OCCLUSION IN THE DIGITAL AGE

A Thesis

by

JACKSON DAVID SAVAGE

Submitted to the Office of Graduate Professional Studies of
Texas A&M University
In partial fulfilment of the requirements for the degree of
MASTER OF SCIENCE

Chair of Committee,	Peter H. Buschang
Committee Members,	Larry Tadlock
	Emet Schneiderman
Head of Department,	Madhu Nair

May 2021

Major Subject: Oral Biology

ABSTRACT

Purpose

Current technology is capable of manipulating and analyzing the dentition digitally, in all three planes of space. Our goal is to use 3D technology to help identify barriers to ideal occlusion in the posterior dentition that may have been previously overlooked.

Materials and Methods

50 pre-treatment models (30 male, 20 female, mean age= 15.9±2.8 years) were scanned using a TRIOS ® 3Shape scanner. The models were digitized, and the posterior dentition was manipulated into ideal cusp-fossa relationships, using Ortho Analyzer™ software, following a seven-step manipulation protocol. The protocol was based on achieving Andrew's Six Keys to Ideal Occlusion[4] as well as a large number of ideal occlusal contacts. After manipulation was complete, all overlaps >0.05 mm or spacing between interdental contacts were recorded as a discrepancy. The sum of the absolute value of all discrepancies was recorded as the total discrepancy on each side. The left and right sides were compared using a Wilcoxon signed ranks test.

Results

In the 50 models evaluated, 62 discrepancies were detected. Approximately 5% of the discrepancies detected were at the canine- 1st premolar contact, 3% of discrepancies were located between at the 1st and 2nd premolar contact, 84% were at the 2nd premolar- 1st molar contact and 8% of the discrepancies were between the 1st and 2nd molar contact. The 2nd premolar -1st molar contacts, which showed the highest prevalence of contact discrepancies, showed median discrepancies of 0.5 and 0.4 mm on the left and right sides, respectively. Over half of the sides

evaluated had a discrepancy at this contact point. In terms of subjects, 64% of individuals had at least one side with a discrepancy at this contact point.

Concerning total discrepancies, approximately 50% on the left and right sides were greater than 0.56 mm and 0.47 mm, respectively. Approximately 46% of sides had no total discrepancy. 25% of sides had total discrepancies that were ≥0.05 mm but <0.5 mm, 19% of sides had total discrepancies ≥0.5 mm but <0.75 mm, 6% of sides had total discrepancies ≥0.75 mm but <1 mm, and 4% of sides had total discrepancies ≥1 mm. 29% of the sides evaluated had a total discrepancy ≥0.5 mm. When considering subjects instead of sides, 44% individuals had at least one side with a total discrepancy ≥0.5 mm. There were no differences between sides at any contact (P>0.09).

Conclusions

Discrepancies in the posterior dentition are not uncommon, with approximately 6% of posterior contacts, 29% of sides, and 44% of individuals having clinically significant discrepancies (discrepancies greater ≥0.5 mm).

The maxillary 2^{nd} premolar- maxillary 1^{st} molar contact may be a common contributor to occlusal discrepancies.

Evaluating the cusp tip of the maxillary 2nd premolar relative to its embrasure may provide insight to the possibility of a class I canine position. In 92% of the posterior dentitions evaluated, if the Maxillary 2^{nd} Premolar was placed appropriately according to the manipulation protocol, the remaining premolars and canines were able to class I cusp-fossa relationship without any interferences.

The utilization of 3D technology may help the clinician as a diagnostic aid and yield insight into potential barriers to ideal occlusal results.

ACKNOWLEDGEMENTS

I would like to thank my committee members, Drs. Buschang, Tadlock, and Schneiderman. Your collective wisdom and guidance have not only made me a better academician and clinician, but a better man as well. None of this would have been possible without you.

I would also like to thank my coresidents. For all the memories and laughs. For all the highs and lows that we experienced together. Thank you for going through this journey with me. I am so blessed to have met you all, and so very thankful for your continued friendships and camaraderie.

Lastly, to my family, the Savages, thank you for your love and support. I owe so much to you all. Thank you for raising me in a loving home with a passion for Christ at its core. I am so very proud to be a Savage.

CONTRIBUTORS AND FUNDING SOURCES

This work was supported by the thesis committee consisting of Drs. Buschang, Tadlock, and Schneiderman. All work for the thesis was completed by the student, under the advisement and with the assistance of the thesis committee members.

This work was made possible by the Robert E. Gaylord Endowed Chair in Orthodontics, and the Department of Graduate Orthodontics and Craniofacial Orthopedics at Texas A&M College of Dentistry.

TABLE OF CONTENTS

Page

ABSTRACT ii

ACKNOWLEDGEMENTS... iv

CONTRIBUTORS AND FUNDING SOURCES v

TABLE OF CONTENTS vi

LIST OF FIGURES viii

LIST OF TABLES ix

CHAPTER I INTRODUCTION...1

Components of an Ideal Occlusion 1
Tooth Size and Ideal Outcomes 4
Bolton Ratio and Its Limitations...7
The Influence of Arch Form 9
Orthodontic Finishing and the Pursuit of Ideal Occlusion 11
Summary and Statement of the Problem 13

CHAPTER II MATERIALS AND METHODS...16

Sample and Inclusion Criteria...16
Manipulation Protocol 16
Statistical Analysis 19
Reliability..20

CHAPTER III RESULTS...21

Considering Only Contacts with Discrepancies..21
Considering All Contacts (Table 1)...22

Page

CHAPTER IV DISCUSSION 23

Discrepancies are Not Uncommon..23
The Maxillary 2nd Premolar- Maxillary 1st Molar Contact is Key..24
Considering Class I Correction: Look at the 2nd Premolar..25
Clinical Implications..26
Consideration for the Future..28
CHAPTER V CONCLUSIONS..29

REFERENCES..30

APPENDIX A FIGURES..37

APPENDIX B TABELS..50

LIST OF FIGURES

Page

Figure 1. Summary of Materials and Methods. 37

Figure 2. Manipulation Protocol: Step One 38

Figure 3. Manipulation Protocol: Step Two 39

Figure 4. Manipulation Protocol: Step Three 40

Figure 5. Manipulation Protocol: Steps Four and Five 41

Figure 6. Manipulation Protocol: Step Six 42

Figure 7. Manipulation Protocol: Step Seven 43

Figure 8. The Number of Discrepancies at each Contact Point 44

Figure 9. Discrepancy Contribution 45

Figure 10. Discrepancies at the 2nd Premolar- 1st Molar Contact 46

Figure 11. Total Discrepancies: Discrepancies Only 47

Figure 12. Percentages of Sides with Various Total Discrepancies 48

Figure 13. Total Discrepancies: All Contacts 49

LIST OF TABLES

Page

Table 1. Discrepancies at Each Contact Point…………………………………………………..50

CHAPTER I

INTRODUCTION

Components of an Ideal Occlusion

It is important to understand the dynamic nature of "ideal occlusion". As our understanding grows, so too does our definition of ideal. As early as 1907 Edward Angle described his prized class I, first molar relationship[1] which is still used to begin describing an ideal occlusion.[2, 3] Angle suggested that normal occlusion occurs in the presence of an appropriate first molar relationship, so long as the teeth are aligned in a smooth, curving line of occlusion[3]. However accurate this may be, is of course insufficient to completely define ideal occlusion.

