angular measurement changes, respectively. The required sample size was calculated using G*Power software®, assuming a type I error equal to 1%, a type II error 5%, and an effect size equal to 0.5. To achieve this study power, a total sample of 75 orthodontic patients was required.

Results

Post-treatment changes

Except for gonial angulation, the random method errors for the angular measurements ranged between 0.24 and 0.71 degrees, and between 0.21 and 1.67 mm for the linear measurements (Table 13). All but one (0.78) of the intraclass correlations were higher than 0.95. The interincisal angle showed a small but statistically significant systematic measurement error.

All the variables showed statistically significant post-retention changes over time (Table 14). Mandibular size increased 0.9 to 1.9 mm, with corpus length showing the greatest increase. The gonial angle decreased by 1.0 degree and the mandibular plane angle decreased by 0.5 degrees. The lower incisors erupted 1.4 mm after orthodontic treatment, and the interincisal angle increased by 2.8 degrees. Lower incisor to A-Pog distance reduced 0.7 mm, upper and lower incisors retroclined approximately 1 degree, and the intermolar angle decreases 5.4 degrees. The functional occlusal plane rotated counterclockwise 1.2 degrees.

Clinical factors

ANOVA, evaluating the effects of the clinical factors, showed no statistically significant interactions between sex, pre-treatment malocclusion, retention method, and extraction pattern (Table 15). Males showed significantly greater increases in ramus height, greater decreases in mandibular plane angle, and greater counterclockwise rotation of the functional occlusal plane than females (Figure 10). The lower incisor to APog distance, interincisal angle, and lower incisor inclination changed significantly less in patients treated with upper and lower first premolars extractions than in patients who underwent other extraction patterns (Figure 11). Cases treated with upper first and lower second premolars also showed significantly greater counterclockwise rotation of the functional occlusal plane. Lower incisors eruption was significantly greater (0.8 mm) in cases retained with fixed than removable retainers (Figure 12A). The rate (mm/yr) of incisor eruption was also greater in younger patients, who followed up a shorter time post-treatment (Figure 13). Patients with pre-treatment class I malocclusions showed a significantly smaller increase in the corpus length than patients with class II malocclusion (Figure 12B).

Discussion

The mandible undergoes clinically meaningful size increases after the age of 15 years. Ramus height, corpus length, and lower anterior facial height increased significantly post-treatment, the mandible rotated forward, and gonial angle decreased. Lower posterior facial height showed more growth than lower anterior facial height, as has been previously shown.[8] The increases were substantial, with ramus height increasing almost twice (1.5 mm), as much as lower anterior facial height (0.8 mm). Importantly, there probably were proportionately greater amounts of mandibular growth in younger than older adults. It has been previously shown that the corpus length increases an average of 1.5 mm between 15 and 20 years of age, compared to a 0.5 mm increase between 31 and 37 years old. [13] Therefore, orthodontists should anticipate more mandibular growth in younger than older adults. Moreover, it indicates that patients should be retained longer than commonly thought because growth has been associated with greater potential for instability. [1, 19]

Males showed greater post-treatment changes than females. Ramus height increased 4 mm more in males than females. Males also showed approximately 2.5° greater counterclockwise rotation of the functional occlusal plane and 2° greater decreases of the mandibular plane angle. Post-treatment FOP decreases were negatively correlated with the ramus height increases, indicating that these differences were growth related. Previous studies comparing untreated males and females have also reported greater growth changes in males than females. [18, 20] This considerable degree of sexual dimorphism might be related to the difference in the timing of growth. The present sample finished orthodontic treatment around 15 years of age, so more mandibular growth potential would be expected in males than females, who are biologically approximately two years younger. [21] Major sex difference in mandibular growth after the mid-'20s might be expected to be more limited. A previous study comparing untreated adults dentofacial changes between 22 and 33 years of age showed no significant differences between males and females. [22]

Orthodontic patients with pre-treatment class II malocclusion had greater post-treatment growth potential than class I patients. Patients with pre-treatment class II malocclusions showed a significantly greater increase (2.6 mm) in the corpus length than patients with class I malocclusion (0.7 mm). Greater post-treatment corpus length increase in class II (1.9 mm) than class I (0.6 mm) patients has been previously reported. [1] The sample in the present study was treated with high-pull headgear, and great concern was given to the vertical dimension control during treatment. The difference in corpus length could be related to the potential and pattern of post-treatment mandibular growth. Post-treatment mandibular plane angle in the present sample decreased substantially in class II patients (- 0.9 degrees) and increased slightly (0.2 degrees) in class I patients. This indicates that class II cases had more favorable growth pattern than class I patients.

Mandibular incisors showed more eruption in cases retained with fixed (1.7 mm) than removable retainers (0.9 mm). No previous study has compared the amounts of incisor eruption associated with different retention protocols. The difference in incisor eruption observed in the present study could be related to the design of fixed retainers, which including two bands on the lower canines and onto which a rigid lingual metal bar was soldered. Anterior arch width and lower incisors inclination might be expected to be better maintained throughout the retention period with fixed retention. Importantly, the lower incisors retroclined 1.6 degrees after fixed retention compared to 0.3 degrees after removable retention. As such, relative extrusion of lower incisors might explain the greater amounts of eruption observed after fixed retainers. Removable acrylic retainers, on the other hand, appeared to have no effects on the amount of incisors eruption (0.9 mm). Similar amounts of incisor eruption have been reported in patients who also finished treatment before the age of 20 years and were followed up over a similar period of time as in the present study. [23]

The mandibular incisors erupt more in the younger than older adults, as previously demonstrated. [13, 23] Previous studies assessing lower incisor eruption of treated and untreated individuals between the 20-40 and 25-45 years of age have reported increases of 0.7 and 0.8 mm, respectively. [23, 24] Post-treatment incisor eruption of 1.4 mm has been reported in patients treated with first premolar extractions, whose ages were comparable to the patients' ages in the present study. [10] Greater eruption in younger adults might be expected because incisor eruption follows the same pattern as mandibular growth. [25]

Post-treatment mandibular incisor inclination decreases substantially after second premolar extractions, but not after the first premolar extractions. Limited changes were observed in the cases treated with lower first premolar extractions (Figure 11), compared to the cases that were treated with second premolar extractions. No previous study has compared the long-term effects of different premolars extraction patterns on incisor inclination changes. Post-treatment literature evaluating incisor inclination has reported retroclination ranging from 1 to 6 degrees. [2, 11] Importantly, previous studies have shown greater incisor retraction during treatment after first than second premolar extractions. [26, 27] The difference identified in the present study was probably related to the distance that the incisors had been moved. Riedel [28] suggested that teeth that are moved extensively during treatment are less likely to relapse toward their original position than teeth not moved as far from their original position. The substantial incisor inclination changes with second premolar extraction could also be related to the lower lip. Since the lower incisors are retracted more when the first premolars are extracted, [26, 29] less pressure from the lower lip might be expected post-treatment.

There was substantial mesial post-treatment tipping of the upper and lower first molars. Mesial tipping of molars after extraction treatment has been previously reported. [30] It could be an indication of short-term relapse. The mechanotherapy of the treating orthodontists included mandibular anchorage preparation by distal tipping the first molars. Mesial post-treatment molar tipping could be an adaptation to the decrease in mesiodistal tooth size that occurs with aging. [31] The anterior component of force could also explain the post-treatment molars angulation changes. [32] When the posterior teeth are occlusally loaded the force is applied above the center of resistance which, considering the axial inclination of teeth, would tend to tip them forward.

Strengths and limitations

The present study assessed mandibular growth and dentoalveolar changes of orthodontic extraction patients. Unlike most previous studies, the sample was large and homogenous, the mechanotherapy was consistent among all of the patients and the follow-up duration was relatively long, approximately 20 years.

However, there are limitations. This longitudinal study was conducted retrospectively, which limits the ability to control confounders and bias. However, long-term observational studies, either in orthodontics or other medical fields, usually use such designs because recruiting and retaining participants for decades after treatment is difficult. The sample was collected based on the availability of records and pre-determined eligibility criteria. The records evaluated in the present sample were taken during the 1970's and 1980's, when full banded standard edgewise appliances were used, which is different than the bonded pre-adjusted edgewise appliances currently used. The appliances could affect the dentoalveolar changes observed. Another limitation could be related to the selection bias, since deciding to take long-term records was based on the willingness of patients to return to the orthodontists, and perhaps the satisfaction of clinicians about the condition of teeth at the follow-up visit. Due to these limitations, the findings of the present study should be interpreted cautiously.

Conclusions

Based on the findings of the present study, the following conclusions pertaining to post-treatment mandibular growth and dentoalveolar changes of extraction patients followed-up between 15 and 35 years of age can be drawn:

- The mandible exhibits substantial post-treatment changes, with size increases ranging from 0.9 to 1.9 mm.
- Males show greater ramal growth and more counterclockwise rotation of the functional occlusal plane and mandibular plane than females.
- The upper and lower incisors retrocline, lower incisor to APog distance decreases, the interincisal angle increases, the first molars tip mesially, and the functional occlusal plane rotates counterclockwise.
- Mandibular incisors erupt on average of 1.4 mm, with greater eruption associated with fixed than removable retainers.
- Post-treatment incisor inclination decreases more with second premolar than first premolars extraction.

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CHAPTER IV

THE SIGNIFICANCE OF DISTAL ROOT TIP OF MANDIBULAR INCISORS ON LONG-TERM ALIGNMENT STABILITY

Synopsis

To evaluate the relationship between post-treatment mandibular incisor angulation and long-term mandibular alignment changes in patients at least 5 years out of retention. The sample included 93 orthodontic patients who were treated with four premolars extractions and full fixed appliances. Their post-treatment and post-retention ages were 16.0 ± 3.4 and 35.0 ± 7.4 years, respectively. The panoramic x-rays were scanned and evaluated using Dolphin 11.90 ® software. Orthodontic models were scanned and measured using Ortho Insight 7.5® software. The mesiodistal angulation of the mandibular incisors, incisor irregularity, and tooth size arch length discrepancy (TSALD) were assessed. Incisor irregularity increased 1.17 mm and TSALD increased 1.04 mm post-treatment. The mandibular incisors finished orthodontic treatment with slight distal tip of their roots; their angulations ranged from 88.0 to 88.7 degrees. The incisor angulations on the left side remained stable, but right side angulations increased significantly. There were no statistically significant relationships between post-treatment incisor angulation and post-treatment mandibular alignment changes. There was a positive correlation between right lateral incisor angulation changes and mandibular alignment changes. Sex, malocclusion, retention method, and extraction pattern had no statistically significant effects on post-treatment mandibular incisor angulations or

alignment changes. Post-treatment mandibular alignment changes are limited. The mandibular incisors, which finished treatment with slight distal root tip, exhibited minimal post-treatment changes. There was no relationship between mandibular incisors angulation at the end of treatment and mandibular alignment changes.

Introduction

Stability of orthodontic treatment is a primary concern for patients and clinicians. Properly managed treatment, along with a proper retention protocol, are the keystones for achieving post-treatment stability. Factors that could affect long-term stability of occlusion can be generally categorized as growth-related factors and treatment-related factors.[1] While mandibular alignment changes after orthodontic treatment have been reported to be limited,[2] full understanding of the specific reasons behind malalignment remain unclear. Investigations of other potential factors, especially treatment-related factors, are needed to further improve post-treatment stability.

One of the treatment-related factors that has not been previously investigated is mandibular incisor angulation. Incisor crowns of untreated subjects with normal occlusion have been reported to be mesially angulated.[3] During orthodontic treatment, the mesiodistal angulation of the incisors are typically altered as the teeth are moved to their final positions. Changes in angulation can occur during the alignment phase, during retraction of teeth in extraction cases, or due to the tip and torque built into the bracket prescription. The tip built into the brackets differs widely from one system to another. For example, Roth and MBT prescriptions have no tip in the lower incisor brackets, while prescriptions such as Alexander, Andrews, and Damon have different degrees of distal tipping, ranging from 2-6 degrees. [4]

To enhance long-term stability, it has been suggested that orthodontic treatment should be finished with a slight distal tip of the lower incisor roots. According to Williams, the lower incisor apices should be tipped distally to the crown, with greater tipping of the lateral than central incisors.[5] The amount of tipping required to achieve stability was not specified. Alexander advised that the lower incisors should finish treatment with the lateral incisor root parallel to the canine root to ensure better stability. For stability, he recommended that the angulations of the central and lateral incisors brackets should be 2 and 6 degrees, respectively.[6]

The primary objective of the present study was to assess the relationship between end of treatment mandibular incisors angulation and long-term mandibular alignment changes. The secondary objective was to evaluate the relationship between post-treatment changes of mandibular incisors angulation and long-term alignment changes. No previous study has investigated the association between lower incisors angulation and long-term mandibular alignment changes.

Materials and Methods

The participants' records were obtained from two private orthodontic practices that used mainly Tweed treatment techniques. This longitudinal observational study was approved by the institutional research board of Texas A&M University (IRB ID: 2017-0305-CD-EXP). To be considered for this study, the patients had to meet the following criteria:

1. Orthodontic patients five or more years out of retention.
2. Treatment plan that included four premolar extractions.
3. A full set of good quality orthodontic records, including post-treatment (T1) and long-term follow up (T2) panoramic x-rays and orthodontic models.
4. No orthognathic surgery as part of their treatment plan.
5. No cases with Class III malocclusion.
6. No missing or heavy restorations in lower incisors.

The sample included 93 orthodontic patients who were treated with four premolar extractions and full fixed appliances. 51 of the subjects were treated with four first premolar extractions, 27 had upper first and lower second premolars extracted, and 15 had four second premolars extracted. The sample included 19 males and 74 females, 34 of whom had Class I and 59 had Class II malocclusions pre-treatment. They were treated by two orthodontists; who retained on average 1.5 and 3.5 years, respectively. Fixed retainers were used in 53 cases and removable acrylic retainers were used in 40 cases (Table 16). The mean post-treatment age was 16.0 years, the post-retention age was 35.0 years, and they were followed-up for an average of 18.9 years.

The panoramic radiographs were scanned using an Epson Expression 11000XL® digital scanner and Silver Fast v8® software, with a 480-dpi preset. After scanning, the images were imported to Dolphin 11.90 ® software. Orthodontic models were scanned using Ortho Insight ® scanner. All of the panoramic measurements were performed using Dolphin ® software; the model measurements were performed using Ortho Insight 7.5® software.

The post-treatment (T1), and post-retention (T2) status, as well as the changes that occurred between T1 and T2, were assessed. Panoramic measurements of incisors mesiodistal angulation were based on the angle (measured on mesial aspect of the tooth) formed by the long axis of the incisors relative to the horizontal reference line, which was defined as a line passing through the center of the mental foramina (Figure 14). Mandibular incisor angulations measured on panoramic radiographs have been shown to be subject to systematic and random errors. Compared to measurements made on typodonts and CBCT images, incisor angulations measured from panoramic images show consistently more distal root tip of the incisors, with greater differences for the lateral than central incisors. [7, 8] The increased risk of random measurement errors with panoramic radiographs have been associated with horizontal head positioning. [9]

Orthodontic model measurements included Little's irregularity index [10] and anterior tooth size arch length discrepancy (TSALD) [11] (Figure 15). All of the measurements were performed by one operator (A.J.S.). Replicate analyses of 22 cases produced random method errors that ranged between 0.23 and 0.27 degrees for the angular measurements, and between 0.17 and .018 mm for the linear measurements (Table 17). All the intraclass correlations were higher than 0.97. There were no statistically significant systematic measurement errors.

Statistical analysis

Statistical package STATA/IC ® 15.1 was used for the analyses. The normality of the distributions was statistically demonstrated using the skewness and kurtosis statistics, as well as the Shapiro Wilk's test. Paired t-tests were used to evaluate the post-treatment changes. Pearson's product-moment correlations were used to evaluate the relationships. The effects of the clinical factors on post-treatment mandibular incisor angulations and alignment changes were evaluated using ANOVA. The required sample size was calculated using G*Power software®, assuming a type I error equal to 1 %, a type II error 10 %, and an effect size equal to 0.4. To achieve this study power a total sample of 86 orthodontic patients was required.

Results

Post-treatment changes

All the variables, except lower left incisor angulation, showed statistically significant post-treatment changes (Table 18). Incisor irregularity increased 1.17 mm, and TSALD increased 1.04 mm (Figure 16). The correlation between the irregularity index changes and TSALD changes was 0.61 ($P < 0.001$). There were 23 patients with an irregularity index greater than 3.5 mm at the follow-up visit (T2); only four patients had irregularity changes (T2-T1) greater than 3.5 mm. All the mandibular incisors finished orthodontic treatment with slight distal root tip. The angulations ranged from 88.0 to 88.7 degrees. The incisor angulations on the left side remained stable, but right incisor angulations increased significantly.

Post-treatment associations

Mandibular incisor angulations at the end of treatment (T1) showed low negative correlations with TSALD changes (Table 19). None were statistically significant. However, the angulation changes of the right lateral incisor were significantly related with the changes in the irregularity index and anterior TSALD changes (Figure 17). Sex, malocclusion, retention method, and extraction pattern had no statistically significant effects on post-treatment mandibular incisor angulation or alignment changes.

Discussion

Long-term mandibular alignment changes after orthodontic extraction are more limited than commonly thought. The findings of the present study showed average increases of 1.04 mm and 1.17 mm in anterior TSALD and incisor irregularity, respectively. Previous studies evaluating mandibular TSALD have reported post-treatment increases ranging from 0.7 to 1.27 mm, with the differences between studies being related to follow-up durations.[12, 13] A recent meta-analysis evaluating irregularity index changes of 30 studies after premolars extraction reported an average change of 1.7 mm.[2] The post-treatment changes in the present study were less than expected based on the duration of the study, perhaps due to the mechanotherapy that both orthodontists used. Both orthodontists finished treatment with the lower incisors upright over the basal bone, they used full banded appliances that created spaces after debanding, and they retained a minimum of 1.5 years. Approximately 75% of the present sample showed incisor irregularities less than 3.5 mm, indicating that only 25% needed treatment after having been out of retention for approximately nineteen years.[14] This demonstrates that it is possible to limit clinically significant post-treatment mandibular alignment changes if biological boundaries are respected during orthodontic treatment and proper retention protocols are followed.

The mandibular incisors finished treatment with slight (1.3 – 2.0 degrees) distal root tip and, on average, they showed only minimal long-term changes. However, the changes were highly variable around these averages. The incisors on the left side remained stable, with almost no change over the 19 years follow-up period. The right incisors exhibited 1.5 degrees of uprighting. The differences between the right and left antimeres could be related to masticatory function, assuming that it is dominant on the right side. No previous study has evaluated incisor angulation after orthodontic treatment.

Mandibular incisor angulation at the end of treatment does not affect post-treatment mandibular alignment changes. Importantly, none of the angulations were associated with the alignment changes. There was sufficient post-treatment variability in mandibular incisor angulation estimates to establish a relationship if one existed.[15] Incisor angulation at the end of treatment for 95% of the sample ranged between 75 and 101.5 degrees, indicating that some of incisors roots were mesially angulated. The observed variability in the incisor angulation could be related to the use of zero-prescription appliances. All the artistic bends were applied individually to each tooth. Given the sample size and the difference among patients in incisor angulation, it is unlikely that a relationship between incisor angulation at the end of treatment and post-treatment mandibular alignment changes actually exists, as previously proposed.[5, 6]

Even though incisor angulation at the end of treatment showed no relationship with mandibular alignment changes, the post-treatment incisor angulation changes of the lower right lateral incisors were significantly associated with the changes in mandibular alignment. This showed that incisors with greater mesial root tip post-treatment exhibited greater mandibular alignment changes. This relationship might be explained by the cornering effect that commonly occurs between the canine and lateral incisor contact.[16] Once the contact slipped, there is a chance that lateral incisor tips distally. Regardless, the association noted in the present study was limited and perhaps clinically insignificant.

This study is not without limitations. Using panoramic x-rays to evaluate mandibular incisor angulation probably affected both the measurements' accuracy and precision. Panoramic radiographs are subject to magnification and individual differences in head positioning during acquisition. [7-9, 17, 18] A 5 degree difference in horizontal head position, to either side, can significantly affect incisor mesiodistal angulation. [9] While such random errors do not affect the measures' central tendencies, they would inflate dispersion and could limit the ability to identify the relationship between incisor angulation and alignment changes. The systematic error associated with panoramic should have little or no effect on the measurements and relationships because both radiographs will be similarly affected. Due to the long-term nature of the present study, the panoramic radiographs were the only records available for evaluating mesiodistal incisor angulations. The estimates of incisor angulation in the present study should be interpreted cautiously and within the context of the limitations identified.

Conclusions

- Post-treatment mandibular alignment changes are limited, with only 1.17 mm and 1.04 mm of irregularity index and TSALD changes, respectively, after 19 years.

- Mandibular incisors finished treatment with slight (1.3 – 2.0 degrees) distal root tip and exhibited minimal post-treatment changes.
- There was no relationship between mandibular incisors angulation at the end of treatment and the post-treatment mandibular alignment changes.
- Post-treatment changes of right lateral incisor angulation were positively correlated with mandibular alignment changes.
- Sex, malocclusion, extraction pattern, and retention method had no significant effects on the incisors angulation and mandibular alignment changes.

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CHAPTER V

POST-TREATMENT RELAPSE OF ORTHODONTICALLY ROTATED ANTERIOR TEETH AND CURVE OF SPEE LEVELING

Synopsis

The present study assessed the long-term stability of orthodontic correction of rotated anterior teeth and the curve of Spee (COS) in the mandible. The sample includes 100 orthodontic patients (19 males, 81 females) treated utilizing to the Tweed philosophy. They started treatment at 12.8 ± 3.5 years of age and finished treatment at 16.0 ± 3.3 years. They were treated with four premolar extractions and retained with either rigid banded fixed or acrylic removable retainers. Orthodontic models were scanned using an Ortho Insight ® scanner and assessed using Dolphin 11.90 ® software. Pre-treatment (T1), post-treatment (T2), and follow-up (T3) models were used to assess the rotational changes of the mandibular canines and incisors, as well as COS changes. During treatment, only the mandibular left canine showed a statistically significant ($p < 0.001$) change, rotating 5.5 degrees in a mesial-out distal-in direction. Post-treatment, the right and left mandibular canines rotated 1.6 and 2.4 degrees, respectively, in a mesial-in distal-out directions. The average COS decreased 2.4 mm during treatment and increased 1.0 mm post-treatment. The deepest point of the COS was located at the premolars pre-treatment, it moves distally to molars during treatment and then relocated mesially to the mesiobuccal cusp tip of the first molars in 60-67% of the cases. The post-treatment rotational and COS changes showed statistically significant low to moderate negative correlations with their treatment changes. There is post-treatment relapse of the rotational and COS changes that occur during treatment. The mandibular lateral incisors showed the greatest potential for post-treatment relapse.

Introduction

One of the most extensively evaluated topics in orthodontic literature is the long-term stability of mandibular alignment. Previous studies have mostly focused on the prevalence of malalignment after orthodontic treatment. [1, 2] A recent meta-analysis showed that post-treatment mandibular malalignment is less than commonly thought, with incisor irregularity increasing an average 1.6 mm over 9 post-treatment years. [3] It appears that multiple factors contribute to the development of malalignment. The development of post-treatment malalignment could be due to relapse or contact slippage, which has been related to growth and vertical eruption, the anterior component of force, point to point tooth contacts, narrow arch form, and post-treatment interproximal restorations. [4] Other factors thought to play a role remain to be tested.

Post-treatment malalignment of mandibular anterior teeth could be a result of post-treatment rotation or labiolingual axial displacement. It is being suggested, without statistical support, that teeth rotated during treatment tend to relapse toward their pre-treatment position. [5, 6] Subsequently Edward [7], who evaluated the effect of circumferential supracrestal fiberotomy (CSF) on incisor irregularity, showed that CSF was effective in alleviating relapse. Importantly, he did not associate the rotational changes that occurred before and after CSF, making it impossible to determine whether there is in fact a relationship between the treatment and post-treatment rotational changes. (i.e. whether there was relapse)

There have only been two studies that have evaluated treatment and post-treatment rotational changes. Without any quantification, one study indicated in the discussion that "as many as half the rotations or displacements returned in a pattern different from the original condition." [8] The other study reported the frequency of teeth with varying degrees of rotational discrepancies before and after treatment, suggesting, again without quantification, that the amount of relapse that occurs may be related to the amount of correction required during treatment. [9] To date, no study has quantified the relationship between the rotational changes that occur during and after treatment, which is necessary to differentiate stability and relapse.

The curve of Spee (COS) also appears to be important for the long-term stability of orthodontic treatment. The COS is one of six keys for normal occlusion and successful orthodontic treatment. [10] It tends to deepen after treatment, [11] due primarily to vertical changes of the anterior teeth. [12] To compensate for these expected changes, it had been suggested to finish orthodontic treatment with a flat or slightly reversed COS. [10] Previous studies have shown that the treatment changes of the COS are negatively correlated with the post-treatment COS changes, [12, 13] indicating post-treatment relapse. However, one study had a short follow-up, [12] and the other did not clearly specify the mechanotherapy used to level the COS. [13] The mechanotherapy is important because leveling of the COS depends on the mechanotherapy that is used. [14]

The primary objective of the present study was to assess the treatment and post-treatment changes in mandibular anterior teeth rotation and the curve of Spee. It is based on a large sample that has been followed-up over an average of 19 years post-treatment. The aim is to help orthodontists determine whether the rotations and COS changes that occur during treatment relapse post-treatment.

Material and Methods

The participants' records were obtained from two private orthodontic practitioners who used the Tweed orthodontic treatment technique. This technique includes sequential appliance placement, sequential tooth movement, and sequential mandibular anchorage preparation. High-pull headgear and anterior elastics were used to control the vertical dimension. The cases were usually finished with the lower incisors upright over basal bone and the curve of Spee over-corrected. This longitudinal observational study was approved by the institutional research board of Texas A&M University (IRB ID: 2017-0305-CD-EXP). To be considered for this study, the patients had to meet the following criteria:

1. Orthodontic patients five or more years out of retention.
2. Treatment plan that included four premolar extractions.
3. A full set of good quality records, including pre-treatment (T1), post-treatment (T2), and long-term follow up (T3) orthodontic models.
4. No orthognathic surgery as part of their treatment plan.
5. No cases with Class III malocclusion.

The sample included 100 orthodontic patients who were treated with four premolars extractions and full fixed appliances. The required sample size was calculated using G*Power software®, assuming a type I error equal to 5%, a type II error 20%, and an effect size equal to 0.3. To achieve this power a total sample of 90 orthodontic patients was required. 56% were treated with four first premolars extractions, 29% had upper first and lower second premolars extracted, and 15% had four second premolars extracted. The sample included 19 males and 81 females; 38 of the patients had Class I and 62 had Class II malocclusions prior to treatment. 47 cases were treated by one orthodontist and 53 cases were treated by the other orthodontist.

The average retention time was 1.5 years for the cases treated by the first orthodontist, and 3.5 years for the second orthodontist. Fixed retainers were used in 57% of the cases and removable retainers were used in 43% (Table 20). The mean pre-treatment age was 12.8 years, the post-treatment age was 16.0 years, and the post-retention age was 35.2 years. They were followed-up on an average of 19.2 years (Table 21). Orthodontic models were scanned using an Ortho Insight ® scanner. After scanning, the 3-D models were imported to Dolphin 11.90 ® software. The rotation of the anterior mandibular teeth as well as changes in the curve of Spee were measured using Dolphin 11.90 ® software.

The pre-treatment (T1), post-treatment (T2) and post-retention (T3) measures, along with the changes that occurred were assessed. All the models were trimmed and oriented using Dolphin 3-D object function. Rotations (Figure 18) of the mandibular canines and incisors were evaluated as the angle at the mesial aspect of each tooth formed by a line pass through mesial and distal contact points and the sagittal reference plane, which was defined as the mid-palatal plane. The positive changes in the rotational angle indicate mesial-in distal-out tooth rotation, while negative changes indicate mesial-out distal-in tooth rotation. The curve of Spee (COS) was evaluated bilaterally as the deepest point from the cusp tips of the posterior teeth to the line passed from the distobuccal cusp tip of the most posteriorly erupted tooth to the incisor tip on the sagittal plane (Figure 19A). The locations of the deepest COS points on the mandibular arch were also recorded. All the measurements were performed by one operator (A.J.S.).

Statistical analysis

The IBM SPSS 25 ® statistical package was used for the analyses. Measurement error was assessed based on 22 replicates. Systematic error was assessed using paired t-test. Random error was assessed using Dahlberg's method errors and intraclass correlations. The normality of the distributions was statistically demonstrated using the skewness and kurtosis statistics, as well as the Shapiro Wilk's test. The data were described with means and standard deviations. Paired t-tests were used to evaluate the treatment (T1-T2) and post-treatment (T2-T3) changes. Pearson's product-moment correlations were used to evaluate the relationships of treatment and post-treatment changes of the mandibular anterior teeth rotation as well as the COS.

Results

All of the intraclass correlations between replicates were higher than 0.98 (Table 22). Method errors ranged from 0.5 to 0.7 degrees for angular measurements and from

0.05 to 0.06 mm for linear measurements. Paired t-tests showed no statistically significant systematic measurement errors.

Mandibular anterior teeth rotation

The anterior mandibular teeth showed greater rotational variability at T1 than at T2 or T3 (Table 23). On average, pre-treatment central and lateral incisor rotational angles approximated 80 and 64 degrees, respectively. Mandibular right and left canines showed average rotational angles of 25 and 31 degrees, respectively. Except for the mandibular canines at T1 ($P < 0.001$), the central incisors at T2 ($P = 0.02$), and the lateral incisors at T3 ($P = 0.04$) there were no statistically significant differences between right and left antimeres.

During treatment (T1-T2), only the lower left canine showed statistically significant rotational changes. It rotated 5 degrees in a mesial-out distal-in direction. Post-retention (T2-T3), only the mandibular canines showed a significant rotational change ($P < 0.001$). The right and left mandibular canines rotated 1.6 and 2.4 degrees, respectively, both in a mesial-in distal-out direction (Figure 20). The mandibular incisors showed no significant rotational changes both during and after treatment.

Curve of Spee

Except for the end of treatment (T2) ($P = 0.03$), there were no statistically significant differences between the right and left COS measurements (Table 23). The average COS decreased from 2.7 mm at pre-treatment (T1) to 0.3 mm post-treatment, and then increased to 1.3 mm post-retention (Figure 21). The treatment and post-treatment changes of the COS were statistically significant ($P < 0.001$). The COS decreased an average of 2.4 mm during treatment and deepening 1.0 mm post-retention.

The location of the deepest point defining the COS showed consistent patterns of change on both the right and left sides of the mandibular arch (Table 24). Pre-treatment, about 50% of the cases had the deepest COS point at the premolars. At the end of treatment, the deepest COS point was most frequently on the mesiobuccal cusps of the first and second molars. In addition, the post-treatment COS in 36% of the cases was negative, indicating over correction (Figure 19B). At the follow-up visit, the deepest COS point was located on the mesiobuccal cusp of mandibular first molars in 60-67% of the cases.

Treatment and post-treatment associations

Both the rotational and COS measures showed statistically significant relationships between their treatment (T1-T2) and post-treatment (T2-T3) changes (Table 25). The rotational correlations were negative and low, ranging from – 0.24 to – 0.43. After Bonferroni correction, the correlations were significant for the lateral incisors ($P < 0.001$), as well as left central incisor ($P = 0.005$).

The COS correlations were also negative and moderate, ranging from – 0.64 to – 0.70. The pre-treatment (T1) and the follow-up (T3) values of mandibular anterior rotations and COS were also significantly correlated. All the variables showed positive correlations, with slightly higher associations for the rotational (0.44 – 0.56) than COS (0.31 – 0.35) measures (Table 25).

Discussion

Prior to treatment, the central incisors exhibited substantially less rotational variability than the lateral incisors and canines. Approximately 68% of the rotational angles of the lateral incisors and canines varied by ± 12.9 to ± 17.2 degrees, respectively, compared to ± 8 degrees for the central incisors. It has been previously shown that the canine is the most severely rotated tooth, followed by second premolar, lateral incisor, central incisor, and the least rotated tooth was the first molar. [9] The differences between teeth could be explained by the eruption sequence of the lower anterior teeth. The central incisor is the first tooth to erupt and there are usually spaces in the primary dentition. [15] As such, variability in central incisor rotational angulation is less likely. Because the canine erupts during the late mixed dentition, rotational angle variability is more likely, especially when there are tooth size arch length discrepancies. Pre-treatment rotational variability could also be related to mandibular arch form. Different arch forms (i.e. wide vs. narrow) have different interdental angles (angle between pairs of contralateral teeth) as well as different contact angles (angle between the contact points of adjacent teeth). [16] Greater stability and less contact slippage might be expected in arches that have larger interdental and contact angles.

Mandibular canines follow a pattern of mesial-in distal-out rotation post-treatment. In the present study, the right and left canines rotated 1.6 and 2.4 degrees, respectively. No previous study has evaluated the mandibular anterior teeth long-term rotational changes. A possible explanation for the rotational pattern of the mandibular canines could be related to the “cornering effect” that has been shown to occur post-treatment. [16] The mandibular arch tends to become more flattened anteriorly post-treatment, which could be partially explained by the rotational pattern observed in the mandibular canines. Another explanation could be related to the anterior component of force. [17] Since the canines are located in the corner of the lower arch, any posterior direction of force might be expected to increase the chance of mesial-in distal-out rotational pattern. The slightly greater post-treatment rotation of left canine in the current sample could be just happening by chance because canines in the present sample showed no relapse.

Teeth that required greater rotation during treatment are more likely to relapse post-treatment. In the present study, the negative rotational changes during treatment were negatively correlated with positive post-treatment changes, and vice versa (Figure 22). In other words, teeth rotated during treatment in one direction tend to relapse post-treatment in the opposite direction. While correlations of treatment and post-treatment rotational changes of mandibular anterior teeth have not been previously demonstrated, they have been reported for maxillary anterior teeth. [18, 19] Both studies reported positive correlations, but only one study reported the actual correlation coefficients. [18] The other study reported positive correlations between the time points (T1 vs. T3), rather than the correlations between treatment and post-treatment changes. [19] Correlations between time points could be misinterpreted as rotational relapse, because the angles could also be related to arch form. Notably, the correlations were significant for the incisors but not the canines after Bonferroni correction for the multiple comparisons. This suggests that there may be a relationship, but a less strong relationship. Relapse of the canines could also be less due to the fact that canines have a larger root surface area, which limits their ability to derotate after correction. The present findings suggest that teeth that undergo greater rotational changes during treatment might require overcorrection, longer retention, and CSF procedure to reduce the possibility of their post-treatment relapse.

The curve of Spee deepens post-treatment. In the present study, the COS increased approximately 1 mm post-treatment. Previous studies evaluated post-treatment stability of the COS reported smaller changes, ranging from 0.3 to 0.5 mm. [11-13] The difference in post-treatment COS change in the present sample could be related to the follow-up duration. The cases in the present sample followed-up on average 19 years, while previous studies had shorter (2-7 years) follow-up durations. [11, 12] Deepening of the COS could be explained by the eruption of mandibular incisors and molars. [126] It has been previously reported that COS of untreated individuals followed-up from 4 to 26 years deepens to 2 mm, which was mainly due to incisors and molars eruption. [20] Regardless, the post-treatment COS changes are limited (1mm), considering the average follow-up duration (19 years).

Importantly, the location of the deepest COS point changes consistently during and after treatment. Pre-treatment, the deepest point of the COS was located at the premolars, and it moved distally during treatment. At the follow-up, the deepest COS point was located, in 2/3 of the sample, at the mesiobuccal cusp of first molars. Similar post-treatment location of the deepest COS point, on the mesiobuccal cusp of first molar, had been previously reported. [12] The pre-treatment location of the deepest COS point in the present sample could be explained by the eruption timing. The average age at T1 was 12 years, when premolars are usually not fully erupted. Distal relocation of the deepest COS point during treatment (T2) could be explained by the mechanotherapy that was used, which included distal tipping of the posterior teeth. At the follow-up (T3), the location of deepest COS point on the mesiobuccal cusp of the first molar, which could have been due to the fact that first molars are the most commonly used tooth during masticatory function. [21] In addition, it has previously been shown that the deepest COS point is displaced distally during treatment and moves slightly mesially post-treatment. [13] It is important for orthodontists to understand that the deepest COS point is not a fixed point, and should be expected to change post-treatment.

The greater the changes of the COS during treatment, the greater the post-treatment relapse. In the present study, the COS treatment changes were negatively correlated with post-treatment changes. A negative correlation (r= -0.42) between the treatment and post-treatment changes of the COS has been previously reported. [13] A possible explanation for the post-treatment COS relapse could be related to the mechanotherapy that was used. The COS in the present sample was overcorrected with greater distal tipping of the mandibular molars. It has been shown that greater distal tipping of molars during treatment is associated with more COS relapse post-treatment. [12] Since the relapse was only partial, the findings of the present study suggest that overcorrection of the COS during treatment could minimize the amount of deepening that occurred post-treatment.