Perhaps the most widely known description of ideal occlusion was provided by Andrews in his "Six Keys to Normal Occlusion" in 1972.[4] Andrews studied 120 models of patients who had never had orthodontic treatment. These models were taken from patients whose teeth were straight and pleasing in appearance, had bites which looked generally correct, and in Andrews' best judgment would not benefit from orthodontic treatment. What Andrews discovered was that these models shared some important characteristics which became the foundation of his six keys. The six keys are as follows:[4]

1. Molar relationship- A class I relationship. It is important to note a distinction between Angle's and Andrews' definition of an optimal, class I molar relationship. Andrews showed that the distal surface of the distobuccal cusp of the upper first permanent molar made contact and occluded with the mesial surface of the mesiobuccal cusp of the lower second molar. Additionally, the mesiobuccal cusp of the upper first molar should rest in

the groove between the mesial and middle cusps of the mandibular first molar, which is consistent with Angle's definition of a class I molar relationship.

2. Crown angulation/ mesiodistal tip- The gingival portion of the long axis of each crown should be distal to the incisal portion, varying with the individual tooth type.
3. Crown inclination/ labiolingual or buccolingual inclination- Upper and lower anterior crown inclination should be sufficient to resist overeruption of anterior teeth and sufficient also to allow proper distal positioning of the contact points of the upper teeth in their relationship to the lower teeth, permitting proper occlusion of the posterior crowns. In the upper posterior crowns, there should be a consistent lingual crown inclination which is slightly more pronounced in the molars. The lingual crown inclination in the lower posterior teeth should progressively increase from the canines through the second molars.
4. Rotations- There should be no rotations present.
5. Spacing- There should be no spaces present.
6. The plane of occlusion should vary from generally flat to a slight curve of Spee.

Andrews suggested that some deviation from ideal should be considered normal, considering that most of the population is afflicted with some form of malocclusion. However, he distinguished abnormal malocclusions from normal malocclusions as those malocclusions that cannot be treated to optimal standards without compromise or surgical intervention.[5]

Another definition of a normal occlusion was that put forth by Stifter, who suggested that occlusion is normal when teeth can perform their primary functions efficiently and the health of the supporting structures is maintained.[6] These functions include mastication, esthetics, speech, and deglutition.[6] Along these same lines, Lundström suggested that normal occlusion is a functionally ideal occlusion.[7] According to Lundström, in a normal, adult occlusion, the following should be present:

1. A complete dentition in both jaws, with no spacing present.
2. The upper teeth should be labial to the lower teeth on biting, with an appropriate overbite of 1-3 mm in the anterior. The palatal cusps of the maxillary dentition articulate with the corresponding and adjacent mandibular teeth.
3. There should be balance in the occlusion on articulation such that there is smooth contact between the arches in incisal and lateral regions.

Like Andrews, Lundstrom emphasized that the aforementioned criteria were ideal, and that there were all-too-often deviations, such as mild spacing or crowding, that cause one to consider the range from ideal that one would accept as an admissible, or normal malocclusion.[7]

In addition to the criteria listed above, it is critical to understand that ideal occlusion is also related to the quality and quantity of contacts shared by the maxillary and mandibular dentition. These areas of contact and near contact (ACNC) define posterior occlusion and function. It has been shown that subjects with normal occlusion have significantly larger ACNC than those with Class I, Class II, and Class III malocclusions and that individuals with larger ACNC are better able to break down foods.[8] Furthermore, subjects with malocclusion (who have smaller ACNC) do not perform as well as those with normal occlusion in regards to masticatory performance.[9-14] Lepley et al.[15] showed that masticatory performance was most closely correlated with occlusal contact area, indicating larger ACNC in subjects with better performance. In that same study, occlusal contact areas were related to greater bite forces and favorable chewing cycle kinematics. These studies corroborate the notion that intimate cusp fossa relationships and class I occlusion are important in that they are critical in determining the ability of the subject to break down food, have higher bite forces, and normal chewing cycle, all of which should be components of an ideal occlusion.

Another characteristic of an ideal occlusion should be long-term occlusal stability. A study by Harris and Behrents[16] assessed the relative stability of the molar relationship in untreated individuals with complete dentitions. They found that the Class I relationship is the most stable. However, Class II relationships became more class II, and Class III cases became more class III. Studies conducted at the University of Washington[17-20] found satisfactory long-term stability of mandibular incisors in approximately one third of the patients. More recent studies from the University of Washington[21-23] and Baylor College of Dentistry[24-26] support the notion that long term stability after orthodontic treatment is achievable in close to 80% of patients. This stability is related to a few common factors such as minimal expansion of the mandibular canines and molars, and retraction with uprighting or minimal movement of the mandibular incisors.

In summary, an ideal occlusion is one that:

1. Meets Andrew's Six Keys to Occlusion.[4]
2. Allows for performance of primary functions.[6, 7]
3. Has intimate posterior intercuspation with large areas of contact and near contact, which are critical for optimal function.[8-15]
4. Is stable before,[16-20] or after orthodontic treatment.[21-26]

Tooth Size and Ideal Outcomes

One of the first steps in orthodontic diagnosis and treatment planning is a detailed analysis of the patient's dentition. This analysis is likely to include a detailed space analysis as well as the assessment of tooth size.[2, 3] It has been well established that in order to achieve ideal occlusion, the maxillary dentition and mandibular dentition must have a proportionality of tooth size such that the sum of the widths of the maxillary dentition must be larger than the sum of the widths of the mandibular dentition. Of course, this relationship was explained in detail by Bolton.[27] Performing a detailed analysis of tooth size and arch form is critical in that it may help the orthodontist identify a tooth-size discrepancy that may prevent the orthodontist from achieving an ideal outcome without some form of intervention such as interproximal reduction or extraction therapy.[28-30]

Tooth size has been studied extensively, perhaps most notably by G.V. Black.[31] Black documented tables of mean tooth sizes based on extensive measurements of multiple teeth of all types. Ballard, in 1944, measured the greatest mesiodistal dimension of the dentition on both sides of the arch in 500 cases. He then compared his findings to those of Black. He found that tooth size is highly variable. In fact, he discovered that in 90% of the 500 cases, there was a significant discrepancy between the left and right pairs of teeth. Additionally, in 82% of these cases, the discrepancy between the left and right antimeres were greater than 0.5 mm.[32] He then went on to discuss interproximal reduction as a potential solution to this discrepancy. Ballard's findings have been somewhat validated in that many other studies have concluded that tooth size discrepancies are not uncommon.[33-35] However, unlike other studies, Ballard's work would suggest that discrepancies in the posterior dentition may be more common than studies measuring a Bolton ratio report.

But are these tooth size discrepancies likely to affect treatment in such a way that an ideal outcome may not be possible without intervention? Using two standard deviations outside of Bolton's ratio is a common marker for determining a clinically significant tooth size discrepancies between jaws, because this would represent a discrepancy of 2-3 mm from Bolton's mean.[36, 37] Freeman et al.[36] calculated a Bolton ratio in a sample of 157 orthodontic patients. A discrepancy was considered clinically significant if its value was outside two standard deviations of Bolton's mean (ratio of 73.9-80.5% for the anterior 6, 87.5-95.1% for the overall 12). Freeman et al.[36] found that, in their sample, 13.4% of cases had overall 12 ratios outside of 2 SD, and 30.6% cases had anterior 6 ratios that fell outside of 2 SD. A study by Crosby and Alexander[37] measured the Bolton Ratios in a sample of 109 orthodontic patients with varying malocclusions. They found no significant difference in the mean mesiodistal ratios when compared to Bolton. However, they found higher standard deviations when compared to Bolton's study. Additionally, they found that there were no significant differences in ratios when comparing types of malocclusion. They went on to suggest that due to the large number of tooth size discrepancies in each group, regardless of malocclusion type, a Bolton analysis should be performed on each patient prior to initiation of treatment. Manke and Miethke[38] found that in a sample of orthodontic patients, 20% had a significant mandibular excess that would merit narrowing during treatment. They also suggested that the presence of a mandibular excess was more common than the presence of a maxillary excess. Bolton found that in a sample of 100 patients in his practice, 29% had a Bolton discrepancy beyond one standard deviation of his ideal mean.[40] These studies would suggest that, in samples of orthodontic patients, we should expect to see a tooth size discrepancy that would affect our treatment goals in roughly 15- 30% of cases.[36-38, 40] Failure to intervene in these cases, via interproximal reduction or extraction therapy, may negate the possibility of ideal alignment without the compromises of inappropriate overbite or overjet.[39] This would suggest that the orthodontist, or any clinician attempting to provide orthodontic care, should not assume that teeth should simply fit together without the ability to troubleshoot and provide an appropriate intervention. However, many of these studies also suggest that a tooth-size discrepancy is most likely to be present in the anterior dentition.