Finally, this study is not without limitations. The patients in the present study were treated during the 1970's and 1980's when full banded standard edgewise appliances were used, which differ substantially from the bonded pre-adjusted appliances currently being used. Standard edgewise appliances require individual wire bending to compensate for the first order (in-out) offsets, which might affect the amount of rotation observed in the present study. In addition, the mechanotherapy used in the present sample included overcorrection of the COS and excessive distal tipping of molars, which might affect the comparability of COS findings with previous studies. Therefore, the results of the present study should be interpreted within the context of these limitations.

Conclusions

Based on the findings of 100 orthodontic patients who were followed-up post-treatment an average of 19 years, the following conclusions can be drawn:

- Only the canines showed a consistent pattern of post-treatment rotational changes, in a mesial-in distal-out direction.
- Mandibular incisors, especially the lateral incisors, showed post-treatment rotational relapse which was negatively correlated with their treatment rotational changes.
- The COS was overcorrected during treatment and it deepened post-treatment.
- The COS also shows a post-treatment relapse, the average COS lost around 40% of the amount of leveling during treatment.

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CHAPTER VI

CONCLUSIONS

Since the present study evaluated several aspects of long-term stability of mandibular alignment after orthodontic treatment, the conclusions will be summarized by chapters starting with chapter II:

Based on 30 studies involving 1859 patients, the following conclusions relating to post-treatment mandibular alignment changes can be drawn:

1. On average, there are only limited amounts of irregularity change after orthodontic treatment. It increases only 1.6 mm, over an average of 9.3 post-treatment years.
2. There is a statistically significant difference in post-treatment irregularity changes between mandibular premolars extraction and non-extraction treatments.
3. There are greater irregularity changes in orthodontic patients who are followed up for longer periods of time.
4. Meta-regression analysis showed that pre-treatment irregularity, the clinical setting, the type of retention, and adjunctive procedures have no significant effects on post-treatment irregularity changes.

Chapter III evaluated post-treatment mandibular growth and dentoalveolar changes and based on the findings of the present study, the following conclusions of extraction patients followed-up between 16 and 35 years of age can be drawn:

1. The mandible exhibits substantial post-treatment changes, with size increases ranging from 0.9 to 1.9 mm.
2. Males show greater ramal growth and more counterclockwise rotation of the functional occlusal plane and mandibular plane than females.
3. The upper and lower incisors retroclined, lower incisor to APog distance decreased, the interincisal angle increased, the first molars tipped mesially, and the functional occlusal plane rotated counterclockwise.
4. Mandibular incisors erupted on average of 1.4 mm, with greater eruption associated with fixed than removable retainers.
5. Post-treatment incisor inclination decreases more with second premolar than first premolars extraction.

Chapter IV investigated the significance of distal root tip in mandibular incisors long-term alignment stability, and based on the findings of the present study the following conclusions can be drawn:

1. Post-treatment mandibular alignment changes are limited, with only 1.17 mm and 1.04 mm of irregularity index and TSALD changes, respectively, after 19 years.
2. Mandibular incisors finished treatment with slight (1.3 – 2.0 degrees) distal root tip and exhibited minimal post-treatment changes.
3. There was no relationship between mandibular incisors angulation at the end of treatment and the post-treatment mandibular alignment changes.

4. Post-treatment changes of right lateral incisor angulation were positively correlated with mandibular alignment changes.
5. Sex, malocclusion, extraction pattern, and retention method had no significant effects on the incisor angulation and mandibular alignment changes.

Chapter V assessed the post-treatment relapse of orthodontically rotated anterior teeth and curve of Spee leveling, and based on the findings of 100 orthodontic patients who were followed-up post-treatment an average of 19 years, the following conclusions can be drawn:

1. Only the canines showed a consistent pattern of post-treatment rotational changes, in a mesial-in distal-out direction.
2. Mandibular incisors, especially the lateral incisors, showed post-treatment rotational relapse which was negatively correlated with their treatment rotational changes.
3. The COS was overcorrected during treatment and it deepened post-treatment.
4. The COS also shows a post-treatment relapse, the average COS lost around 40% of the amount of leveling during treatment.

APPENDIX A

FIGURES

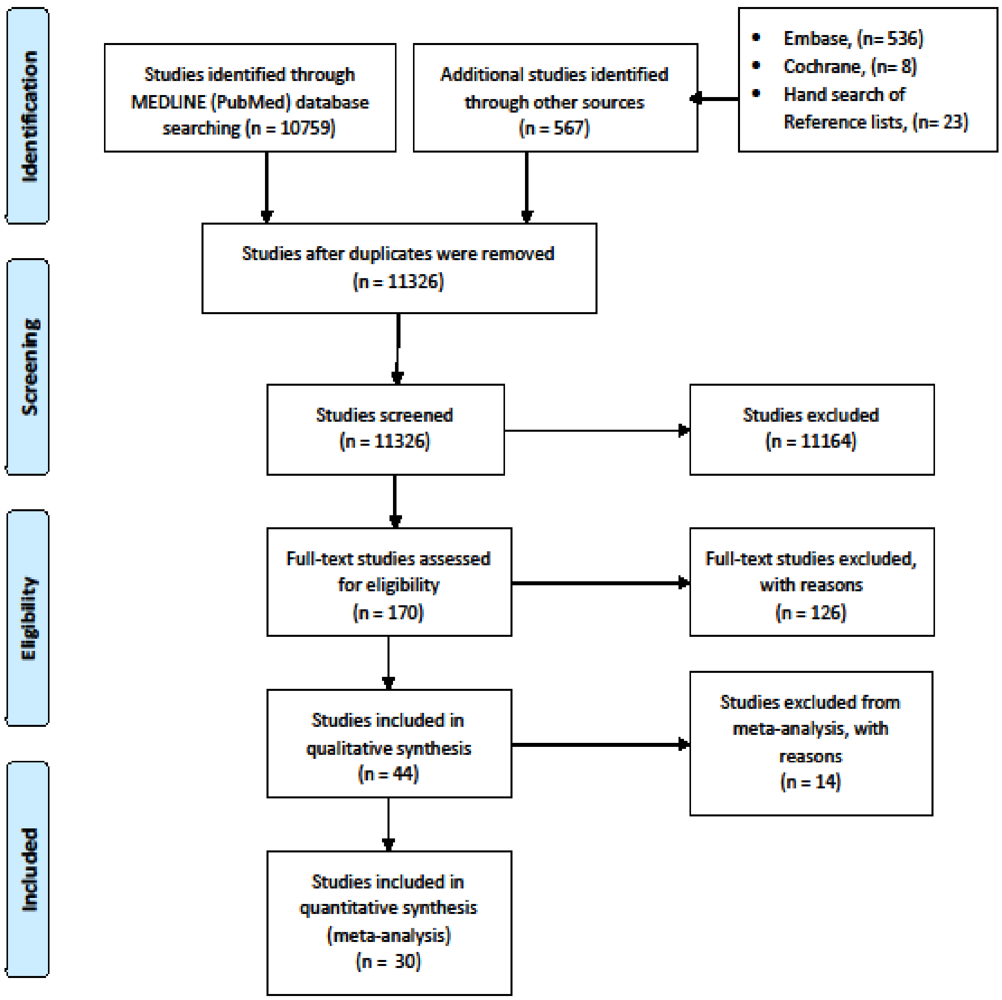

Figure 1. Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) study flow diagram.

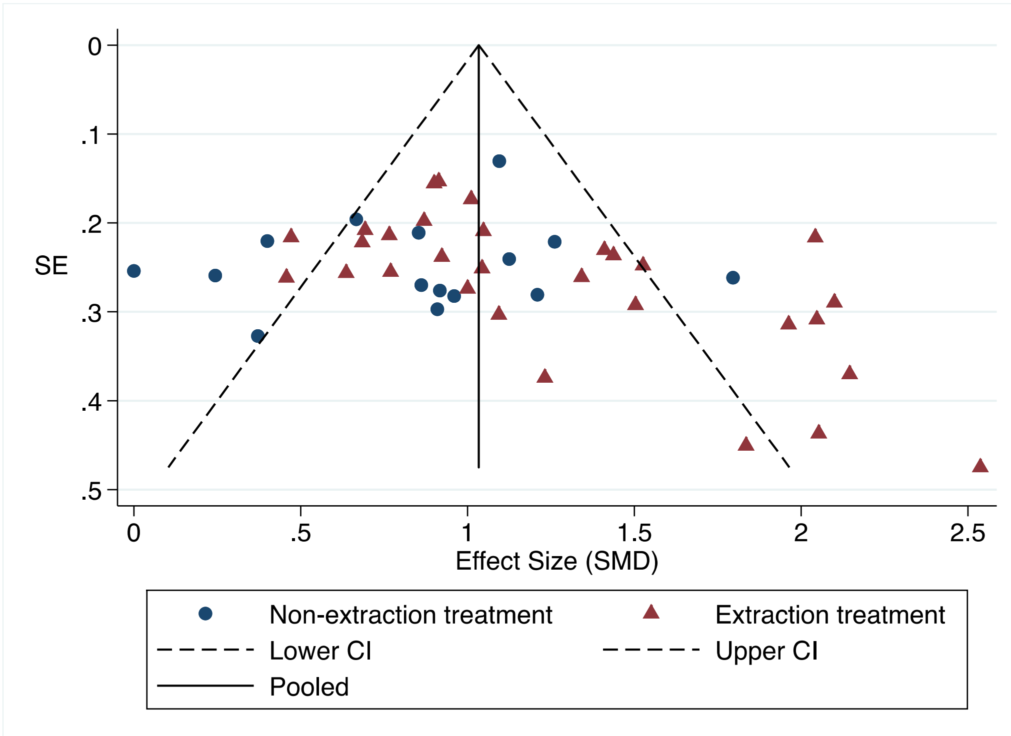

Figure 2. Funnel plot, with pseudo 95% confidence limits, of included studies based on treatment protocol (Extraction vs Non-Extraction). SE: Standard Error; 95% CI: Confidence interval.

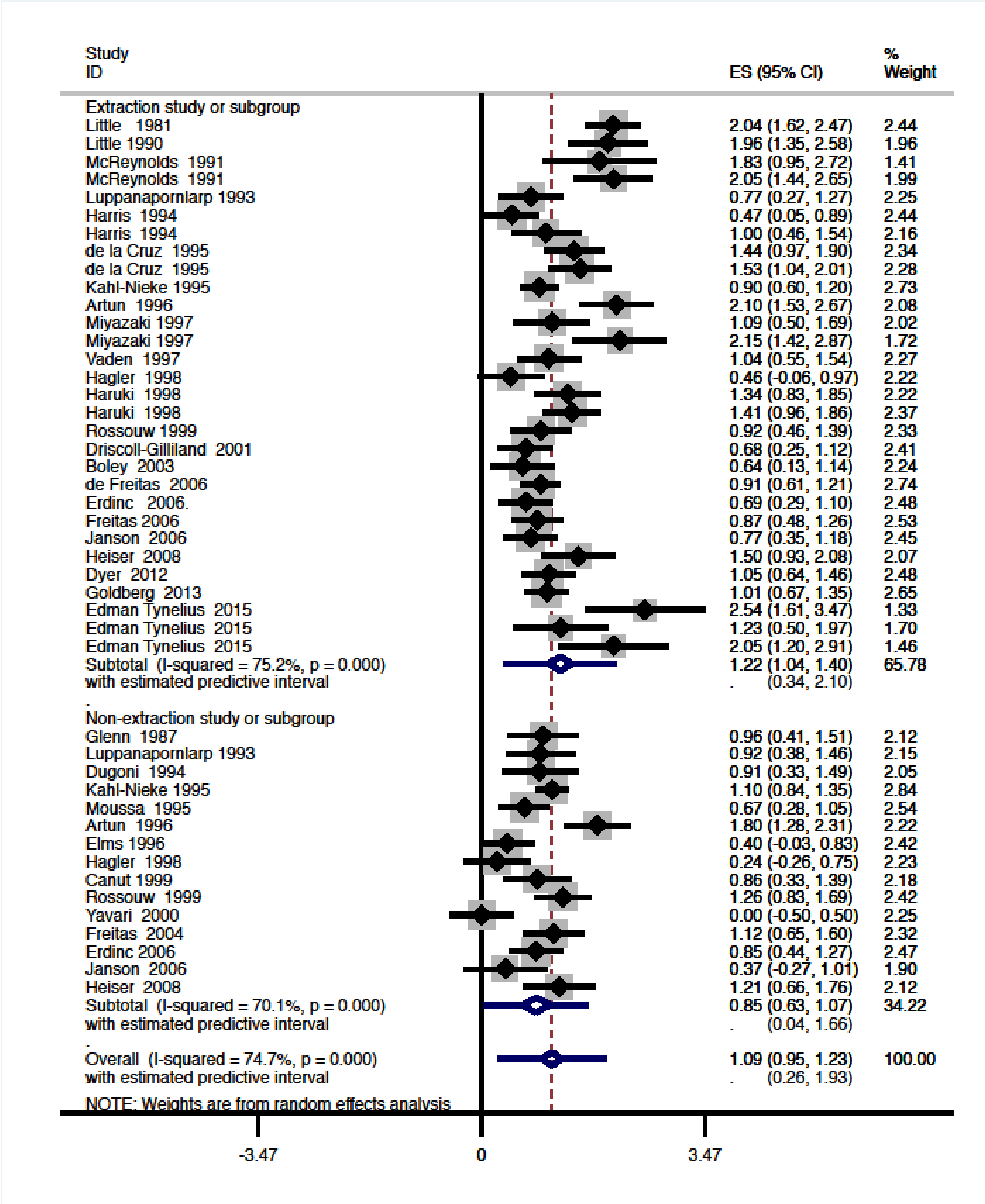

Figure 3. Forest plot of summary effect (SMD) comparing extraction vs. non-extraction treatment.

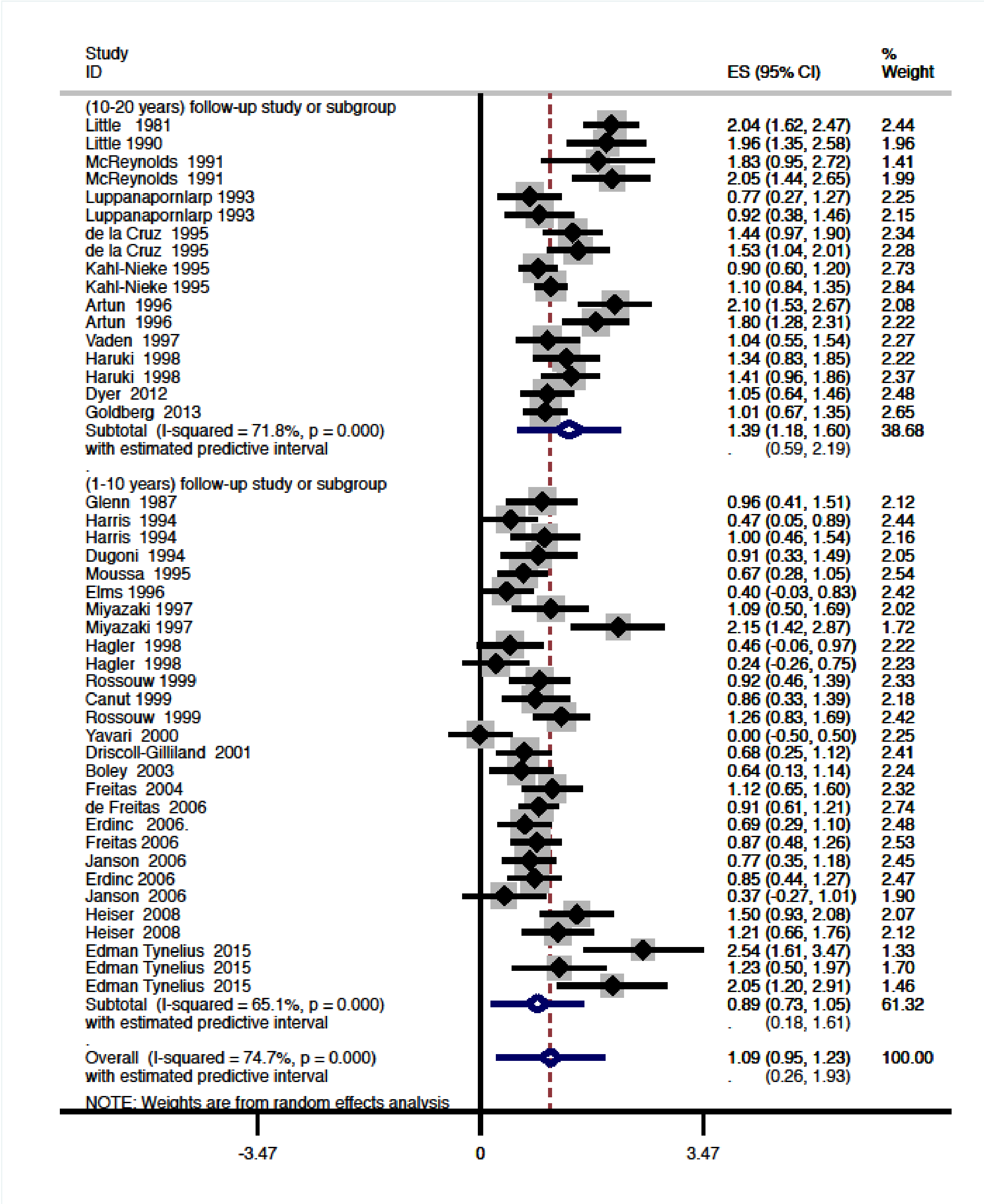

Figure 4. Forest plot of summary effect (SMD) based on follow-up duration (1-10 year vs. 10-20 year).

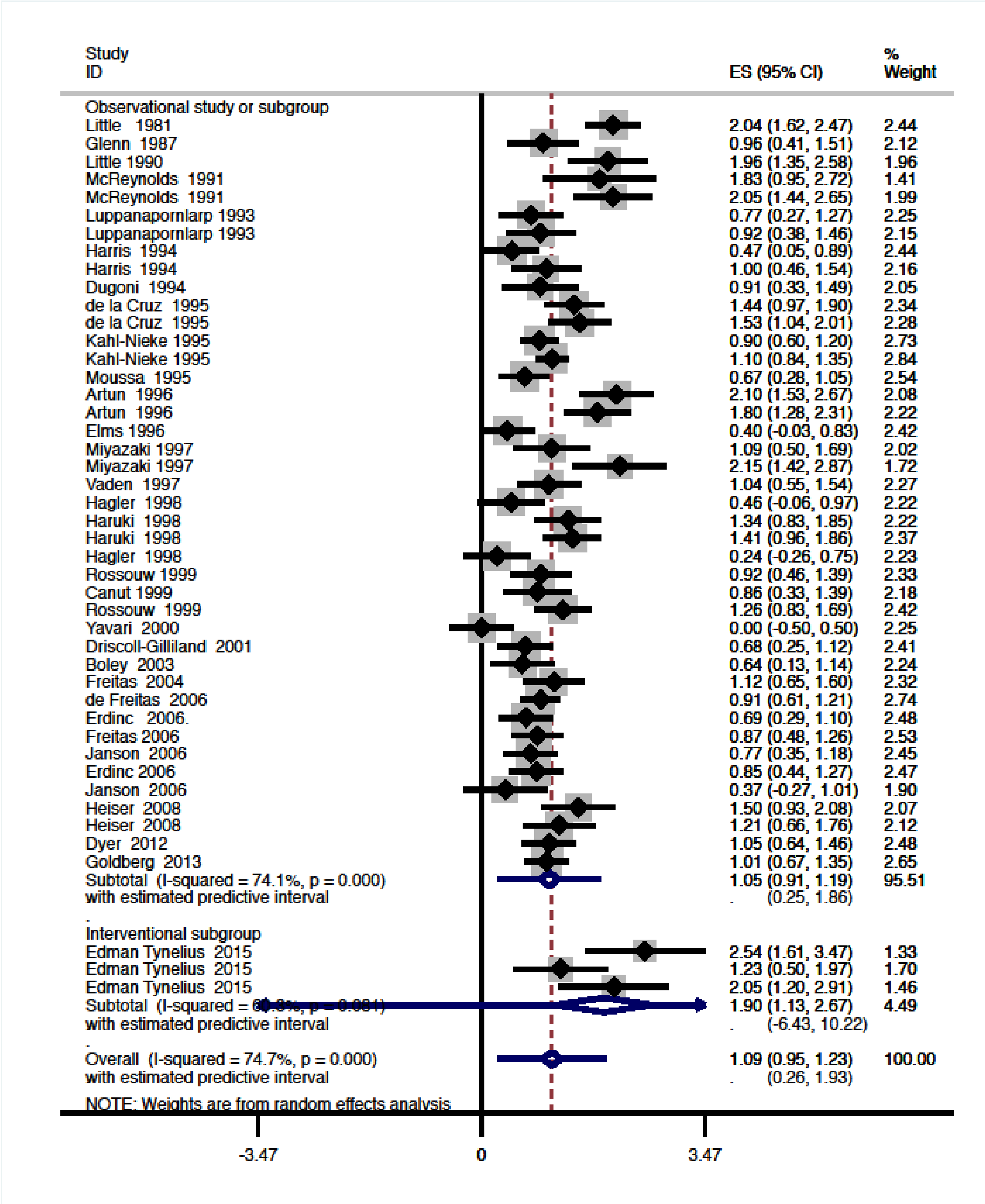

Figure 5. Forest plot of summary effect (SMD) based on study design (observational vs. interventional).

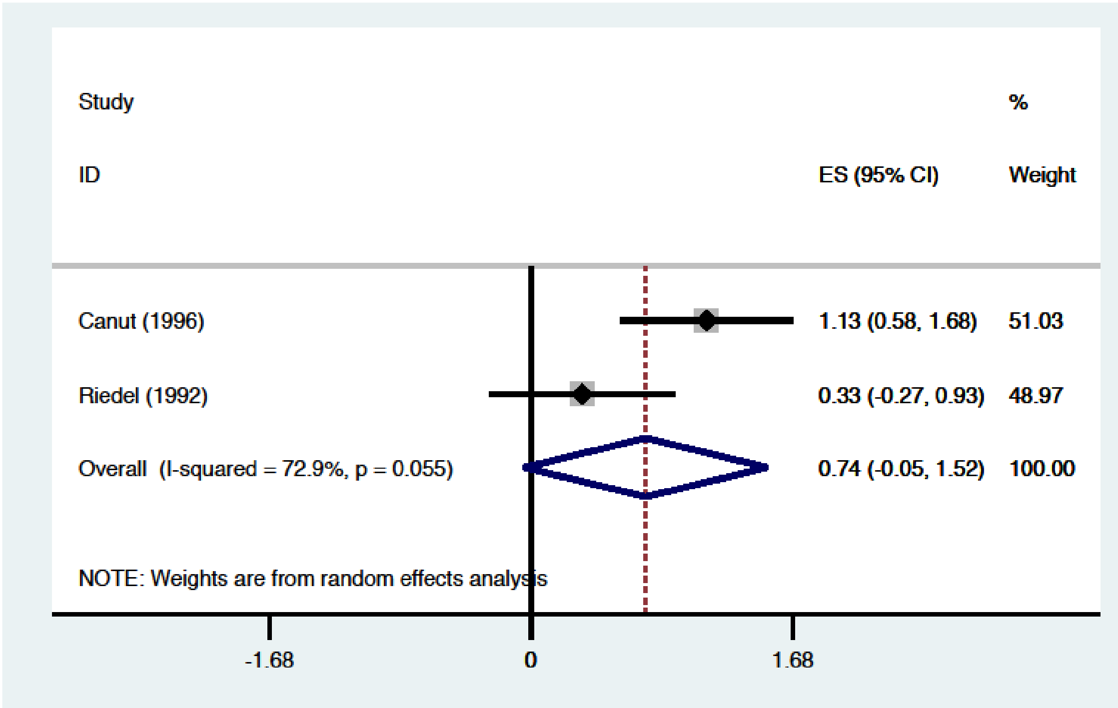

Figure 6. Forest plot of alignment changes (mean difference), along with 95 % confidence intervals, after lower incisor extraction.

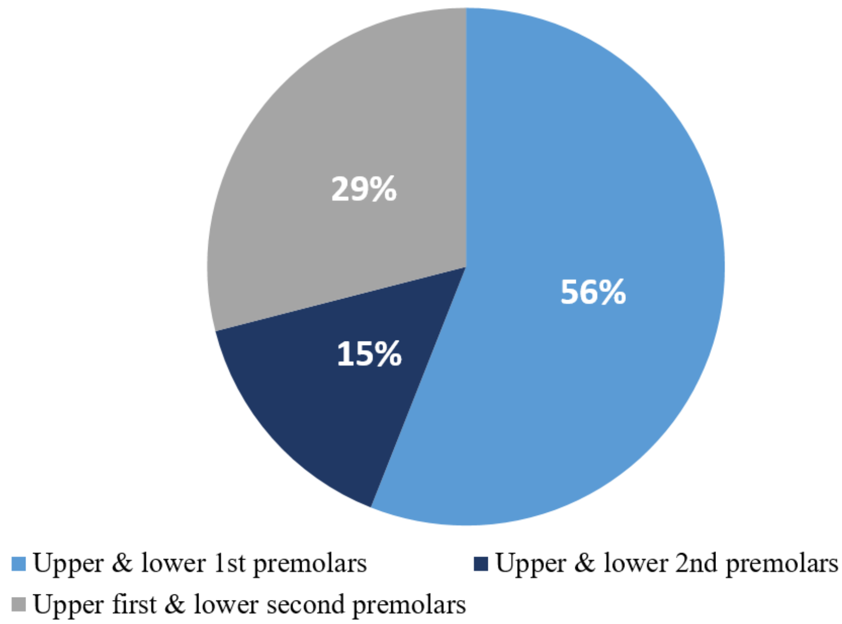

Figure 7. Extraction patterns of patients included in the sample (n=100).

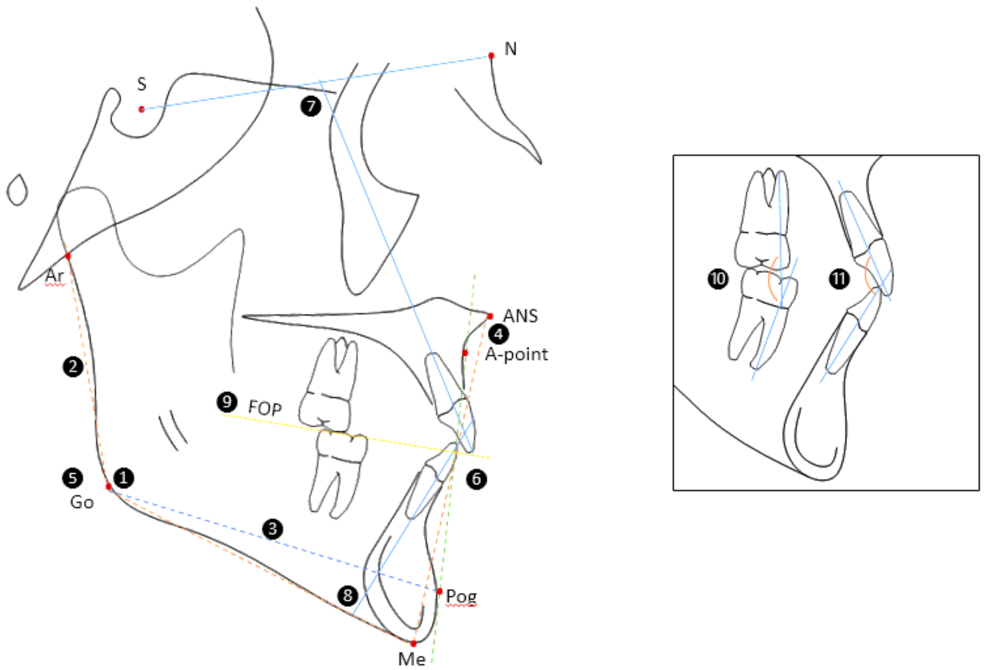

Figure 8. Cephalometric tracing landmarks and measurements. 1. Gonial angle. 2. Ramus height. 3. Corpus length. 4. Lower anterior facial height. 5. Mandibular plane angle. 6. Lower incisor to A-pog distance. 7. Upper incisor to SN angle. 8. Lower incisor to MP angle. 9. Functional occlusal plane to SN angle. 10**.** Intermolar angle. 11.Interincisal angle.

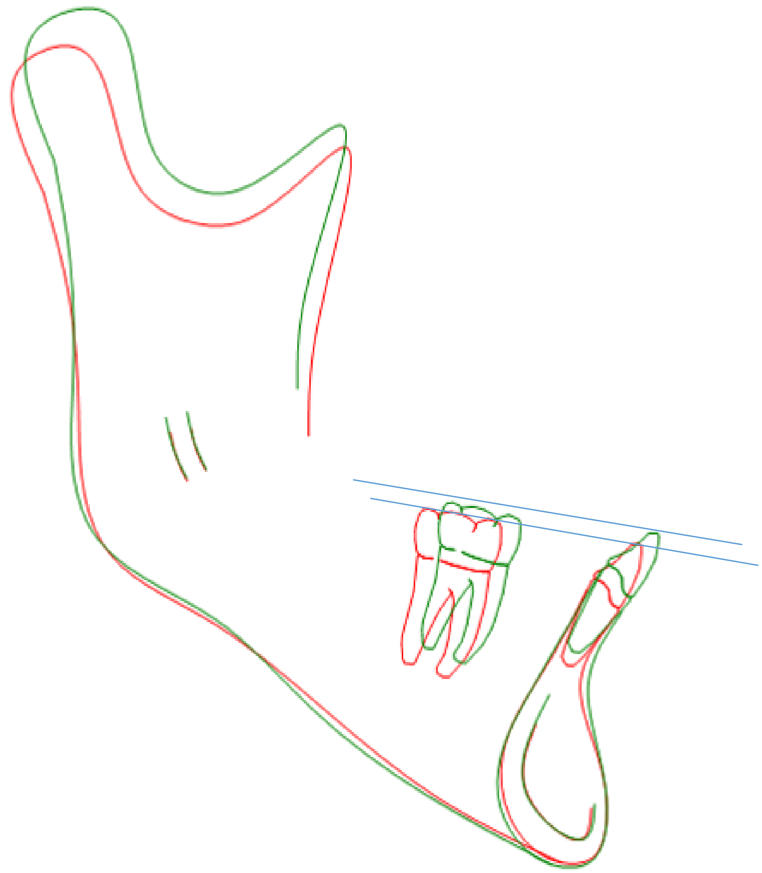

Figure 9. Measurement of lower incisor eruption based on stable structures for mandibular superimpositions. Incisor eruption measured as a vertical distance from incisal tip perpendicular to the occlusal plane at the end of treatment (T1).

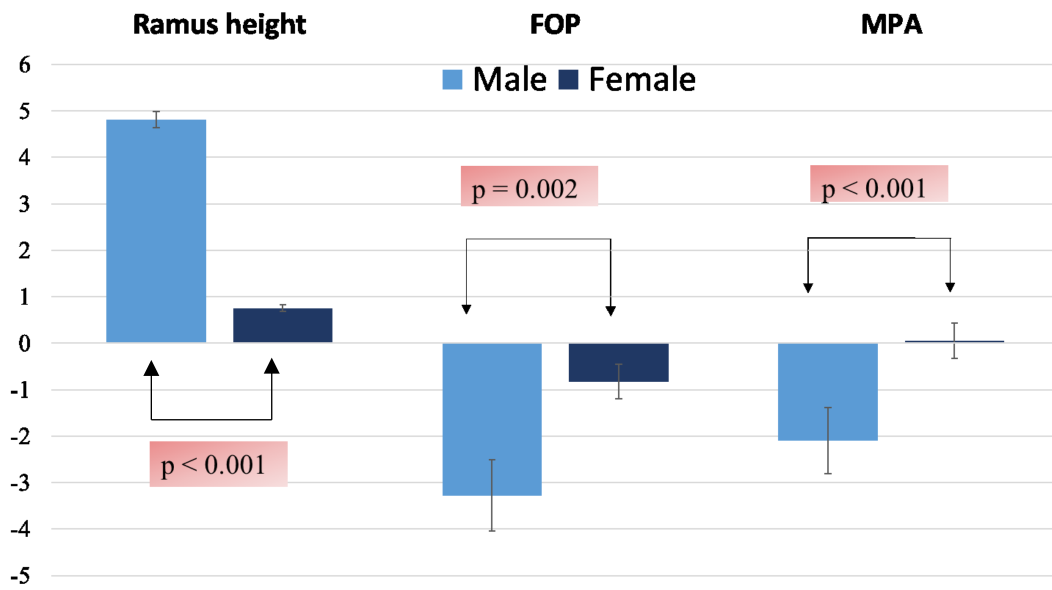

Figure 10. Variables showing statistically significant differences between sex, along with standard errors.

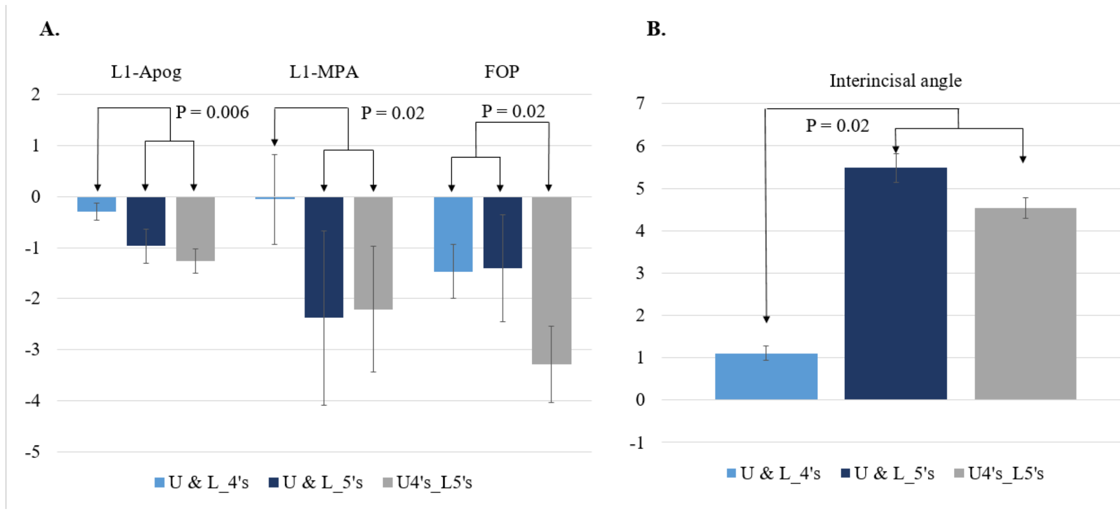

Figure 11. Variables showing statistically significant differences between extraction patterns, along with standard errors.

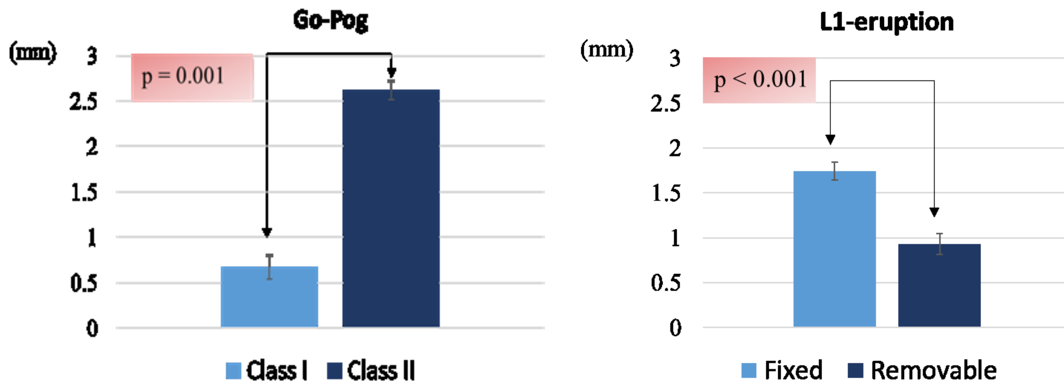

Figure 12. Mean differences between A) retention methods and B) malocclusions, along with standard errors.