This may be due a limitation of the Bolton Ratio. As mentioned previously, Ballard's study would suggest that discrepancies in the posterior dentition should be more common. So how is it that we are not detecting them?

Bolton Ratio and Its Limitations

Bolton developed his analysis in 1952 to evaluate the relationship of the mandibular and maxillary dentition.[27] His analysis creates a ratio of the sum of the mandibular and maxillary dental widths. He suggests that these ratios should be approximately 91.3% for the overall molar to molar, and approximately 77.2% for the ration of the anterior six teeth. When these formulas are applied as a diagnostic aid, the clinician can detect the presence of a maxillary or mandibular excess or deficiency. Bolton suggested that a discrepancy greater than one standard deviation outside of his mean ratio would require consideration of an intervention such as interproximal reduction or extraction therapy.[40] He indicated that this analysis should be routinely performed, regardless of malocclusion type, due to the prevalence of tooth size discrepancies. However, the Bolton Analysis is limited in that it is a function of anterior and posterior mesiodistal dental widths, which fails to consider other contributors of posterior occlusion such as cusp-fossa relationships or arch form, which thereby change the mesiodistal dimension which each posterior tooth occupies. This is problematic when you consider that not all patients are created equal, and that the dentition may have different spatial relationships depending on factors such as the curves of Spee and Wilson and the arch form in which the teeth are positioned.

The concept that spatial relationships and arch form can alter the Bolton index has been demonstrated. Halazonetis[41] examined the effects of the radius of the mandibular arch, the differences in the maxillary and mandibular arch radii, and the effects of various incisor labiolingual thicknesses on the Bolton ratio. Halazonetis discovered that the Bolton ratio is affected by the shape of the dental arch and the incisal edge thickness. As the radius of the anterior segment goes from more curved to flatter, the Bolton ratio increased. This would suggest that a maxillary deficiency could be treated by flattening the anterior arch form, and a maxillary excess could be treated by increasing the curvature of the anterior segment. However, Halazonetis showed that the incisal edge thickness was the most influential factor. In fact, a 1 mm change in incisal edge thickness may affect the Bolton ratio by as much as 5%, which represents almost a 3 mm tooth size discrepancy. These findings led Halazonetis to conclude that when assessing any suspected tooth-size discrepancy, a low or high Bolton value may not represent a true discrepancy, and an ideal value may not guarantee an ideal occlusion. He also went on to suggest that his study was limited, and that further investigation needed to be performed, specifically concerning the relationship of the posterior teeth to these parameters.

Steyn et al.[42] attempted to quantify how changes in the arch circumference affect a change in anterior arch length. Arch circumference was the width of the arch connecting the interproximal contact points from distal of the canine to the distal of the contralateral canine in millimeters, and the anterior arch length was defined as the distance from the central incisor contact point to a perpendicular line connecting the distal interproximal contact points of the canines (Figure). They discovered that the shorter the arch length, the more critical the arch circumference. In other words, for every millimeter change in arch circumference, the overjet will be affected to a greater degree in a case with a smaller arch length than in a case with a larger arch length. These findings were supported by Epker and Fish who found that changing the curvature of the arch resulted in changes in overjet unless the arch length was adjusted in order to maintain the same canine relationships.[43] These studies clearly demonstrate that the Bolton ratio can be affected by the shape of the arch form, incisal edge thickness, and that overjet can compensate for an apparent Bolton discrepancy.[41-43] However, these studies are all limited in that they do not extend their investigations to the posterior dentition. This limitation is unfortunate when you consider that the posterior dentition has been shown to have great variability in tooth size and shape,[32] and there is more interproximal enamel available in the posterior dentition for an intervention such as interproximal reduction, should a true tooth size discrepancy exist.[44]

The Influence of Arch Form

The forms of the dental arches are clearly influential regarding their effect on the anterior dentition and the Bolton ratio.[41-43] But what constitutes an ideal arch form and how does arch form influence other dental parameters? There have been many attempts to characterize and describe the dental arch. Bonwill,[45] as early as 1884, outlined a set of geometric principles for an ideal dental arch that he felt was most conducive to the movement of the jaws in mastication. He used a series of equilateral triangles to develop a guide for setting artificial teeth in denture fabrication. He felt that the ideal dental arch should not be "horseshoe" shaped, which was a common shape used for dentures at the time. Bonwill's setup was later applied to the field of orthodontics by Hawley.[46] Hawley believed in Bonwill's work and suggested that if the teeth are normal and uniform in size, there must be an ideal arch which, when filled, will accommodate all the contact points and allow for a correct occlusion. Hawley developed an arch form based on the mesiodistal widths of the anterior dentition, canine to canine. The six front teeth fit the arc of a circle whose radius is defined by their widths. The posterior segments, distal to the canines, are arranged in a straight line which is related to a series of equilateral triangles, like Bonwill. Hawley goes on to suggest that the line of posterior dentition, and the base of the triangle to which it extends, should be based on the anatomy of the patient's alveolar ridge. In other words, the posterior line of occlusion should be positioned over the ridge to accommodate the forces of mastication and preserve the proper functional movements of the jaw. Therefore, Hawley implied that the ideal arch is unique to each patient and is defined by the width of the anterior teeth, and the shape of the basal bone which they occupy.

Although the Bonwill-Hawley theory was once held in high esteem, it has more recently been refuted even though it bears a striking resemblance to many of the standard arch form templates used in orthodontics to this day.[1,47,48] The refutation seems mostly related to disagreements in the location and quantity of curvature in the arch. Williams suggested that the arc of the anterior teeth should lie on a circle whose radius is determined by the mesiodistal widths of the permanent dentition molar to molar, not simply canine to canine.[49] In contrast, Hellman contended that it is faulty to assume that the dimension of the teeth should play any role in determining the ideal arch. Hellman, after studying a large sample of skulls, stated that he found there to be no correlation between the widths of the incisors or molars and the shape of the dental arches.[50] G.V. Black described the ideal arch as a semi-ellipse. However, he stated that there is often great variation, where some patients display a straight line from the bicuspids through the molars, while others display a slight curvature.[31] Izard studied skulls with normal archforms and found that 75% were elliptical, 25% parabolic, and 5% other (square or U-shaped).[47]