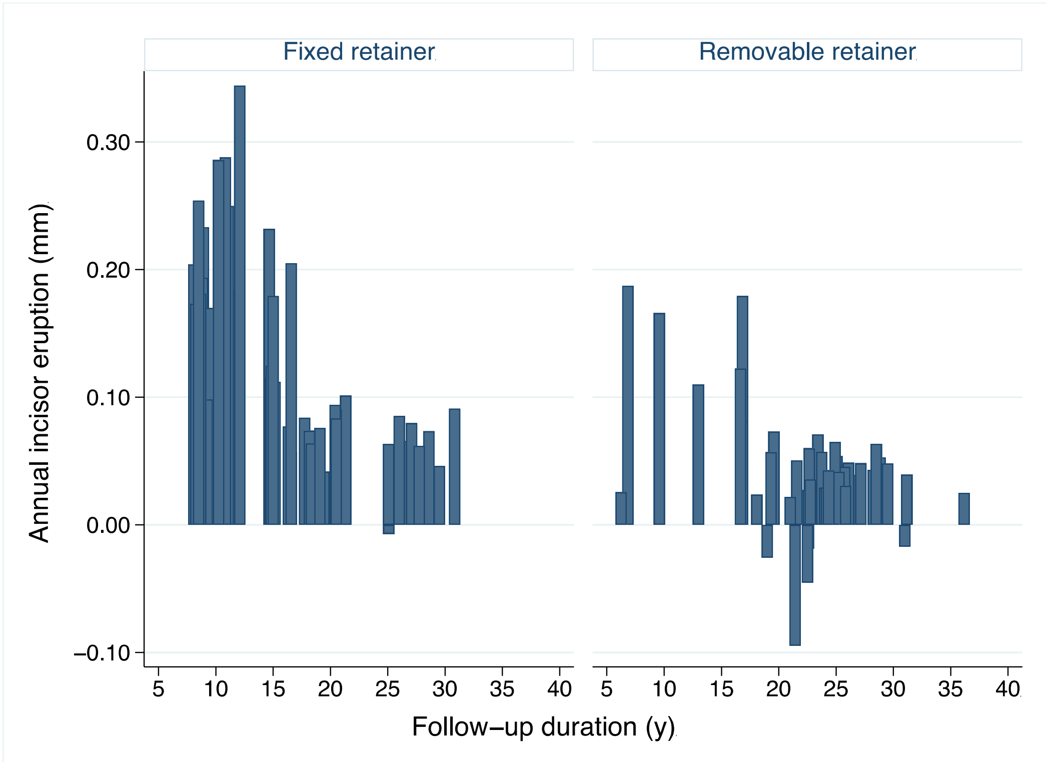

Figure 13. Annual mandibular incisor eruption after different retention methods showed a pattern of a greater eruption in patients who followed-up shorter, the average age at post-treatment was 15 years.

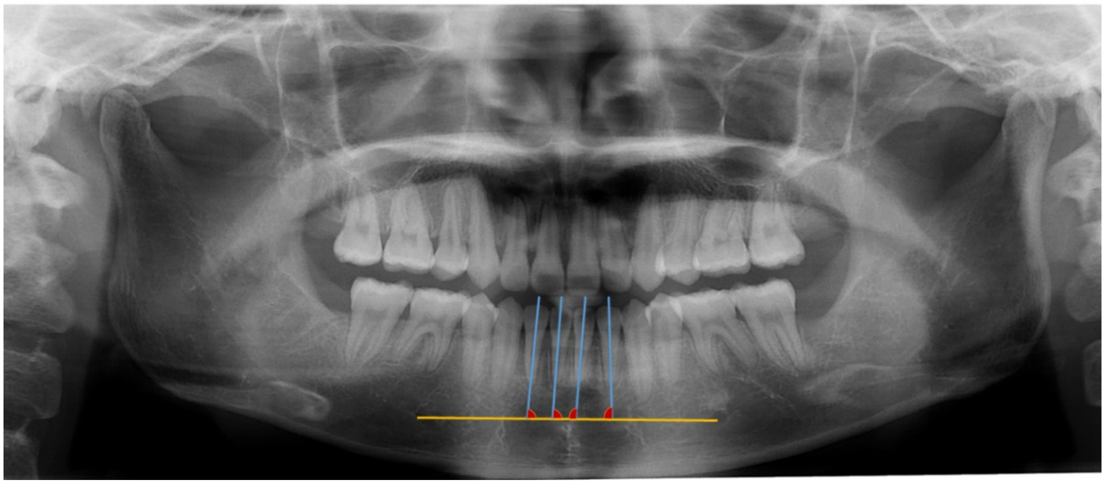

Figure 14. Angulation measurement of lower incisors. The yellow line indicated the horizontal reference line drawn in relation to the mental foramens. The mesial angles were used with value less than 90 degree indicates distal root tip and more than 90 degree indicates mesial root tip.

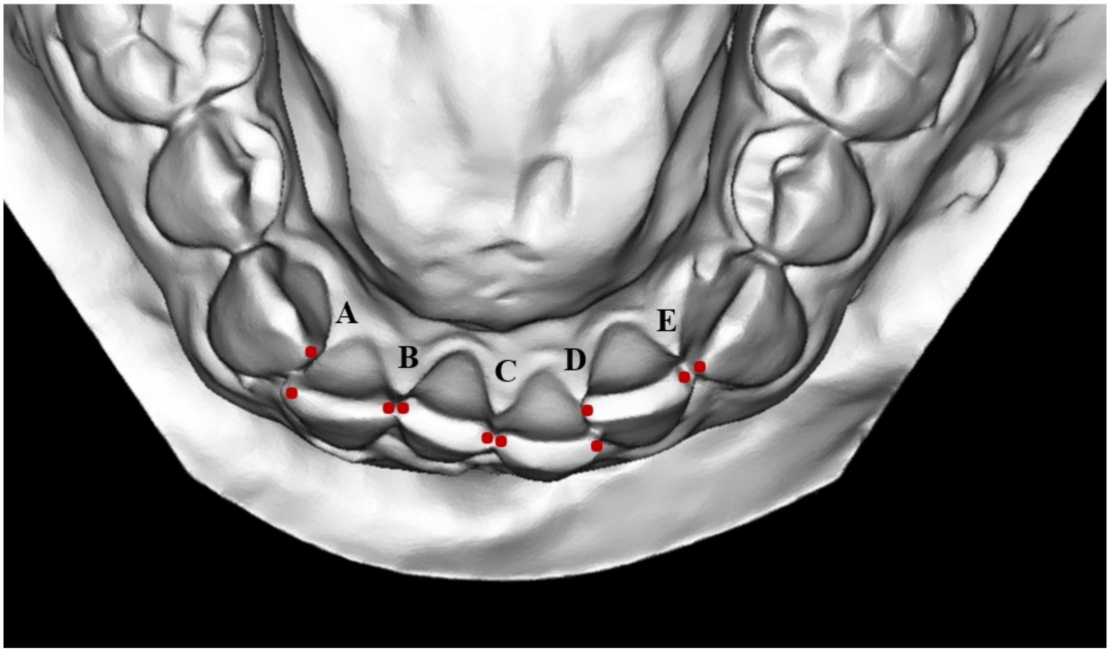

Figure 15. A. Little's irregularity index: measured as the distance between the incisal edges from mesial of lower right canine to lower left canine (A+B+C+D+E).

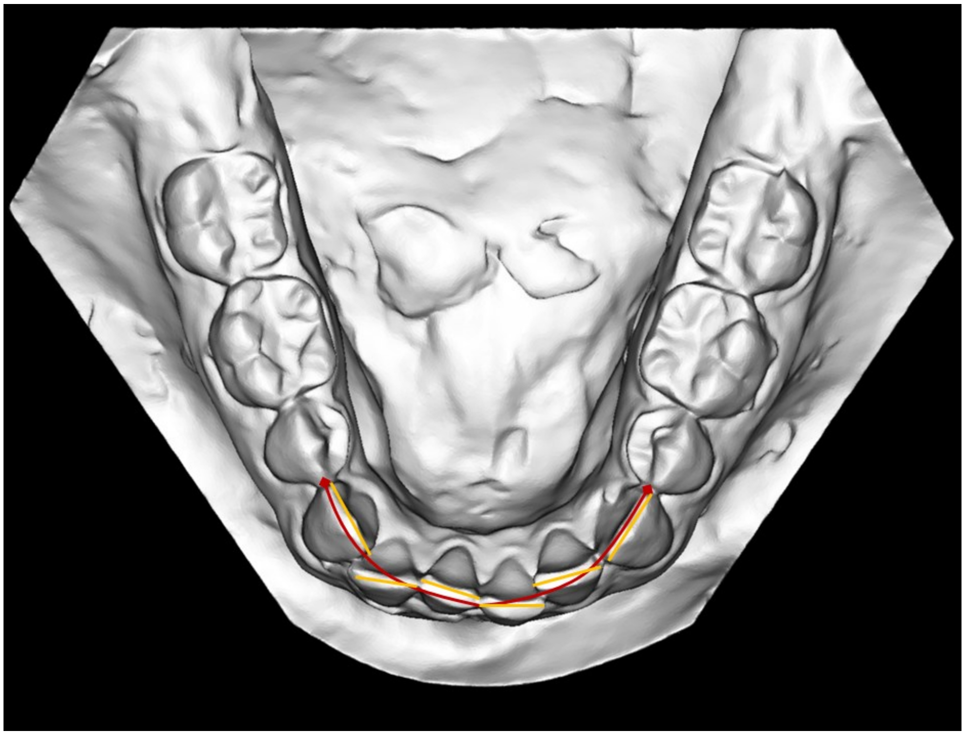

Figure 15. B. Anterior TSALD: measured as the difference between the sum of teeth size from lower canine to canine and the anterior arch perimeter.

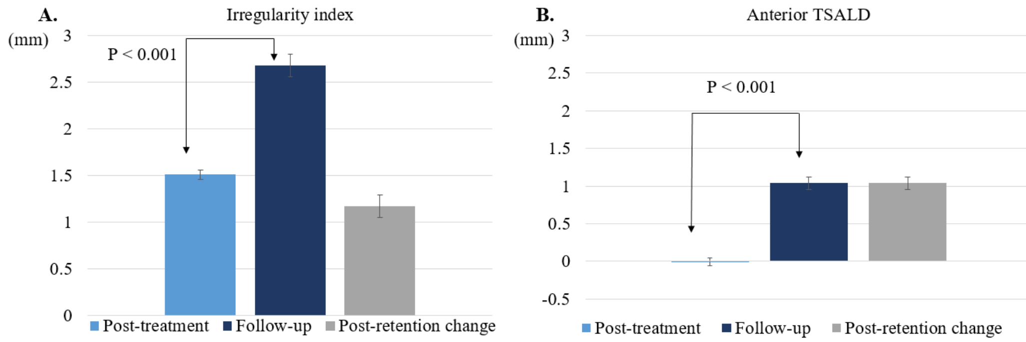

Figure 16. The means of A) Irregularity index and B) Anterior TSALD at the different evaluation stages, along with standard errors.

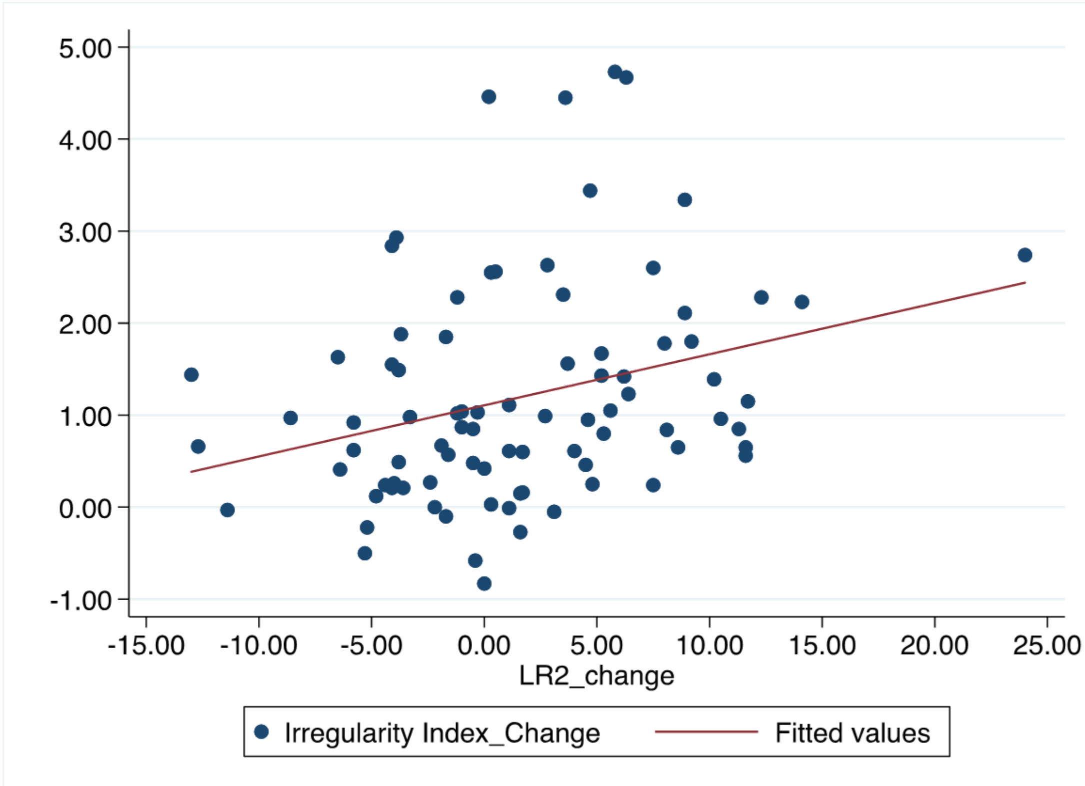

Figure 17. A. Scatter plot of lower right lateral incisor angulation change and mandibular irregularity index changes.

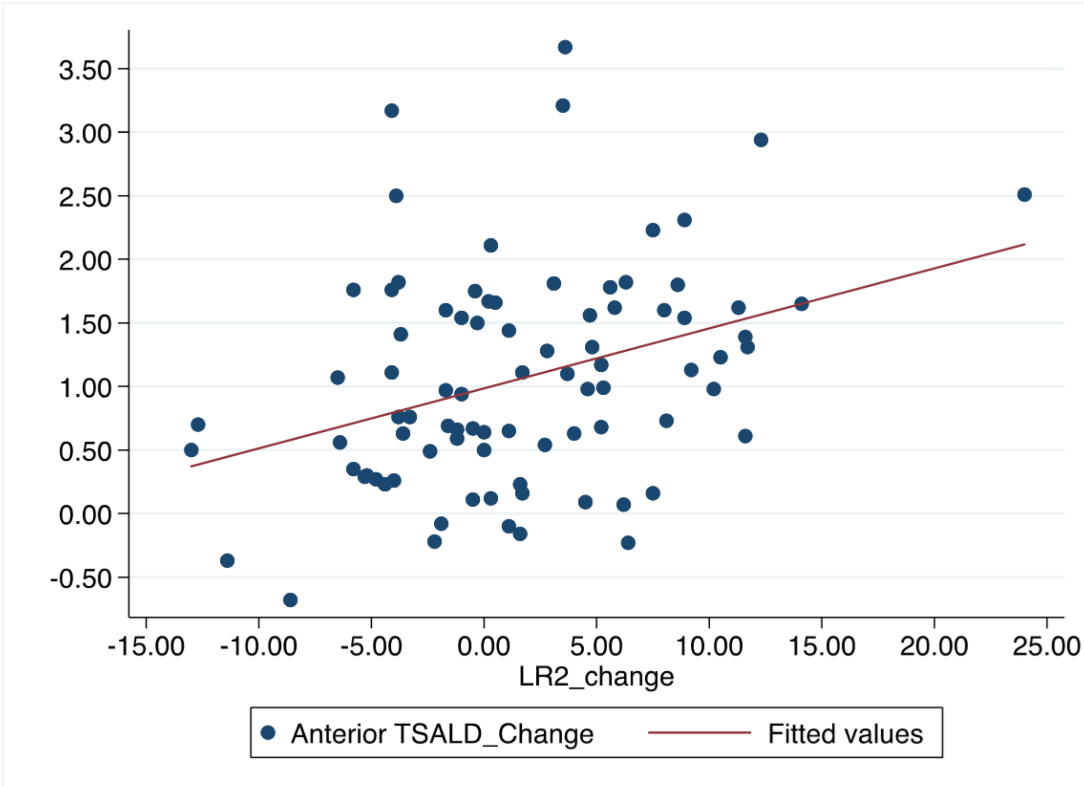

Figure 17. B. Scatter plot of lower right lateral incisor angulation change and mandibular anterior TSALD changes.

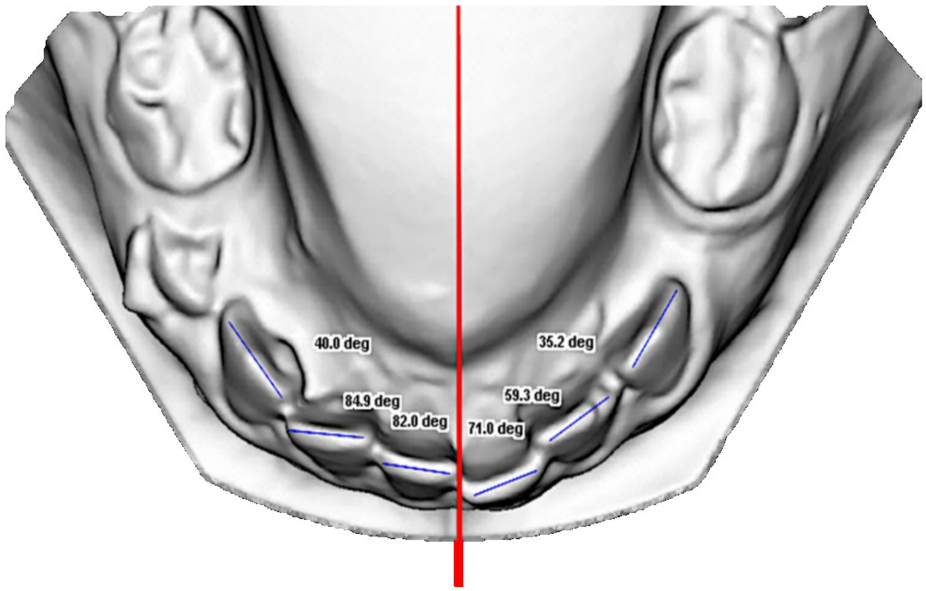

Figure 18. Rotational angles of the mandibular anterior teeth, measured as the angle at the mesial aspect of each tooth formed by a line pass through incisal edge and sagittal plane.