It has been proposed that the original mandibular intercanine width should be used as a guide to determine the appropriate archform for each patient. De La Cruz et al.[51] found that the greater the change in shape of the arch during orthodontic treatment, the greater the tendency for a change post-retention. The patient's pretreatment arch form appeared to be the best guide to future arch form stability. Similarly, Felton and Sinclair[52] found that roughly 70% of the cases that had changes in arch form during treatment had significant long-term post-treatment changes, leading them to recommend individualization of the archform to help obtain ideal long-term stability. Myser et al.[53] found that post-retention changes were related to post-treatment anterior arch perimeter, intercanine width, and arch form. They suggested that narrower arch forms are more likely to show post-treatment malalignment changes. These studies seem to all corroborate the notion that the stability of the archform seems to be dependent on the patient's initial archform, and that changes to this archform, or alteration of the intercanine width, will result in increased risk of instability. This is supported by other studies that would suggest maintenance of the intercanine width and the mandibular archform as a staple of stability.[26,54]

Orthodontic Finishing and the Pursuit of Ideal Occlusion

There is value in achieving a stable, class I, intercuspated occlusion. But just how successful are we at achieving ideal occlusion, with all of its components? In an attempt to drive the profession forward by helping to determine the adequacy of treatment results, the American Board of Orthodontics created the Objective Grading System (OGS). The OGS scores post-treatment models based upon eight criteria: Alignment, Marginal ridges, Buccolingual inclination, Occlusal contacts, Occlusal relationship, Overject, Interproximal contacts, and Root angulation.[55] Although perfection in all these categories may be impossible to achieve in some cases, one should hope to get close. However, a study by Fleming et al.[56] showed that in 138 Angle class I nonextraction patients, the partial mean overall OGS score was 24.9 +/- 8.0 (a score of >27 is failing). Occlusal contact was the most important component contributing to the overall score, followed by alignment. Unfortunately post treatment occlusal discrepancies are not uncommon.

Furthermore, it has also been shown that orthodontic treatment tends to result in an overall decrease in the number of occlusal contacts.[57-59] Sullivan et al..[57] showed that, when compared with untreated controls, treatment with fixed appliances diminished the number of occlusal contacts. Furthermore, they noted that orthodontic treatment may lead to an appreciable permanent reduction in occlusal contacts which is not always compensated by post treatment settling. Haydar et al.[60] compared patients treated with fixed appliances retained with a Hawley to patients treated with fixed appliances retained with a positioner, and untreated controls. The total mean number of contacts at the end of treatment for both treated groups was significantly less than that of the untreated group. This is problematic, considering that long term occlusal stability should be one of the goals of orthodontic treatment and that greater area of occlusal contact has been shown to be related to enhanced masticatory performance,[12-14] normal chewing cycles,[61-64] and greater bite forces.[65,66]

Why is it that orthodontically treated patients show occlusal discrepancies post-treatment? One possibility is that there are tooth size or positional discrepancies that the orthodontist failed to detect. Given such discrepancies, an ideal occlusion would not be possible without an intervention such as interproximal reduction or repositioning. A study by Shellhart et al.[67] showed that significant measurement error can occur when performing a Bolton Analysis on crowded pre-treatment models. In other words, crowding may make it difficult for the orthodontist to accurately predict the presence of a tooth-size discrepancy pre-treatment. Unfortunately, it is not uncommon for these discrepancies to reveal themselves in the finishing stages of orthodontic treatment [28,68]

And how do orthodontists react to a perceived discrepancy? In a study performed by Barcoma et al.[69] 873 orthodontists responded to a survey designed to elicit their opinions on interproximal reduction (IPR) and its use in clinical practice. The survey response suggested that two-thirds of orthodontists reported performing IPR on a routine basis to gain intra-arch space. Nearly half of them reported a preference for performing IPR on anterior teeth over posterior teeth because it was “easier to perform than IPR on posterior teeth”. This brash application of

IPR is perhaps problematic if one considers that the orthodontist may be creating a Bolton discrepancy where one did not exist, and failing to apply IPR to the posterior dentition, where a true discrepancy may exist.

Furthermore, it may very well be that tooth-size discrepancies are not the reason for the perceived occlusal discrepancies. For example, according to Andrew's,[4] it is possible for the mesiobuccal cusp of the upper first molar to occlude in the groove between the mesial and middle cusps of the lower first permanent molar (representing a class I relationship as sought by Angle[1]) and yet have what appears to be a class II canine and premolar relationship. Andrews showed that the closer the distal surface of the distobuccal cusp of the upper first permanent molar approaches the mesial surfaces of the mesiobuccal cusp of the lower second molar, the greater the likelihood of appropriate cusp/embrasure relationships of the premolars and canines (Figure). If the upper first molar is not in an appropriate position (approximating the lower second molar) the orthodontist might claim that there was a tooth size discrepancy preventing ideal, class I intercuspation. However, the reality is that ideal cusp fossa relationships could have been achieved by seating the distobuccal cusp of the upper first molar.

Summary and Statement of the Problem

Class I intercuspated, normal occlusion is important because it is related to greater areas of contact and near contact,[8] which are related to enhanced masticatory performance,[12-14] normalized chewing cycles,[61-64] and stability[16]. These are all components of an ideal occlusion, and the orthodontist should make every effort to pursue ideal outcomes. However, orthodontic treatment tends to decrease occlusal contact area,[57-59] and occlusal contact has been shown to be a major contributor to higher Objective Grading System scores.[56] Is it simply a lack of skill that leads to these post-treatment discrepancies? Perhaps there is more to the equation. Studies have shown that tooth size discrepancies are not uncommon,[33-35] and that these tooth size discrepancies can be difficult to detect pre-treatment due to factors such as crowding.[67] This may lead to the orthodontist perceiving an occlusal discrepancy in the finishing stages of treatment.[26,68] This poses an interesting dilemma in that it may be difficult for the orthodontist to know if there is a true tooth size discrepancy that would require alteration of tooth size, or if there or other contributors to the perceived discrepancy such as poorly positioned teeth, or poorly coordinated archforms. This very scenario sets the stage for the present study.

The Bolton Ratio is clearly influenced by archform,[41-43] and the position of the teeth (which may alter their mesiodistal dimension), and there is a shortage of studies that have continued their investigations in this regard to include the posterior teeth. Based on the studies presented, it would seem unwise to assume that teeth should simply fit together, and equally unwise to apply interproximal reduction “willy-nilly”. Additionally, many of the studies that attempt to quantify the prevalence of clinically significant Bolton discrepancies suggest that the prevalence of Overall Bolton discrepancies is roughly half as common as Anterior Bolton discrepancies (roughly 13% Overall, and 30% Anterior).[36-38] These studies suggest that the contribution of the posterior dentition to clinically significant Bolton discrepancies may be even less than 13%. This conflicts with the studies by G.V. Black and Ballard that show a high degree of variability in the posterior dentition, which would suggest that posterior tooth size discrepancies should be more common.[31,32]

We suggest that the underestimated contribution of the posterior dentition to clinically significant Bolton discrepancies has likely caused the orthodontic community to completely ignore the Overall Bolton ratio. If they do not detect an Anterior Bolton discrepancy, they may falsely assume that there wouldn’t be a posterior discrepancy. Or, an Anterior Bolton discrepancy is detected, interproximal reduction is applied to the anterior dentition only, and the orthodontist falsely assumes that the remaining dentition will fit together into appropriate occlusal relationships.

The present study will attempt to position the posterior dentition in ideal cusp-fossa relationships and evaluate whether the teeth would fit together without alteration. This will be done digitally, in the 3Shape Ortho Analyzer™ software. The teeth will be placed on an archform that matches the original archform of the mandibular dentition, as this has been shown to be important for stability.[26,54] The goal is to discover if the posterior teeth fit together, and if not, where the most common discrepancies are located. This will provide insight as to what the orthodontist should be looking for to troubleshoot and identify barriers to ideal occlusion that may be present in an unaltered posterior dentition.

CHAPTER II

MATERIALS AND METHODS

Sample and Inclusion Criteria

Pre-treatment models were chosen from a large sample of completed cases treated by the Orthodontics and Dentofacial Orthopedics department at Texas A&M College of Dentistry. The first 50 models that met the following criteria were selected:

- Complete permanent dentition present with or without 3rd molars.
- Models in ideal condition with no major damage, nodules or voids in any critical areas (interproximal/ occlusal surfaces).
- No obvious deviation from anatomical norms (including crowns or restorations) that would lead to obvious discrepancies.

Of the 50 models that were selected, 30 were male, 20 were female, and the average age of the sample was 15.92±2.79 years. The models were scanned using a TRIOS ® 3Shape scanner, which has been shown to be one of the most accurate scanners on the market, accurate down to as little as 6-7 microns.[80,81,82] The models were then digitized and manipulated into ideal occlusion using 3Shape Ortho Analyzer™ software. This software is capable of manipulating the dentition in all three planes of space in 0.01 mm increments.

Manipulation Protocol

The manipulation protocol was designed to make the "ideal" position as objective as possible and was based on achieving Andrews' keys to occlusion[4] as well as a large number of occlusal contacts. The protocol involves seven steps (Figure 1):

The first step aligned the standard plans. The sagittal and coronal planes were aligned perpendicular to the maxillary occlusal plane (i.e., sagittal plane) of the digital model (Figure 2). The occlusal place was defined by points on the central grooves of the maxillary first molars and the incisal edge of the maxillary central incisors.

The second step created an ideal arch form (Figure 3)**.** A custom archform was made that replicated the original mandibular archform (so as not to increase the intercanine width during manipulation). This archform was used as a guide such that the mandibular functional cusps layed on the archform, and the central grooves of the maxillary dentition, for which they articulate with, layed on the archform after manipulation. The archform was parabolic in nature and based on a line of best fit connecting points on the buccal cusps of the mandibular second molars to the cusp tips of the mandibular canines. The maxillary archform was copied from the mandibular.

The mandibular dentition was idealized in the next step by removing rotations (buccal cusps on the archform with central grooves parallel to archform), levelling the curve of wilson until it was mild to none (accepted range of 0-1 mm difference between buccal and lingual cusps), levelling the curve of spee until it was mild to none (visually the curve of spee needed to be relatively flat, but a mild curve of spee was accepted if it fit the natural curvature of the alveolar bone), and setting ideal interarch contacts (Figure 4). All of these criteria conformed to the shape of the custom archform. Since the software is capable of moving teeth at 0.01 mm increments, it can detect potential interferences or overlaps of 0.01 mm. For the purposes of this study, any contact that was ≤0.05 mm in depth was considered an ideal contact. Anything <0 was spacing, and anything >0.05 mm in overlap was considered a discrepancy or interference. The reason for choosing a range of 0.00-0.05 mm as an ideal contact is due to the fact that these models are ridged and are not capable of any physiologic movement that may occur in a natural bite, and 0.05 mm is well below the threshold of what one would consider worthy of intervening with interproximal reduction, and is therefore, clinically insignificant.

The next step idealized the maxillary first molar position (Figure 5). According to Andrews[4], the distobuccal cusp of the maxillary first molar should approximate the mesiobuccal cusp of the mandibular second molar. Additionally, the mesiobuccal cusp of the maxillary first molar should rest in the groove between the mandibular mesial and middle cusps. The maxillary first molar position was considered ideal if it met the aforementioned criteria, as well as there being no rotation (the central groove parallels the archform), and having at least four ideal occlusal contacts shared between the mandibular first and second molar (palatal cusps of the maxillary first molar contacting the central groove of the mandibular first molar and marginal ridges of the first and second mandibular molars, and the mandibular first molar buccal cusps contacting the central groove of the maxillary first molar). It is important to note that the minimum number of required occlusal contacts was four, but every effort was made to position the molar such that we could achieve more than four ideal contacts or greater surface area of contact, which was often the case. Additionally, it became evident very quickly that some maxillary first molars simply cannot meet all of the aforementioned criteria. Specifically, it became obvious that not all maxillary first molars are capable of making contact with the mesiobuccal cusp of the mandibular second molar while simultaneously having their mesiobuccal cusp lie within the groove between the mandibular first molar mesial and middle cusps. In this scenario, precedence was given to the mesiobuccal cusp lying in the groove, rather than the distobuccal cusp making contact with the lower second molar.

Idealizing of the maxillary second molar position was then performed (Figure 5). The mesiobuccal cusp had to rest between the mesial and distobuccal cusps of the lower second molar and share at least two ideal occlusal contacts (Palatal cusp of the upper second molar making contact with the central groove of the lower second molar and mesiobuccal cusp of the lower second molar making contact with the mesial marginal ridge of the maxillary second molar)

The next step was to idealize the maxillary 2nd premolar through the canine (Figure 6), in that order, until they met the following criteria: their buccal cusp tips rest in their opposing embrasure, they share at least two ideal contacts with their opposers, no rotations. The mandibular buccal cusps make contact with the marginal ridges of the maxillary premolars, and the palatal cusps of the maxillary premolars should make contact with the distal pits of the mandibular premolars.

Each arch was individually inspected to ensure that all the aforementioned criteria are met (Figure 7). If they were not, the process was repeated starting with the first step. It is important to note that during steps 5-6, if ideal contacts could not be achieved, only then would any changes be made to the position of the mandibular dentition. These changes would only involve subtle changes to the curve of spee and wilson and the mandibular dentition still had to meet the aforementioned criteria.

Statistical Analysis

After completion of the manipulation protocol, any overlap greater than 0.05 mm, or spacing in the maxillary dentition was recorded as a discrepancy at that contact (Figure 7). Spacing between the maxillary dentition was measured from the point of each tooth with the closest proximity to one another, parallel to the occlusal plane. Spacing between the maxillary dentition was regarded as a discrepancy in the mandibular dentition. The total discrepancy for each side was calculated by taking the sum of the absolute value of all contact discrepancies. The frequency of discrepancies at each contact was recorded. Because the individual contact and total discrepancies were not normally distributed, they were described using medians and interquartile ranges. The left and right sides were compared using a Wilcoxon signed ranks test. There were no differences between left and right sides (Table 1).

Reliability

Reliability was measured by calculating the method error for each contact point using the following formula: $\sqrt{(\sum \text{differences}^2/2n)}$. The method error ranged from 0.23 mm- 0.33 mm at the 1st to 2nd premolar contact to the first molar to second molar contact respectively.

CHAPTER III

RESULTS

Considering Only Contacts with Discrepancies

There was a total of 62 discrepancies detected (Figure 8). Approximately 5% of the discrepancies detected were at the canine- 1^{st} premolar contact, 3% of discrepancies were located between at the 1^{st} and 2^{nd} premolar contact, 84% were at the 2^{nd} premolar- 1^{st} molar contact and 8% of the discrepancies were between the 1^{st} and 2^{nd} molar contact (Figure 9).

The 2^{nd} premolar -1^{st} molar contacts, which showed the highest prevalence of contact discrepancies, showed median discrepancies of 0.5 and 0.4 mm on the left and right sides respectively (Figure 10). Approximately 25% of the discrepancies were greater than .73 mm on the left side and .67 mm on the right side. 52% of the sides evaluated had a discrepancy at this contact point. In terms of subjects, 64% of subjects had at least one side with a discrepancy at this contact point.