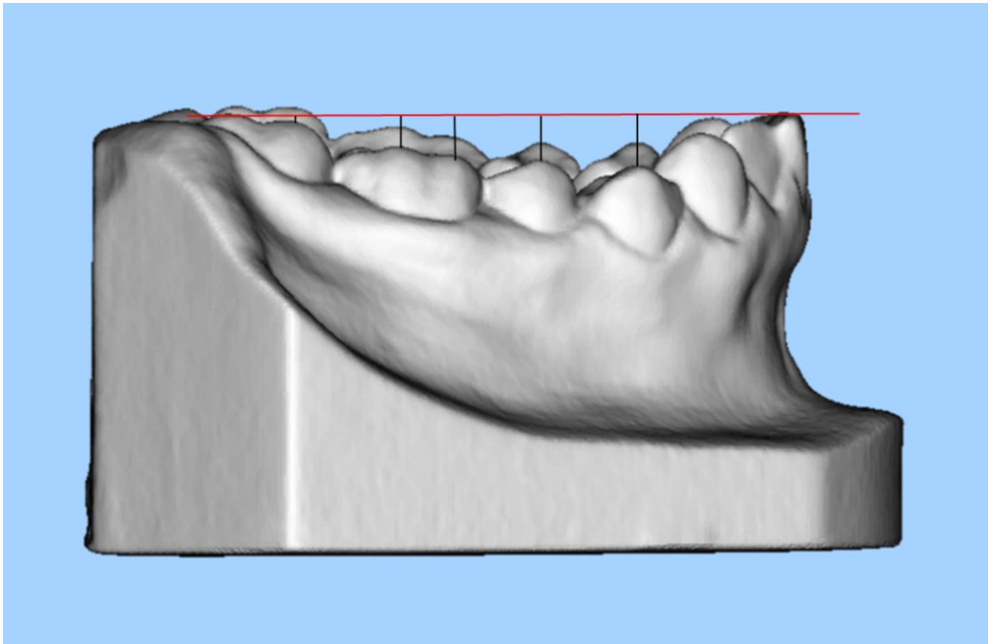

Figure 19 A. Curve of Spee at pre-treatment (T1), evaluated as the deepest point from the cusp tips of posterior teeth to the reference line (red) passing from the cusp tip of the most posteriorly erupted tooth to the incisor tip on the sagittal plane.

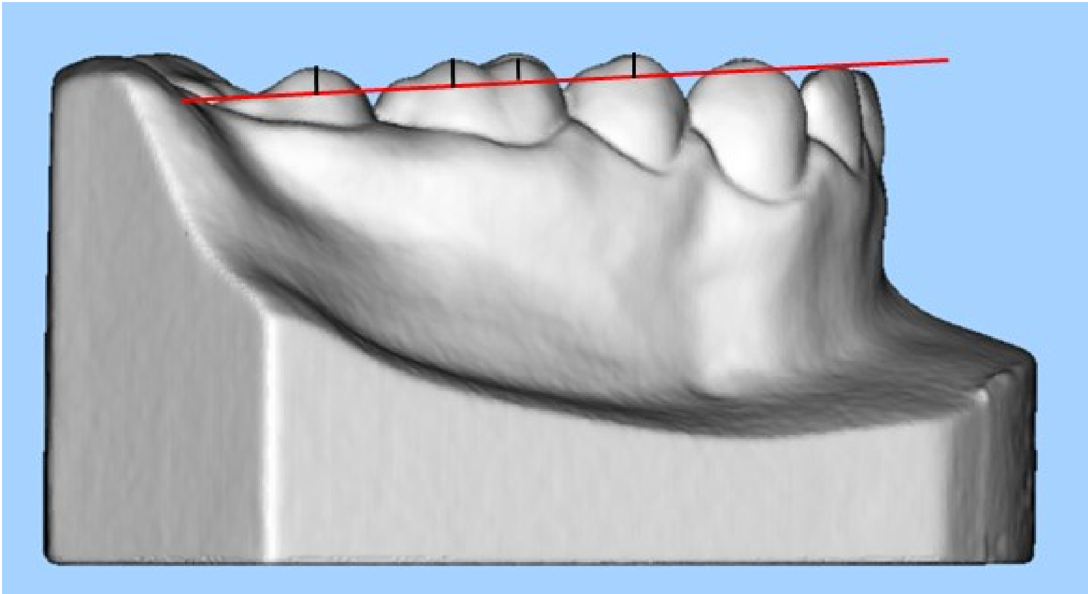

Figure 19 B. Curve of Spee at post-treatment (T2). Mandibular arch treated using Tweed technique, where the lower arch was over leveled to resemble a reverse curve. The value of COS recorded as a negative in these cases.

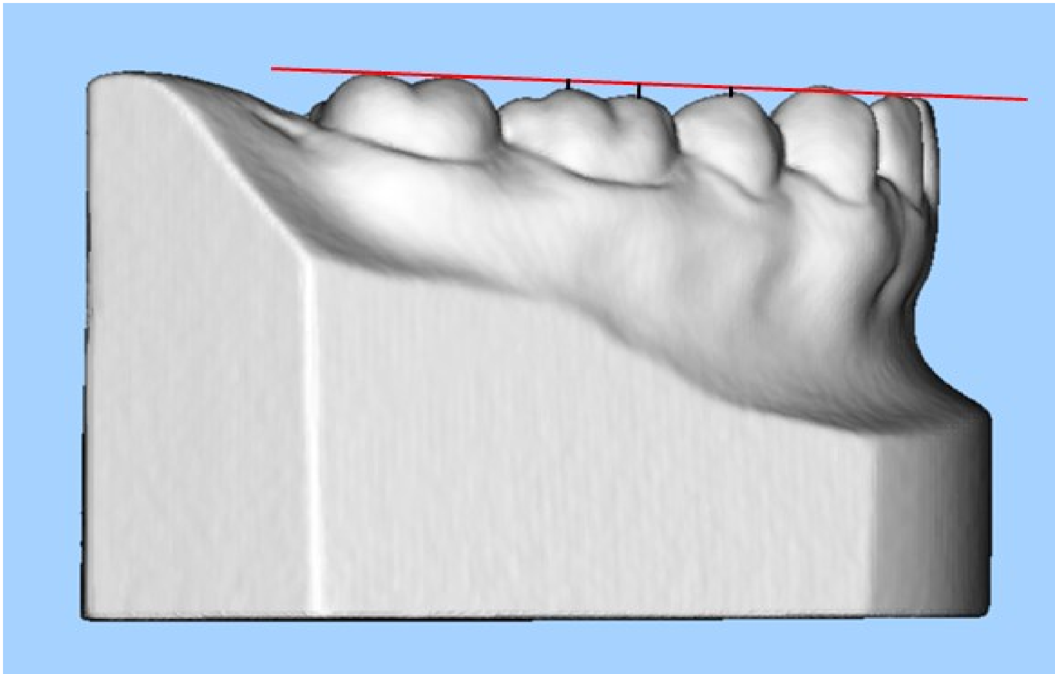

Figure 19 C. Curve of Spee at the follow-up (T3) visit, 28 years post-treatment. The COS showed a recovery from overcorrection to being flat to slightly deep at the mesiobuccal cusp of first molar.

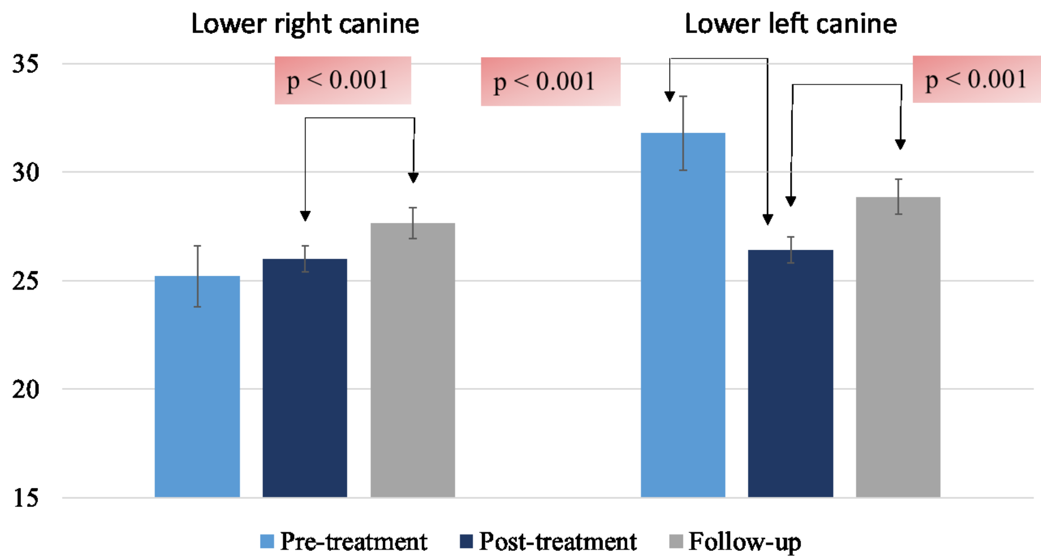

Figure 20. Mandibular canine rotational angles at the three time points; along with standard errors.

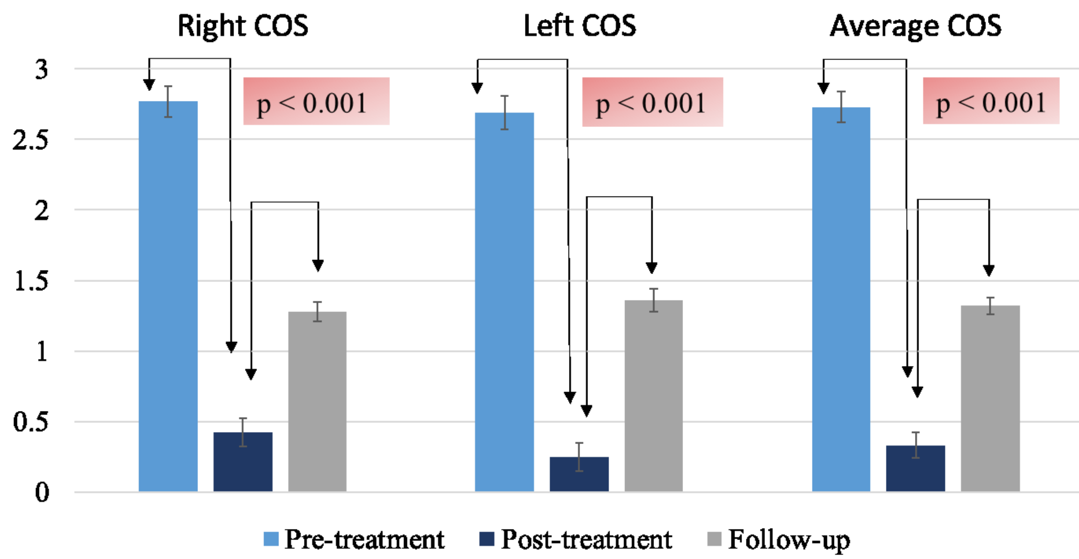

Figure 21. Curve of Spee at the three time points; along with standard errors.

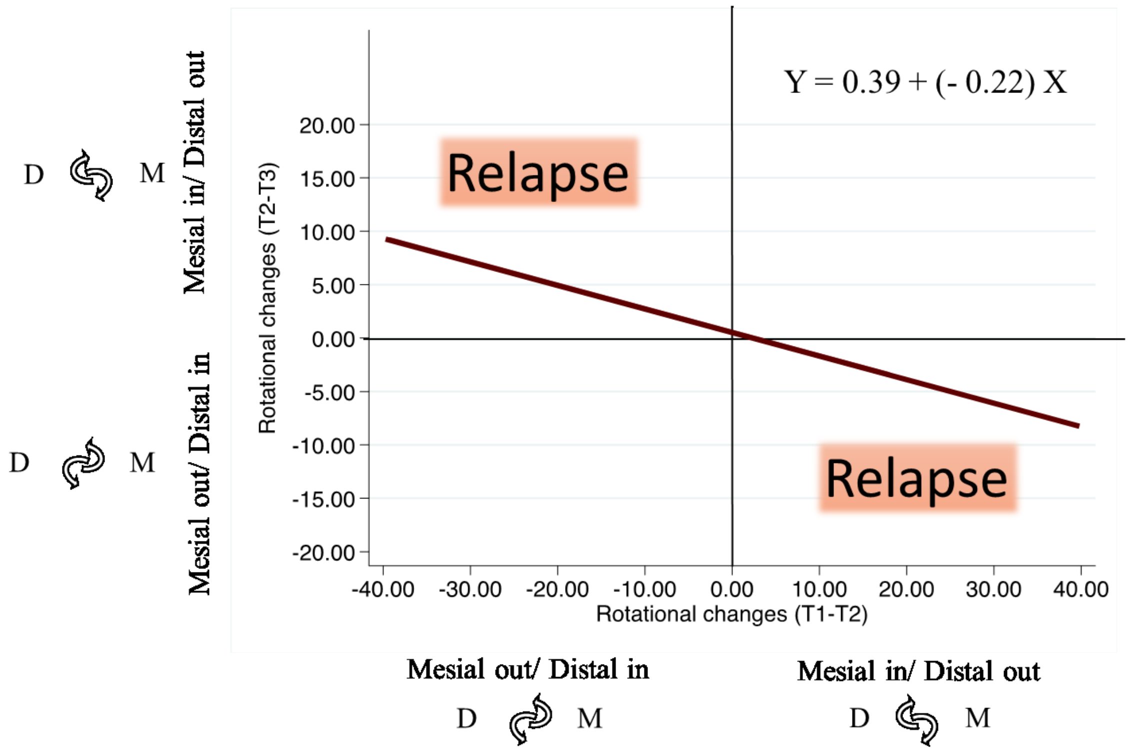

Figure 22. Relationship of treatment and post-treatment rotational changes of mandibular left lateral incisor. It illustrates the amount and direction of treatment (T1-T2) rotation (x-axis) and post-treatment (T2-T3) relapse (y-axis).

APPENDIX B

TABLES

Table 1. Search strategy used with Medline (PubMed) database.

Terms	Search results
1. (orthodontic) AND retention[Title/Abstract]	1357
2. (orthodontic) AND relapse[Title/Abstract]	687
3. (orthodontic) AND stability[Title/Abstract]	1320
4. (((((orthodontic) AND lower incisors[Title/Abstract]) OR lower teeth[Title/Abstract]) OR lower anterior teeth[Title/Abstract]) OR mandibular incisors[Title/Abstract]) OR mandibular anterior teeth[Title/Abstract]	2470
5. ((orthodontic) AND alignment[Title/Abstract]) OR malalignment[Title/Abstract]	3716
6. (((((((orthodontic) AND lower incisors[Title/Abstract]) OR lower teeth[Title/Abstract]) OR lower anterior teeth[Title/Abstract]) OR mandibular incisors[Title/Abstract]) OR mandibular anterior teeth[Title/Abstract])) OR lower front teeth[Title/Abstract]	2516
7. ((orthodontic) AND long term[Title/Abstract]) AND follow-up[Title/Abstract]	369
8. (((ORTHODONTIC) AND postorthodontic[Title/Abstract]) OR post-orthodontic[Title/Abstract]) OR post orthodontic[Title/Abstract]	169
9. ((orthodontic) AND fraenectom[Title/Abstract]) OR frenectom[Title/Abstract] OR frenectomy[Title/Abstract]	120
10. ((((orthodontic) AND fiberotom[Title/Abstract]) OR fibreotom[Title/Abstract])) OR fiberotomy	49

Table 1. Continued.

Terms	Search results
11. ((orthodontic$) AND retain*[Title/Abstract]) OR retainer[Title/Abstract]	1705
12. (orthodontic$) AND late mandibular crowding[Title/Abstract]	3
13. (Orthodontic$) AND TOOTH MIGRATION[Title/Abstract]	24
14. ("Orthodontics"[Mesh] OR orthodontics[Title/Abstract]) AND ("Orthodontic Retainers"[Mesh] OR retainer[Title/Abstract])	1028
15. postorthodontic[Title/Abstract]	97
16. postorthodontic[Title/Abstract] AND ("Orthodontics"[Mesh] OR orthodontics[Title/Abstract]) AND ("Orthodontic Retainers"[Mesh] OR retainer[Title/Abstract])	11
17. ("Incisor"[Mesh] OR lower incisor[Title/Abstract]) AND ("Orthodontics"[Mesh] OR orthodontics[Title/Abstract]) AND ("Orthodontic Retainers"[Mesh] OR retainer[Title/Abstract])	189
18. "Recurrence"[Mesh] AND (("Orthodontics"[Mesh] OR orthodontic[Title/Abstract]) AND ("Orthodontic Retainers"[Mesh] OR retainer[Title/Abstract])) AND "Incisor"[Mesh]	40
Total before removing duplicates	15902
Total after removing duplicates	10760

Table 2. Excluded studies with reasons.

Reason	Results (No. of studies excluded)
Study design unacceptable (case reports, review article, etc.)	27
Little irregularity index either; not used, reported as percent, or measured at T3 only.	72
Reported LII in mixed sample (combined extraction and non-extraction)	12
Still in retention or less than 1 year out of retention	7
Full text not in English	1
Double Publication/ Sampling	3
Lower arch untreated, or no full fixed appliance (FFA) treatment	4
	Total: 126

Table 3. Studies excluded from meta-analysis with reasons

Studies	Reason
12 studies	Poor quality
2 studies	Lower incisors extraction studies
1 study	No variance measure
Total: 14	

* One study was both poor quality and investigated lower incisor extraction.

Table 4. Characteristics of studies included in meta-analysis.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Intervention	Follow Up (y)	Adjunctive	Retention Type	T3-T2 LII Mean & SD (mm)
Artun et al 1996 [21]	• Longitudinal (Pre-Post) study. • University clinics.	78 (33/45)	NR	31.1 ± 5	E NE	14 ± 4.6	NO	NR	• 3.15±1.5 • 2.55± 1.42
Boley et al 2003 [22]	• Longitudinal (Pre-Post) study. • Private practice.	32 (9/23)	15.5 (12.8-41.7)	31.6 (24.3-51.1)	E	≥ 5	IPR	L3-3	• 0.7 ± 1.1
Canut and Arias 1999 [23]	• Longitudinal (Pre-Post) study. • N.R.	30 (10/20)	15.14 ± 2.99	22.1 ± 3.59	NE	7 ± 2.8	NO	N.R.	• 2.24 ± 2.6
de Freitas et al 2006 [24]	• Longitudinal (Pre-Post) study. • University clinics.	94 (50/44)	NR	NR	E	5.3 ± 1.6	NO	L3-3	• 1 ± 1.15
de la Cruz et al 1995 [25]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	87 (31/56)	15y 8m	33 y 7 m	E	≥ 10	NO	L3-3	• CL I: 2.3±1.6 • CLII Div1: 2.9±1.9
Driscoll-Gilliland et al 2001 [19]	• Longitudinal (Pre-Post) study. • Private practice.	43 (21/22)	15.2 ± 1.1	28.9 ±3.6	E	≥ 5	NO	L3-3	• 1.3 ± 1.9
Dugoni et al 1995 [26]	• Longitudinal (Pre-Post) study. • Private practice.	25 (8/17)	13y7m ± 1y6m	27 y 11 m ± 4 y 9 m	NE	9.5	CSF, IPR	L3-3	• 1.61 ±1.77

*E, Extraction. NE, Non-Extraction. NR, not reported.