Concerning total discrepancies, approximately 50% on the left and right sides were greater than 0.56 mm and 0.47 mm, respectively (Figure 11). Approximately 46% of sides had no total discrepancy, while the remaining 54% had a total discrepancy. 25% of sides had total discrepancies that were ≥0.05 mm but <0.5 mm, 19% of sides had total discrepancies ≥0.5 mm but <0.75 mm, 6% of sides had total discrepancies ≥0.75 mm but <1 mm, and 4% of sides had total discrepancies ≥1 mm (Figure 12). 29% of the sides evaluated had a total discrepancy ≥0.5 mm. When considering subjects instead of sides, 44% individuals had at least one side with a total discrepancy ≥0.5 mm.

Considering All Contacts (Table 1)

The median contact discrepancies when all contacts were included were all zero. With the exception of the 2nd premolar-1st molar right side contact, the 75th percentiles were also zero. 25% of the 2nd premolar-1st molar right side contacts were greater than 0.4 mm. The 1st molar-2nd molar contacts showed 1.29 and 1.01 of spacing on the left and right sides respectively.

Based on the sum of the absolute value of all contacts, the median total discrepancy on the left was 0.30 mm with a range of 0-1.02 mm, and the median total discrepancy on the right was 0.08 mm with a range of 0-0.84 mm.

Only 34% of individuals had no discrepancies on either side, indicating that the dentition would fit together without any alteration of tooth size after meeting the manipulation protocol criteria.

CHAPTER IV

DISCUSSION

Discrepancies are Not Uncommon

The present study would suggest that it would be folly to assume that the posterior dentition will fit together in ideal cusp fossa relationships without any intervention or compromise. 54% of the sides evaluated had a discrepancy. 29% of the sides had a total discrepancy of ≥0.5 mm. In terms of subjects, 44% of individuals had at least one side with a total discrepancy ≥0.5 mm. But is this likely to be clinically significant?

Freeman et al[36] found that, in a sample of 157 patients, 13.4% had overall "12" ratios outside of 2 standard deviations from Bolton's mean, and 30.6% of individuals had anterior "6" ratios that fell outside of 2 standard deviations, which they deemed clinically significant. Similarly, Crosby and Alexander[37] found that 22% of patients had a significant tooth size discrepancy. These studies used 2 standard deviations away from Bolton's mean as their marker for clinical significance, which can represent about a 2 mm Bolton Discrepancy. Bolton himself suggested that a discrepancy greater than one standard deviation outside of his mean ratio (which represents approximately 1 mm) would require consideration of an intervention such as interproximal reduction or extraction therapy.[40] He indicated that his analysis should be routinely performed, regardless of malocclusion type, due to the prevalence of tooth size discrepancies.[40]

All of these studies seem to support the present study in suggesting that tooth size discrepancies are not uncommon. Furthermore, a discrepancy of ≥ 0.5 mm (found in 44% of subjects on at least one side) is likely to be clinically significant when you consider that this discrepancy is made up of the posterior dentition alone, and the cumulative discrepancy, including the opposing side and the anterior dentition, is likely to be larger. Considering that interproximal reduction can be administered with strips as narrow as 0.1 mm, this may also be practical. It's also important to note that the present study is different from the aforementioned studies in that it is not mesiodistal tooth size alone that accounts for the detected discrepancy, but the cusp-fossa relationships as well. The higher percentage of discrepancies detected in the present study may be due to the nature of the manipulation protocol and the criteria it requires for ideal occlusion.

The Maxillary 2nd Premolar- Maxillary 1st Molar Contact is Key

The key relationship seems to be the contact between the maxillary 2nd premolar and the maxillary 1st molar. Roughly 84% of the detected discrepancies were between the 2nd premolar-1st molar contact. Approximately half of the individuals in this study had a discrepancy on the left or right side at this contact, and this discrepancy was roughly 0.5 mm on both sides. Additionally, in 34% of individuals, if there was no discrepancy at this contact, there were no discrepancies at any other contact. There are unique characteristics of the maxillary 2nd premolar that may be contributing to the presence of this discrepancy. First, the maxillary 2nd premolar has a buccal cusp tip that is often mesial to the mesiodistal center of the crown.[70] Second, the maxillary 2nd premolar has a uniquely rounded distal surface when compared to other premolars and can be more varied in appearance than other premolars.[70] These anatomical features may partially explain the frequency of discrepancies detected at this contact.

Another contributor to this discrepancy may be the methodology. For the purposes of this study, the buccal cusps had to approximate their respective embrasures to meet the requirements of the manipulation protocol. In order for the buccal cusp tip of a 2nd premolar to rest in its embrasure, it may have to be placed more distal due to the buccal cusp being mesial of center. Is this phenomenon likely to be of consequence? The Objective Grading System (OGS) established by the American Board of Orthodontics suggests that the buccal cusps of the maxillary premolars should align with (or be within 1 mm of) the embrasures or contacts between the mandibular premolars and first molar.[55] They also suggest that the mesiobuccal cusps of the maxillary molars should align with (or be within 1 mm of) the buccal grooves of the mandibular molars.[55] This leeway allows for finishing the cusp tip within 1 mm of its embrasure without consequence to the overall score. The very nature of the OGS is to evaluate the quality of treatment outcomes, which implies that this leeway may be of little consequence. Some of the discrepancies detected at this contact may have been eliminated by moving the maxillary 1st molar distally to accommodate the 2nd premolar. However, this may have removed the mesiobuccal cusp of the 1st molar from its appropriate embrasure and diminished the opportunity of the 1st molar to share appropriate occlusal contacts.

Considering Class I Correction: Look at the 2nd Premolar

In 92% of the individuals, if the Maxillary 2nd Premolar was placed appropriately according to the manipulation protocol (with or without a discrepancy between the 1st molar) , the remaining premolars and canines were able to enjoy a class I cusp-fossa relationship without any interference. In other words, 92% of individuals had no discrepancy on either side anterior to the maxillary 2nd premolar- 1st molar contact.

Angle suggested that normal occlusion occurs in the presence of an appropriate first molar relationship, so long as the teeth are aligned in a smooth, curving line of occlusion.[3] Andrews' definition of an optimal, class I molar relationship is different from Angle's. Andrews suggested that in addition to the mesiobuccal cusp of the upper first molar resting in its groove (consistent with Angle), the distal surface of the distobuccal cusp of the upper 1st permanent molar should make contact and occlude with the mesial surface of the mesiobuccal cusp of the lower second molar.[4] This is an important distinction. The present study would suggest that an individual is likely to share ideal, class I posterior relationships anterior to the maxillary 2^{nd} premolar, if its buccal cusp is in its embrasure. The distobuccal cusp of the maxillary 1^{st} molar approximating the mesiobuccal cusp of the mandibular 2^{nd} molar may help to facilitate this. This was shown by Andrews (Figure). Class I correction may be inhibited by faulty positioning of the maxillary 1^{st} molar. However, the present study would suggest that if the individual has a class I 2^{nd} premolar, it is highly likely that they should be able to have a class I canine. Of course this is in the presence of the other criteria in the manipulation protocol and does not account for the anterior teeth or factors such as available overjet, incisal edge thickness, anchorage, or patient compliance, which can all affect the ability of the clinician to achieve class I correction.

Clinical Implications

The purpose of this study is not to prod the orthodontic community and have them perform 0.1 mm of interproximal reduction to facilitate a perfect posterior occlusion. The purpose is to help clinicians to think critically and be able to identify barriers to ideal occlusion that may have been previously overlooked. Although perfection may be impossible to achieve, its pursuit is noble, and its benefits are substantial. Class I occlusion has been linked to greater areas of contact and near contact[8], which is related to enhanced masticatory performance,[12,13,14] normal chewing cycles,[61-64] greater bite forces,[65,66] and stability.[16] Greater bite forces are also related to stronger musculature,[71,72] more hypodivergent growth patterns, and greater bone quantity and quality, which could all play a role in the stability of individuals with intimate posterior cusp fossa relationships.[73,74,75]

The present study found that only 32% of individuals had no discrepancies on either side at any contact, implicating that the dentition might not fit together without any alteration of tooth size or some form of compromise in 68% of the individuals. This may pose a challenge to anyone attempting to achieve the best occlusal result possible and may have implications with do-it-yourself aligner companies that may not be capable of troubleshooting and performing appropriate interproximal reduction that may be needed for the patient. This is potentially more problematic when you consider that the present study suggests that posterior discrepancies are common, which contradicts other studies that suggest that tooth size discrepancies are more prevalent in the anterior, and relatively uncommon in the posterior dentition.[36,37,76]

The prevalence of posterior discrepancies in this study suggest that the orthodontic community may greatly benefit from the implementation of this technology when evaluating their patients. The greatest concern would be the required time and cost. However, as technology progresses, the protocol outlined in this document, or a protocol of similar nature, will likely become fully automated utilizing artificial intelligence. This may eliminate the temporal concerns, or even end up saving the orthodontic community a significant amount of time. The best time to apply these technologies may be prior the bonding appointment (with fabrication of custom indirect bonding trays) and after alignment, when most of the anteroposterior problems are corrected but lingering discrepancies in ideal occlusal relationships exist (to provide insight into which teeth may be responsible for creating a discrepancy). This may end up leading to more accurate bracket placement, shorter treatment times, higher quality occlusal finishes with greater areas of contact and near contact, and increased post-treatment settling.

Consideration for the Future

The manipulation protocol outlined in this study could be applied to any dentition. For the purposes of this study, the anterior teeth were not included. However, anyone following the manipulation protocol could use OrthoAnalyzer™ software to digitize and manipulate the anterior dentition as well. It is important to understand that these dentitions are located within the confines of the craniofacial complex, and therefore, have biological limitations to the possibilities of positioning. For example, the individuals may have a skeletal discrepancy that would prevent achieving the desired occlusion without surgery or compensations in incisor angulation.

There are a wide range of potential benefits to the utilization of 3D systems. These systems have been applied as aids in diagnosis and treatment planning, and utilized in the fabrication of lingual appliances, customized brackets and bracket prescriptions, machine-milled or 3D printed indirect bonding jigs, and robotically bent archwires.[77,78,79] But none of these applications will hold value without the ability of the clinician to know the target. More studies need to be performed to assess the accuracy of digital set-ups, and their application as a diagnostic aid. As technology evolves, so too will our understanding of occlusion. It should go without saying that the ultimate goal of the utilization of these technologies should be to improve patient outcomes, not simply make the lives of the clinician easier.

CHAPTER V

CONCLUSIONS

Discrepancies are not uncommon, with approximately 6% of posterior contacts, 29% of sides, and 44% of individuals having clinically significant discrepancies (discrepancies greater ≥0.5 mm). Only 34% of individuals had no discrepancies on either side. It is likely that the unaltered posterior dentition may not fit together into ideal cusp fossa relationships without intervention or compromise.

The maxillary 2nd premolar- maxillary 1st molar contact may be a common contributor to occlusal discrepancies. 64% of subjects had a discrepancy at this contact point on at least one side. The median discrepancies at this contact were 0.5 and 0.4 mm on the left and right sides respectively.

When troubleshooting class I correction, evaluating whether the cusp tip of the maxillary 2nd premolar is in its embrasure may provide insight to the possibility of a class I canine position. In 92% of the individuals, if the Maxillary 2nd Premolar was placed appropriately according to the manipulation protocol, the remaining premolars and canines were able to enjoy a class I cusp-fossa relationship without any interferences.

Utilization of 3D technology may help the clinician as a diagnostic aid and yield insight into potential barriers to ideal occlusal results.

REFERENCES

1. Angle EH. Treatment of malocclusion of the teeth. Angle's System. Seventh Edition, Philadelphia: SS White Dental Mfg. Co., 1907.

2. Graber TM. Orthodontics: Principles and practice. Philadelphia: W.B. Saunders Company, 1961.

3. Profit WR. Contemporary orthodontics. Second Edition, St. Louis: Mosby Year Book, 1993.

4. Andrews LF. The six keys to normal occlusion. Am J Orthod, 62 (1972), pp. 296-309.

5. Andrews LF. Straight wire concept and appliance. San Diego, California: L.A. Wells Publisher, 1989.

6. Stifter JA. A study of Pont's, Howes', Rees', Neff's and Bolton's Analyses on Class I adult dentitions. Angle Orthod 1958: 28: 215-225.

7. Lundström A. Intermaxillary tooth width ratio and tooth alignment and occlusion. Acta Odontol Scand 1954: 12:265-292.

8. Owens S, Buschang PH, Throckmorton GS, Palmer L, English J. Masticatory performance and areas of occlusal contact and near contact in subjects with normal occlusion and malocclusion. Am J Orthod Dentof Orthop. 121(6);602-609.

9. Shiere FR, Manly RS. The effect of the changing dentition on masticatory function. J Dent Res 1952; 30:526-33.

10. Omar SM, McEwen JD, Ogsion SA. A test for occlusal function. The value of a masticatory efficiency test in the assessment of occlusal function. Br J Orthod 1987; 14:85-90.

11. Luke DA, Lucas PW. Chewing efficiency in relation to occlusal and other variations in the natural human dentition. Br Dent J 1985; 159:401-5.

12. Akeel R, Nilner M, Nilner K. Masticatory efficiency in individuals with natural dentition. Swed Dent J 1992; 16:191-8.

13. Kobayashi T, Honnia K, Nakajima T, Handa K. Masticatory function in patients with mandibular prognathism before and after orthognathic surgery. J Oral Maxillofac Surg 1993; 51:997-1001.

14. Henrikson T, Ekberg E-C, Nilner M. Masticatory efficiency and ability in relation to occlusion and mandibular dysfunction in girls. Int J Prosthodont 1998; 11:125-32.

15. Lepley C, Throckmorton G, Parker S, Buschang PH. Masticatory performance and chewing cycle kinematics-are they related? Angle Orthod. 2010;80(2):295-301.

16. Harris EF, Behrents RG. The intrinsic stability of Class I molar relationship: a longitudinal study of untreated cases. Am J Orthod Dentofacial Orthop. 1988. Jul;94(1):63-7.

17. Little RM, Wallen TR, Riedel RA. Stability and relapse of mandibular anterior alignment—first premolar extraction cases treated by traditional edgewise orthodontics. Am J Orthod 1981; 80:349-65.

18. Little RM, Riedel RA, Årtun J. An evaluation of changes in mandibular anterior alignment from 10 to 20 years postretention. Am J Orthod Dentofacial Orthop 1988; 93:423-8.

19. Little RM, Riedel RA, Engst ED. Serial extraction of first premolars—postretention evaluation of stability and relapse. Angle Orthod 1990; 60:255-62.

20. Little RM, Riedel RA, Stein A. Mandibular arch length increase in the mixed dentition: postretention evaluation of stability and relapse. Am J Orthod Dentofacial Orthop 1990; 97:393-404.

21. Haruki, Little RM. Early vs late treatment in crowded extraction cases: a postretention evaluation of stability and relapse. Angle Orthod 1998; 68:61-8.

22. Kashner J. Does higher quality of treatment translate into a higher quality long term result [thesis]? Seattle: University of Washington; 1999.