Table 4. Continued.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Intervention	Follow Up (y)	Adjunctive	Retention Type	T3-T2 LII Mean & SD (mm)
Dyer et al 2012 [2]	• Longitudinal (Pre-Post) study. • Private practice.	52 (0/52)	NR	39.4	E	24.7	NO	Either L3-3 Or Removable Retainer	• 1.1 ± 1.05
Tynelius et al 2015 [4]	• Randomized Control Trial (RCT). • Private practice.	49 (16/33)	14.3 ± 1.5	21	E	(5-9)	IPR in one group	Lower 3-3, IPR, Positioner	• 1.7± 0.67 • 1.7± 1.38 • 3.1±1.51
Elms et al 1996 [27]	• Longitudinal (Pre-Post) study. • Private practice.	42 (8/34)	14.5 (12.1-17.6)	23.1 (18.2-28)	NE	6.5	IPR	L3-3	• 0.4±1
Erdinc et al 2006 [28]	• Longitudinal (Pre-Post) study. • N.R.	96 (38/60)	16y3m	20 y 11 m	E NE	4.6	NO	Removable Retainer	• 0.97 ±1.4 • 0.99±1.16
Freitas et al 2004 [5]	• Longitudinal (Pre-Post) study. • University clinics.	40 (16/24)	15y7m	20 y 5 m	NE	5	NO	L3-3	• 1.08 ± 0.96
de Freitas et al 2006 [29]	• Longitudinal (Pre-Post) study. • University clinics.	56 (29/27)	NR	NR	E	5.1	NO	L3-3	• 1 ± 1.15
Glenn et al 1987 [30]	• Longitudinal (Pre-Post) study. • Private practice.	28 (NR)	14y9m	26 y 7 m	NE	8	NO	NR	• 1.2 ± 1.25
Goldberg et al 2013 [7]	• Longitudinal (Pre-Post) study. • Private practice.	75 (31/44)	15.4 (14.8 - 16.3)	32 (26.9 - 36.7)	E	16.5	NO	L3-3	• 0.9 ± 0.89
Hagler et al 1998 [31]	• Longitudinal (Pre-Post) study. • N.R.	60 (13/47)	18.2	25.9	E NE	7.8	NR	NR	• 1.5 ± 3.28 • 0.8 ± 3.28

*E, Extraction. NE, Non-Extraction. NR, not reported.

Table 4. Continued.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Intervention	Follow Up (y)	Adjunctive	Retention Type	T3-T2 LII Mean & SD (mm)
Haruki and Little 1998 [8]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	83 (19/64)	15y5m ± 19.98 m	31 y 5m ± 5.6	E	15.9 ± 5	NO	L3-3	• Early treatment 1.53±1.14 • Late treatment 2.75±1.95
Heiser et al 2008 [33]	• Longitudinal (Pre-Post) study. • Private practice.	60 (12/48)	GP1: 14.13± 3.78 GP2: 15.1 ± 4.38	GP1: 21.7 ± 4.16 GP2: 22.4 ± 6.4	E NE	GP1; 6.3 ± 2.8 GP2; 6.5 ± 3	NO	Removable Retainer	• 2.09±1.39 • 2.02±1.67
Janson et al 2006 [34]	• Longitudinal (Pre-Post) study. • University clinics.	66 (29/37)	NR	21	E NE	• 3.9 • 3.1	NO	L3-3	• 0.98 ± 1.28 • 0.55 ± 1.48
Kahl-Nieke et al 1995 [1]	• Longitudinal (Pre-Post) study. • University clinics.	226 (NR)	NR	31.2 ± 4.8	E NE	15.7 ± 4.4	NO	NR	• 1.8 ± 2 • 2.3 ± 2.1
Little et al 1990 [35]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	30 (6/24)	14y4m (12y7m-17y)	29y 1m (24y3m-42y3m)	E	11.25 (9.3-22.6)	NO	NR	• 2.59 ± 1.32
Little et al 1981 [20]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	65 (24/41)	15y2m (12y6m-19y11m)	30y1m (25y-43y4m)	E	12.6 (9.6-23.9)	NO	NR	• 2.9 ± 1.42
Luppanapornlarp and Johnston 1993 [36]	• Longitudinal (Pre-Post) study. • University clinics.	62 (26/36)	14.8	30.2	E NE	15.3 (10.8 - 22.5)	NR	NR	• 2.6±3.38 • 3.1±3.38
McReynolds and Little 1991 [37]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	46 (11/35)	15.3	30 y 8m	E	• 14.4 • 16.6	NO	L3-3	• 2±1.09 • 2.6±1.27

*E, Extraction. NE, Non-Extraction. NR, not reported.

Table 4. Continued.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Intervention	Follow Up (y)	Adjunctive	Retention Type	T3-T2 LII Mean & SD (mm)
Miyazaki et al 1997 [38]	• Longitudinal (Pre-Post) study. • University clinics.	48 (NR)	GP1: 22y4m (18y1m-28y5m) GP2: 14y (12y2m-16)	GP1: 26y7m (20y7m-33y4m) GP2: 18y6m (15y6m-22y10m)	E	≥ 1	NO	Removable Retainer	• Adults: 1.28±1.17 • Adolescents: 2.36±1.1
Moussa et al 1995 [39]	• Longitudinal (Pre-Post) study. • Private practice.	55 (16/39)	15.7 ± 2.6	30.2 ± 5.3 (20.8-51.1)	NE	8 ± 3.1	NO	L3-3	• 0.8 ± 1.2
Rossouw et al 1999 [40]	• Longitudinal (Pre-Post) study. • N.R.	88 (NR)	14.7 (11.1-24.2)	21.5 (16.2 - 33.5)	E NE	5	NO	NR	• 1.2 ± 1.3 • 1.4 ± 1.11
Vaden et al 1997 [41]	• Longitudinal (Pre-Post) study. • Private practice.	36 (7/29)	15.3 ± 1.95	30.5 ±2.84	E	15	NO	Either L3-3 Or Removable Retainer	• 1.44 ± 1.38
Harris and Vaden 1994 [32]	• Longitudinal (Pre-Post) study. • Private practice.	74 (NR)	GP1: 15.1± 1.53 GP2: 32.2 ± 5.85	GP1: 21.7 ± 2.08 GP2: 36.2 ±5.72	E	GP1; 6.6 ± 1.3 GP2; 4.1 ± 2.7	NO	Hawley Retainer	• Early treatment 0.41 ±0.87 • Late treatment 0.54±0.54
Yavari et al 2000 [42]	• Longitudinal (Pre-Post) study. • Private practice.	31 (NR)	NR	NR	NE	≥ 2	NO	L4-4	• 0 ± 1.1

*E, Extraction. NE, Non-Extraction. NR, not reported.

Table 5. Characteristics of studies excluded from meta-analysis.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Intervention	Follow Up (y)	Adjunctive	Retention Type	T3-T2 LII Mean & SD (mm)
Canut 1996 [43]	• Longitudinal (Pre-Post) study. • Private practice.	26 (NR)	15.1	25.4	Lower incisor Ex.	5-8	NO	NR	• 1.13 ± 2
Ciger et al 2005 [44]	• Longitudinal (Pre-Post) study. • University clinics.	18 (8/10)	NR	NR	NE	5.3 ± 1.8	NO	Hawley Retainer	• 4.6 ± 2.3
Demir et al 2012 [45]	• Longitudinal (Pre-Post) study. • University clinics.	42 (12/30)	NR	NR	NE	2	NO	Removable Retainers	• Hawley GP: 0.70 ± 0.59 • Essix GP: 0.81 ± 0.71
Ferris et al 2005 [46]	• Longitudinal (Pre-Post) study. • Private practice.	20 (9/11)	13.7 ± 1.1	24.3	NE	7.9	IPR	Either L3-3 Or Removable Retainer	• 1.11 ± 1.53
Sadowsky et al 1994 [53]	• Longitudinal (Pre-Post) study. • Private practice.	22 (6/16)	NR	NR	NE	6.3 ± 1.8	IPR	L3-3	• 1.4 ± 1.77
Hansen et al 1997 [47]	• Longitudinal (Pre-Post) study. • University clinics.	24 (15/9)	NR	19.6 ± 1.2	NE	≥ 3	NO	Lower 3-3 & No retainer	• 1.6 ± 1.81

* E, Extraction. NE, Non-Extraction. NR, not reported. ARS, Air-rotor Stripping.

Table 5. Continued.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Interventio n	Follow Up (y)	Adjunctiv e	Retention Type	T3-T2 LII Mean & SD (mm)
Little et al 1988 [48]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	31 (NR)	15y5m (12y1m - 18y8m)	43y3m	E	20	NO	NR	• 4.36
Little et al 1990 [49]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	26 (15/11)	13y7m (11y9m - 18y3m)	25y 8m (20y1m - 41y1m)	NE	≥ 6	NO	NR	• 3.96 ± 2.07
Little and Riedel 1989 [50]	• Longitudinal (Pre-Post) study. • University clinics & Private practice.	30 (NR)	15y5m (11y11m-24y5m)	32y1m	NE	14.25	NO	NR	• 2.31
Pancherz and Bjerklin 2014 [51]	• Longitudinal (Pre-Post) study. • University clinics.	12 (10/2)	14 ± 0.7	45.8 ± 1.7	NE	31.8 ± 1.26	NO	Fixed & Removable & no retention	• 1.7 ± 3.56
Paquette et al 1992 [6]	• Longitudinal (Pre-Post) study. • University clinics.	63 (32/31)	14.2	28.6	E NE	14.5 (9-20)	NO	NR	• 2.4 • 3

* E, Extraction. NE, Non-Extraction. NR, not reported. ARS, Air-rotor Stripping.

Table 5. Continued.

Study ID (Author & Date)	Study Design & Clinical Setting	Sample size n (M/F)	Age at T2 (y)	Age at T3 (y)	Intervention	Follow Up (y)	Adjunctive	Retention Type	T3-T2 LII Mean & SD (mm)
Riedel et al 1992 [52]	• Longitudinal (Pre-Post) study. • University clinics &Private practice.	42 (15/27)	20y1m (12y1m-47y7m)	35 y 3m (24y10m - 57y8m)	Lower incisor Ex. (1vs.2 incisor)	12y9m (6y6m - 24y)	NO	Removable Retainers	• 1-incisor E: 0.33 ± 0.34 • 2-incisors E: 0.36 ± 0.34
Zafarmand et al 2014 [54]	• Longitudinal (Pre-Post) study. • University clinics.	40 (NR)	• E: 17y8m • NE: 18y9m	• E: 24y6m • NE: 24y7m	E NE	6	NO	Removable Retainers	• 2.1 ± 1.15 • 1.6 ± 0.7
Gorucu-Coskuner et al 2017 [55]	• Longitudinal (Pre-Post) study. • University clinics.	44 (14/30)	• E: 16 ± 3.1 • NE: 15 ± 1.22 • ARS: 15.6 ± 1.39	• E: 19.65 ± 2.03 • NE: 18.17 ± 0.8 • ARS: 19.54 ± 1.65	E NE ARS	≥ 3	IPR in one group	Removable Retainers	• 1.96 ± 1.57 • 3.59 ± 2.07 • 2.38 ± 1.72

* E, Extraction. NE, Non-Extraction. NR, not reported. ARS, Air-rotor Stripping.

Table 6. Cochrane collaboration's risk of bias assessment tool for randomized clinical trials.

Author and year	**Random sequence generation (selection bias)**	**Allocation concealment (selection bias)**	**Blinding of outcome assessment (detection bias)**	**Incomplete outcome data (attrition bias)**	**Selective reporting (reporting bias)**	**Other bias**	**Overall Risk of bias**
Tynelius et al 2015 [4]	Low	Low	Low	High	Low	Unclear	High

*Blinding of participants and study personnel "Performance bias" domain was unfeasible to assessed.

Table 7. Qualitative assessment of longitudinal observational studies.

Study	Study question	Eligibility criteria and study population	Study participants representative of clinical populations of interest	All eligible participants enrolled	Sample size	Inter-vention clearly described	Outcome measures clearly described, valid, and reliable	Blinding of outcome assessors	Follow-up rate	Statistical analysis	Multiple outcome measures	Overall grade
Artun et al 1996 [21]	●	●	○	●	●	●	●	○	CD	●	○	Fair
Boley et al 2003 [22]	●	●	○	●	●	●	●	○	CD	●	○	Fair
Canut 1996 [43]	●	●	○	●	○	●	●	○	CD	●	○	Poor
Canut and Arias 1999 [23]	●	●	NR	○	●	●	●	○	CD	●	○	Fair
Ciger et al 2005 [44]	●	○	○	NR	○	●	●	○	CD	●	○	Poor
de Freitas et al 2006 [24]	●	●	○	●	●	●	●	○	CD	●	○	Fair
de la Cruz et al 1995 [25]	●	●	NR	●	●	●	●	○	CD	●	○	Fair
Demir et al 2012 [45]	●	●	○	●	○	●	●	○	CD	●	○	Poor
Driscoll-Gilliland et al 2001 [19]	●	●	○	○	●	●	●	○	CD	●	○	Fair
Dugoni et al 1995 [26]	●	●	○	●	○	●	●	○	CD	●	○	Fair
Dyer et al 2012 [2]	●	●	○	●	●	●	●	○	CD	●	○	Fair

* It was not applicable to assess #12 domain, Group-level interventions and individual-level outcome efforts.

* CD, can't determine, NA, not applicable, NR, not reported.

Table 7. Continued.

Study	Study question	Eligibility criteria and study population	Study participants representative of clinical populations of interest	All eligible participants enrolled	Sample size	Inter-vention clearly described	Outcome measures clearly described, valid, and reliable	Blinding of outcome assessors	Follow-up rate	Statistical analysis	Multiple outcome measures	Overall grade
Elms et al 1996 [27]	●	●	○	○	●	●	●	○	CD	●	○	Fair
Erdinc et al 2006 [28]	●	●	NR	●	●	●	●	○	CD	●	○	Fair
Ferris et al 2005 [46]	●	●	○	○	○	●	●	○	CD	●	○	Poor
Freitas et al 2004 [5]	●	●	○	NR	●	●	●	○	CD	●	○	Fair
de Freitas et al 2006 [29]	●	●	○	CD	●	●	●	○	CD	●	○	Fair
Glenn et al 1987 [30]	●	●	○	○	○	●	●	○	CD	●	○	Fair
Goldberg et al 2013 [7]	●	●	○	CD	●	●	●	○	CD	●	○	Fair
Hagler et al 1998 [31]	●	●	○	●	●	○	●	○	CD	●	○	Fair
Hansen et al 1997 [47]	●	●	○	NR	○	●	●	○	CD	●	○	Poor
Harris and Vaden 1994 [32]	●	●	○	●	●	●	●	○	CD	●	○	Fair

* It was not applicable to assess #12 domain, Group-level interventions and individual-level outcome efforts.

* CD, can’t determine, NA, not applicable, NR, not reported.

Table 7. Continued.

Study	Study question	Eligibility criteria and study population	Study participants representative of clinical populations of interest	All eligible participants enrolled	Sample size	Inter-vention clearly described	Outcome measures clearly described, valid, and reliable	Blinding of outcome assessors	Follow-up rate	Statistical analysis	Multiple outcome measures	Overall grade
Haruki and Little 1998 [8]	●	●	◯	●	●	●	●	◯	CD	●	◯	Fair
Heiser et al 2008 [33]	●	●	◯	●	●	●	●	◯	CD	●	◯	Fair
Janson et al 2006 [34]	●	●	◯	CD	●	●	●	◯	CD	●	◯	Fair
Kahl-Nieke et al 1995 [1]	●	●	◯	◯	●	●	●	◯	◯	●	◯	Fair
Little et al 1988 [48]	●	●	NR	NR	●	●	●	◯	CD	◯	◯	Poor
Little et al 1990 [49]	●	●	NR	NR	◯	●	●	◯	CD	●	◯	Poor
Little and Riedel 1989 [50]	●	●	NR	CD	●	●	●	◯	CD	◯	◯	Poor
Little et al 1990 [35]	●	●	NR	●	●	●	●	◯	CD	●	◯	Fair
Little et al 1981 [20]	●	●	NR	CD	●	●	●	◯	CD	●	◯	Fair
Luppanapornlarp and Johnston 1993 [36]	●	●	◯	●	●	◯	●	◯	CD	●	◯	Fair

* It was not applicable to assess #12 domain, Group-level interventions and individual-level outcome efforts.

* CD, can't determine, NA, not applicable, NR, not reported.

Table 7. Continued.

Study	Study question	Eligibility criteria and study population	Study participants representative of clinical populations of interest	All eligible participants enrolled	Sample size	Inter-vention clearly described	Outcome measures clearly described, valid, and reliable	Blinding of outcome assessors	Follow-up rate	Statistical analysis	Multiple outcome measures	Overall grade
Kahl-Nieke et al 1995 [1]	•	•	○	○	•	•	•	○	○	•	○	Fair
Little et al 1988 [48]	•	•	NR	NR	•	•	•	○	CD	○	○	Poor
Little et al 1990 [49]	•	•	NR	NR	○	•	•	○	CD	•	○	Poor
Little et al 1990 [34]	•	•	NR	•	•	•	•	○	CD	•	○	Fair
Little et al 1981 [35]	•	•	NR	CD	•	•	•	○	CD	•	○	Fair
Luppanapornlarp and Johnston 1993 [36]	•	•	○	•	•	○	•	○	CD	•	○	Fair
McReynolds and Little 1991 [37]	•	•	NR	CD	•	•	•	○	CD	•	○	Fair
Miyazaki et al 1997 [38]	•	○	NR	CD	•	•	•	○	CD	•	○	Fair

* It was not applicable to assess #12 domain, Group-level interventions and individual-level outcome efforts.

* CD, can't determine, NA, not applicable, NR, not reported.

Table 7. Continued.

Study	Study question	Eligibility criteria and study population	Study participants representative of clinical populations of interest	All eligible participants enrolled	Sample size	Inter-vention clearly described	Outcome measures clearly described, valid, and reliable	Blinding of outcome assessors	Follow-up rate	Statistical analysis	Multiple outcome measures	Overall grade
Moussa et al 1995 [39]	●	●	○	○	●	●	●	○	CD	●	○	Fair
Pancherz and Bjerklin 2014 [51]	●	●	○	○	○	●	●	○	○	○	○	Poor
Paquette et al 1992 [6]	●	●	○	●	●	○	●	○	CD	●	○	Fair
Riedel et al 1992 [52]	●	●	NR	CD	●	●	●	○	CD	●	○	Fair
Rossouw et al 1999 [40]	●	●	NR	CD	●	●	●	○	CD	●	○	Fair
Sadowsky et al 1994 [53]	●	○	○	○	○	●	●	○	CD	●	○	Poor
Vaden et al 1997 [41]	●	●	○	CD	●	●	●	○	CD	●	○	Fair
Yavari et al 2000 [42]	●	●	○	●	●	●	●	○	CD	●	○	Fair
Zafarmand et al 2014 [54]	●	●	○	CD	○	●	●	○	CD	●	○	Poor
Gorucu-Coskuner et al 2017 [55]	●	●	○	CD	○	●	●	○	CD	●	○	Poor

* It was not applicable to assess #12 domain, Group-level interventions and individual-level outcome efforts.

* CD, can't determine, NA, not applicable, NR, not reported.

Table 8. Meta-regression table of potential explanatory factors of variation in the effect size estimate.

Characteristics	No. of observation s	Constant		Effect		Tau^2	I^2 - residual	Adjusted R^2
		Estimate	Probabilit y	Estimate	Probabilit y			
Follow up duration (1-10y vs 10-20y)	45	0.89	<0.001	0.49	0.002	0.138	67.9 %	32.8 %
Treatment protocol (Ex vs. Non-Ex)	45	0.85	<0.001	0.37	0.026	0.185	73.7 %	9.9 %
Study Design	45	1.05	<0.001	0.83	0029	0.186	73.6 %	9.2 %
Retention type (Fixed vs Removable)	27	1.05	<0.001	0.11	0.65	0.228	74.8 %	5.5 %
Adjunctive procedures use	41	0.75	0.008	0.42	0.14	0.191	73.8 %	4.7 %
Pre-treatment irregularity index	41	0.68	0.032	0.08	0.15	0.215	75.7 %	4.0 %
Clinical setting (Academic vs Private)	31	1.09	<0.001	-0.15	0.41	0.157	68.2 %	1.7 %

* Tau^2; estimate of between-study variance.

* I^2 residual; % residual variation due to heterogeneity.

* Adjusted R^2; Proportion of between-study variance explained.

Table 9. Summary of standardized mean difference (SMD) and mean difference (MD) of post-treatment irregularity changes in different clinical comparisons.

Comparison	SMD of irregularity change (95% C.I.)	P-value	I^2	MD of irregularity change (mm) (95% C.I.)	P-value	I^2
Overall	1.09 (0.95 - 1.23)	< 0.001	74.7 %	1.63 (1.39 - 1.86)	< 0.001	91.1 %
Treatment approach						
Extraction	1.22 (1.04 - 1.40)	< 0.001	75.2 %	1.74 (1.46 - 2.02)	< 0.001	90.2 %
Non-Extraction	0.85 (0.63 - 1.07)	< 0.001	70.1 %	1.40 (0.96 - 1.85)	< 0.001	92.9 %
Follow-up duration						
1-10 years	0.89 (0.73 - 1.05)	< 0.001	65.1 %	1.22 (1.01 - 1.44)	< 0.001	81.2 %
10-20 years	1.39 (1.18 - 1.60)	< 0.001	71.8 %	2.25 (1.91 - 2.60)	< 0.001	89.9 %
Study design						
Interventional	1.90 (1.13 - 2.67)	< 0.001	60.3 %	2.16 (1.25 - 3.07)	< 0.001	71.7 %
Observational	1.05 (0.91 - 1.19)	< 0.001	74.1 %	1.60 (1.35 - 1.84)	< 0.001	91.5 %
Retention methods						
Fixed	1.04 (0.82 - 1.27)	< 0.001	76.3 %	1.42 (1.06 - 1.79)	< 0.001	91.0 %
Removable	1.15 (0.82 - 1.48)	< 0.001	71.0 %	1.48 (0.96 - 1.99)	< 0.001	88.2 %
Clinical setting						
Private	0.94 (0.69 - 1.17)	< 0.001	70.2 %	1.21 (0.87 - 1.55)	< 0.001	85.1 %
Academic	1.08 (0.89 - 1.27)	< 0.001	65.7 %	1.81 (1.43 - 2.20)	< 0.001	91.8 %
Adjunctive procedure use						
Used	0.71 (0.38 - 1.04)	< 0.001	32.1 %	1.06 (0.43 - 1.70)	0.001	81.3 %
Not used	1.18 (1.02 - 1.33)	< 0.001	75.1 %	1.65 (1.39 - 1.90)	< 0.001	91.0 %

* I^2: measure of heterogeneity. C.I.: Confidence interval. P-value: probability of post-treatment change.

Table 10. Sample characteristics of patients evaluated for mandibular growth and dentoalveolar changes.

Characteristics	N	Category	N	Category
Sex	19	Males	81	Females
Pre-treatment Malocclusion	38	Class I	62	Class II
Retention Method	57	Fixed	43	Removable

Table 11. Summary of follow-up duration and patients ages (years) at different evaluation stages.

	Mean	Standard deviation
Post-treatment (T1)	15.98	3.33
Post-retention (T2)	35.22	7.42
Follow-up duration (T2 – T1)	19.24	7.23

Table 12. Radiographic landmarks definitions.

Landmark	Abbreviation	Definition
Sella	**S**	The center of the pituitary fossa of the sphenoid bone.
Nasion	**N**	The junction of the frontonasal suture at the most posterior point on the curve at the bridge of the nose.
Articulare	**Ar**	The point at the junction of the posterior border of the ramus and the inferior border of the posterior cranial base.
Gonion	**Go**	A point located on the curvature of the angle of the mandible located by bisecting the angle formed by lines tangent to the posterior ramus and the inferior border of the mandible.
Menton	**Me**	The lowest point on the symphyseal shadow of the mandible seen on lateral cephalogram.
Pogonion	**Pog**	The most anterior point on the contour of the bony chin.
A-point	**A-point**	The most posterior midline point in the concavity between anterior nasal spine and prosthion.
Anterior nasal spine	**ANS**	The anterior tip of the sharp bony process of the maxilla at the lower margin of the nasal opening.
Upper incisor tip	**U1 Tip**	Incisal tip of most anterior maxillary incisor
Upper incisor apex	**U1 Apex**	The most apical curvature of the maxillary incisor root
Lower incisor tip	**L1 Tip**	Incisal tip of most anterior mandibular incisor
Lower incisor apex	**L1 Apex**	The most apical curvature of the mandibular incisor root

Table 12. Continued.

Landmark	Abbreviation	Definition
Upper first molar mesiobuccal cusp tip	**U6 MB tip**	The tip of the mesiobuccal cusp of the maxillary first molar
Upper first molar mesiobuccal root apex	**U6 Apex**	The most apical curvature of the maxillary first molar mesiobuccal root
Lower first molar mesiobuccal cusp tip	**L6 MB tip**	The tip of the mesiobuccal cusp of the mandibular first molar
Lower first molar mesial root apex	**L6 Apex**	The most apical curvature of the mandibular first molar mesial root

Table 13. Random and systematic errors assessed with intraclass correlation, Dahlberg method error, and paired t-test.

Variable	ICC	method error	Paired t-test (p-value)
Gonial angle (Ar-Go-Me)	0.78	2.40	0.64
Ramus height (Ar-Go)	0.98	1.67	0.58
Corpus length (Go-Pog)	0.95	1.54	0.99
Lower facial height (ANS-Me)	0.99	0.41	0.63
Lower incisors eruption	0.99	0.41	0.99
Lower incisor- APog distance	0.98	0.21	0.57
Interincisal angle	0.99	0.55	0.01
Upper incisor-SN angle	0.99	0.43	0.97
Lower incisor-MP angle	0.98	0.71	0.30
Intermolar angle	0.99	0.24	0.50
Functional occlusal plane (FOP-SN)	0.99	0.57	0.05
Mandibular plane angle (MPA)	0.99	0.72	0.06

Table 14. Post-retention changes of radiographic measures between post-treatment (16.0 years) and post-retention (35.2 years) (n =100).

Variable	Abbreviation	Units	Post- treatment (T1)		Follow-up (T2)		Post-retention Changes (T1-T2)		
			Mean	SD	Mean	SD	Mean	SD	Prob.
Gonial angle	Ar-Go-Me	degree	128.71	5.80	127.68	5.87	- 1.03	3.11	< 0.001
Ramus height	Ar-Go	mm	47.06	5.40	48.58	6.86	1.52	3.71	< 0.001
Corpus length	Go-Pg	mm	76.25	5.58	78.14	5.56	1.88	2.87	< 0.001
Lower anterior facial height	ANS-Me	mm	70.65	6.93	71.54	6.99	0.89	2.45	< 0.001
Mandibular plane angle	MPA	degree	36.05	6.19	35.58	6.75	- 0.46	2.30	0.02
Lower incisor Eruption	L1-Erup	mm	--	--	--	--	1.39	0.90	< 0.001
Lower incisor_APog distance	L1-APog	mm	1.24	1.54	0.56	1.84	- 0.68	1.37	< 0.001
Inter incisal angle	IIA	degree	131.74	6.78	134.50	7.76	2.76	7.43	< 0.001
Upper incisor inclination	U1-SN	degree	102.71	6.78	101.42	6.73	-1.28	4.68	0.003
Lower incisor inclination	L1-MP	degree	89.49	6.27	88.47	5.84	-1.02	4.64	0.01
Inter molars angle	IMA	degree	172.78	5.71	167.40	3.89	-5.38	5.38	< 0.001
Functional occlusal plane	FOP-SN	degree	17.99	4.78	16.76	5.01	-1.23	3.33	< 0.001

Table 15. Four factor ANOVA evaluating changes of evaluating variables (T1-T2), adjusting for follow-up durations and each variable at the end of treatment (T1).

Variable	Intercept		Sex		Retention		Extraction pattern		Malocclusion		Follow-up		Covariate [1]	
	F	*Prob.*	*F*	*Prob.*	*F*	*Prob.*	*F*	*Prob.*	*F*	*Prob.*	*F*	*Prob.*	*F*	*Prob.*
Gonial angle	4.22	0.04											4.86	0.03
Ramus height	42.10	< 0.001	22.4	< 0.001										
Corpus length	16.06	< 0.001							12.31	0.001			12.66	0.001
Lower anterior facial height											5.65	0.01		
Mandibular plane angle	13.07	< 0.001	14.8	< 0.001										
Lower incisor eruption	266.83	< 0.001			23.9	< 0.001							--	--
L1-APog distance	9.28	0.003					5.46	0.006					7.76	0.006
Interincisal angle	23.66	< 0.001					4.06	0.02					21.13	< 0.001
Upper incisor inclination	13.73	< 0.001											15.34	< 0.001
Lower incisor inclination	23.39	< 0.001					3.74	0.02					25.93	< 0.001
Intermolar angle	124.57	< 0.001											135.5	< 0.001
Functional occlusal plane	4.26	0.04	9.86	0.002			3.68	0.02					14.11	< 0.001

[1] The value of the variable at the end of treatment was used as a covariate.

Table 16. Sample characteristics of patients evaluated for mandibular incisors angulation.

Characteristics	N	Category	N	Category
Sex	19	Males	74	Females
Pre-treatment Malocclusion	34	Class I	59	Class II
Retention Method	53	Fixed	40	Removable

Table 17. Random and systematic errors assessed with intraclass correlation, Dahlberg method error, and paired t-test.

Variable	Abbreviation	Units	ICC	method error	Paired t-test (p-value)
Irregularity index	Irreg. index	mm	0.99	0.17	0.77
Tooth size arch length discrepancy	TSALD	mm	0.97	0.18	0.82
Right central incisor angulation	LR2 angle	deg.	0.99	0.23	0.19
Right lateral incisor angulation	LR1 angle	deg.	0.99	0.24	0.31
Left central incisor angulation	LL1 angle	deg.	0.99	0.27	0.33
Left lateral incisor angulation	LL2 angle	deg.	0.99	0.27	0.56

Table 18. Long-term changes of mandibular incisors angulation and outcome measures, at post-treatment (16 years) and post-retention (35 years) (n =93).

Variables	Units	Post- treatment (T1)		Follow-up (T2)		Post-retention Changes (T1-T2)		
		Mean	SD	Mean	SD	Mean	SD	Prob.
Irregularity Index	mm	1.51	0.57	2.68	1.30	1.17	1.20	< 0.001
Anterior TSALD	mm	- 0.003	0.54	1.04	0.83	1.04	0.84	< 0.001
Right lateral incisor	deg.	88.30	6.63	89.87	4.95	1.61	6.37	0.01
Right central incisor	deg.	88.69	5.36	90.16	4.18	1.51	5.97	0.01
Left central incisor	deg.	87.95	5.01	88.13	4.53	0.04	5.50	0.46
Left lateral incisor	deg.	88.23	6.70	88.34	4.95	0.01	5.93	0.49

Table 19. Pearson's product-moment correlations evaluating relationship between alignment changes (irregularity index and anterior TSALD) and mandibular incisors angulation (degree) at the end of treatment (T1), and post-treatment (T1-T2) (n = 93).

Variable	**Time**	**Correlation with *Irregularity change***	**P-value**	**Correlation with *anterior TSALD change***	**P-value**
Right lateral incisor angulation	T1	- 0.10	0.30	- 0.19	0.06
Right central incisor angulation	T1	-0.005	0.95	-0.04	0.70
Left central incisor angulation	T1	-0.01	0.90	-0.13	0.19
Left lateral incisor angulation	T1	-0.01	0.86	-0.18	0.07
Right lateral incisor angulation	T1-T2	0.29	0.005	0.35	0.001
Right central incisor angulation	T1-T2	0.18	0.08	0.20	0.06
Left central incisor angulation	T1-T2	0.18	0.09	0.01	0.87
Left lateral incisor angulation	T1-T2	0.10	0.36	0.06	0.52

Table 20. Sample characteristics of patients evaluated for post-treatment relapse of anterior teeth rotation and COS leveling (n = 100).

Characteristics	N	Category	N	Category
Sex	19	Males	81	Females
Orthodontist	47	Orthodontist 1	53	Orthodontist 2
Pre-treatment Malocclusion	38	Class I	62	Class II
Retention Method	57	Fixed	43	Removable

Table 21. Summary of follow-up duration and patients ages (years) at different evaluation stages.

	Mean	Standard Deviation
Pre-treatment	12.8	3.5
Post-treatment	16.0	3.3
Post-retention	35.2	7.4
Follow-up duration	19.2	7.2

Table 22. Intrarater correlations (ICC), Dahlberg's method errors, and paired t-tests based on 22 replicates measure of lower right (LR) and lower left (LL) rotational angles, and the curve of Spee (COS).

Variable	Unit	ICC	Method error	Paired t-test (p-value)
LR3 rotation angle	deg.	0.98	0.61	0.25
LR2 rotation angle	deg.	0.99	0.47	0.45
LR1 rotation angle	deg.	0.98	0.63	0.38
LL1 rotation angle	deg.	0.99	0.61	0.93
LL2 rotation angle	deg.	0.99	0.67	0.32
LL3 rotation angle	deg.	0.99	0.51	0.06
COS Right	mm	0.99	0.05	0.97
COS Left	mm	0.98	0.06	0.72

Table 23. Summary statistics of pre-treatment, post-treatment, and post-retention changes of mandibular anterior teeth rotation (degree), and the curve of Spee (mm).

Variable	**Pre- treatment (T1)**		**Post-treatment (T2)**		**Follow-up (T3)**		**Treatment changes (T1-T2)**			**Post-treatment Changes (T2-T3)**		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Probability	Mean	SD	Probability
Lower right canine	25.20	14.27	26.01	6.75	27.65	7.61	0.50	13.20	0.36	1.64	5.34	0.001
Lower right lateral incisor	64.17	12.89	63.84	5.42	62.67	8.89	-0.30	12.01	0.40	-1.17	7.25	0.05
Lower right central incisor	80.38	8.36	81.78	4.46	81.58	6.87	1.25	7.47	0.05	-0.19	6.04	0.37
Lower left central incisor	81.20	8.93	80.45	4.48	81.21	8.33	-0.78	7.91	0.16	0.75	6.58	0.12
Lower left lateral incisor	64.75	15.04	63.61	6.52	64.33	9.60	-1.16	13.73	0.20	0.71	6.95	0.15
Lower left canine	31.79	17.18	26.40	6.90	28.85	8.23	-5.45	15.01	< 0.001	2.44	5.78	< 0.001
Right COS	2.77	1.18	0.42	1.09	1.28	0.76	-2.36	1.57	< 0.001	0.86	1.05	< 0.001
Left COS	2.69	1.27	0.25	1.06	1.36	0.88	-2.44	1.69	< 0.001	1.11	1.23	< 0.001
Average COS	2.73	1.11	0.33	0.98	1.32	0.69	-2.40	1.51	< 0.001	0.99	1.01	< 0.001

Table 24. Frequency of farthest point above or below the reference line used to determine the curve of Spee at pre-treatment, post-treatment, and post-retention (n= 100).

Deepest point	Pre-treatment (T1)		Post-treatment (T2)		Post-retention (T3)	
	Right COS	Left COS	Right COS	Left COS	Right COS	Left COS
1st primary molar	5	5	--	--	--	--
2nd primary molar	15	17	--	--	--	--
Premolar	50	47	14	11	12	10
Mesiobuccal cusp of first molar	26	27	31	32	60	67
Distobuccal cusp of first molar	3	3	23	26	22	12
Mesiobuccal cusp of second molar	1	1	31	31	5	11
Distobuccal cusp of second molar	--	--	1	--	1	--

Table 25. Pearson product-moment correlation of treatment changes (T1-T2) and post-treatment changes (T2_T3) of curve of Spee (COS), and rotational changes of mandibular anterior teeth.

		T1-T2 with T2-T3		**T1 with T3**	
Variable	No. of observations	Correlation	P- value	Correlation	P- value
Lower right canine rotation	86	- 0.27	0.01	0.45	< 0.001
Lower right lateral incisor rotation	97	- 0.34	< 0.001*	0.47	< 0.001
Lower right central incisor rotation	95	- 0.26	0.009	0.44	< 0.001
Lower left central incisor rotation	96	- 0.27	0.005*	0.49	< 0.001
Lower left lateral incisor rotation	96	- 0.43	< 0.001*	0.56	< 0.001
Lower left canine rotation	87	- 0.24	0.02	0.52	< 0.001
Right COS	100	- 0.64	< 0.001*	0.31	0.001
Left COS	100	- 0.66	< 0.001*	0.35	< 0.001
Average COS	100	- 0.70	< 0.001*	0.35	< 0.001

* Significant after Bonferroni adjustment p-value, $\alpha / 6 = 0.008$