23. Årtun J, Garol JD, Little RM. Long term stability of mandibular incisors following successful treatment of Class II Division 1 malocclusions. Angle Orthod 1996; 66:229-38.

24. Glenn G, Sinclair PM, Alexander RG. Nonextraction orthodontic therapy: posttreatment dental and skeletal stability. Am J Orthod Dentofacial Orthop 1987; 92:321-8.

25. Elms TN, Buschang PH, Alexander RG. Long-term stability of Class II, Division 1, nonextraction cervical face-bow therapy: I. Model analysis. Am J Orthod Dentofacial Orthop 1996; 109:271-9.

26. Jimmy C. Boley, Jeffrey A. Mark, Rohit C. L. Sachdeva, and Peter H. Buschang. Long-term stability of Class I premolar extraction treatment. Am J Orthod Dentofacial Orthop 2003; 124:277-87

27. Bolton WA. Master of Science in Dentistry in the Department of Orthodontics Thesis, School of Dentistry, University of Washington. 1952.

28. Sperry TP, Worm FW, Isaacson RJ, Spiedel TM. Tooth-size discrepancy in mandibular prognathism. Am J Orthod 1977: 72(2):183-190.

29. Harris EF, VCaden JL, Williams RA. Lower incisor space analysis: a contrast of methods. Am J Orthod Dentofac Orthop 1987: 92:375-380.

30. Moorrees CFA, Reed RB. Biometrics Of crowding and spacing of the teeth in the mandible. Am J Orthod Dentofac Orthop 1954:77-88.

31. Black. GV. Descriptive anatomy of the human teeth. Fourth Edition, Philadelphia: SS White Dental Mfg. Co., 1902.

32. Ballard ML. Asymmetry in tooth size: A factor in the etiology, diagnosis and treatment of malocclusion. Angle Orthod 1944: 1467-70.

33. Ballard ML. A fifth column within dental occlusions. Am Journal Orthod 1956: 42:116-134.

34. Neff CW. Tailored occlusion with the anterior coefficient. Am J Orthod 1949; 35:309-314.

35. Thurlow RC. Atlas of orthodontic principles. Second edition, St. Louis: C.V. Mosby, 1977

36. Freeman, JE, Maskeroni AJ, Lorton L. Frequency of Bolton tooth-size discrepancies among orthodontic patients. Am J Orthod Dentofac Orthop 1996; 110:24-27.

37. Crosby DR, Alexander CG. The occurrence of tooth size discrepancies among different malocclusion groups. Am J Orthod Dentofac Orthop 1989;95(6):457-61.

38. Manke M, Miethke RR. (Size of the anterior Bolton index and frequency of the Bolton discrepancy in the anterior tooth segment in untreated orthodontic patients) German Translation. Fortschritte der Kieferorthopädie. 1983;44(1):59-65.

39. Neff CW. Tailored occlusion with the anterior coefficient. Am J Orthod 1949; 35:309-314.

40. Bolton WA. The clinical application of tooth-size analysis. Am J Orthod 1962; 48:504-529.

41. Halazonetis DJ. The Bolton ratio studied with the use of spreadsheets. Am J Orthod Dentofac Orthop 1996; 109:215-219.

42. Steyn, CL, Harris AMP, du Preez RJ. Anterior arch circumference adjustment-how much? Angle Orthod 1996; 14:143-149.

43. Epker BN, Fish LC. Dentofacial deformities: integrated orthodontic and surgical correction. St. Louis: C.V. Mosby Company, 1986.

44. Stroud JL, English J, Buschang PH. Enamel thickness of the posterior dentition: its implications for nonextraction treatment. Angle Orthod. 1998;68(2):141-6.

45. Bonwill WGA. Geometrical and mechanical laws of articulation. Transactions of the Odontol Soc Penn 1884-1885:119-133.

46. Hawley CA. Determination of the normal arch, and its application to orthodontia. Dental Cosmos 1905; 47:541-557.

47. Izard G. New method for the determination of the normal arch by the function of the face. Int J Orthod 1927; 13:582-595.

48. White LW. Individualized ideal arches. J Clin Orthod 1978;12(11):779-787.

49. Williams PN. Determining the shape of the normal arch. Dental Cosmos 1917; 59:695-708.

50. Hellman M. Dimensions versus form in teeth and their bearing on the morphology of the dental arch. Int J Orthod and Oral Surgery 1919;615-651.

51. De La Cruz R, Sampson P, Little RM, Artun J, Odont, Shapiro PA. Long-term changes in arch form after orthodontic treatment and retention. Am J Orthod Dentof Orthop 1995; 107(5):518-530.

52. Felton JM, Sinclair PM. A computerized analysis of the shape and stability of the mandibular arch form. Am J Orthod Dentof Orthop 1987; 92:478-83.

53. Myser SA, Campbell PM, Boley J, Buschang PH. Long-term stability: postretention changes of the mandibular anterior teeth. Am J Orthod Dentof Orthop. 2013 Sep;144(3):420-9.

54. Artun J, Garol JD, Little RM. Long-term stability of mandibular incisors following successful treatment of Class II, Division 1 malocclusions. Angle Orthod 1996; 66:229-38.

55. Casko JS, Vaden JI., Kokich VG, et al. The American Board of Orthodontics Objective Grading System for Dental Casts and Panoramic Radiographs. Am J Orthod Dentof Orthop 2000; 114:589-599.

56. Fleming JW, Buschang PH, Kim KB, Oliver DR. Posttreatment Occlusal Variability Among Angle Class I Nonextraction Patients. Angle Orthod 2008;78(4): 625–630.

57. Sullivan B, Freer TJ, Vautin D, Basford KE. Occlusal contacts: Comparison of orthodontic patients, posttreatment patients, and untreated controls. J of Prosthet. 1991;65(2):232-237.

58. Djeu G, Shelton C, Maganzini A. Outcome assessment of Invisalign and traditional orthodontic treatment compared with the American Board of Orthodontics objective grading system. Am J Orthod Dentof Orthop. 2005;128(3):292-298.

59. Papadimitriou A, Mousoulea S, Gkantidis N, Kloukos D. Clinical effectiveness of Invisalign® orthodontic treatment: a systematic review. Prog Orthod. 2018 Sep 28;19(1):37.

60. Haydar B, Cier S, Saatçi P. Occlusal contact changes after the active phase of orthodontic treatment. Am J Orthod Dentof Orthop. 1992;102(1):22-28.

61. Gibbs CH, Messerman T, Reswick JB, Derda J. Functional movements of the mandible. J Prosthet Dent. 1971;26: 604–620.

62. Proschel P, Hoffmann M. Frontal chewing patterns of the incisor point and their dependence on resistance of food and type of occlusion. J Prosthet Dent. 1988; 59:617–624.

63. Buschang PH, Throckmorton GS, Austin D, Wintergerst AM. Chewing kinematics of subjects with deep bite malocclusion. Am J Orthod Dentof Orthop. 2007; 131:627–634.

64. Tome W, Yashiro K, Takada K. Orthodontic treatment of malocclusion improvesimpaired skillfulness of masticatory jaw movements. Angle Orthod. 2009; 79:1078–1083.

65. Bakke M, Holm B, Jensen BL, Michler L, Möller E. Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. Scand J Dent Res. 1990;98(2):149-58.

66. Bakke M, Michler L, Möller E. Occlusal control of mandibular elevator muscles. Scand J Dent Res. 1992 Oct;100(5):284-91.

67. Shellhart WC, Lange DW, Kluemper GT, Hicks EP, Kaplan AL. Reliability of the Bolton tooth size analysis when applied to crowded dentitions. Angle Orthod 1995;65(5):327-34.

68. Thurlow RC. Atlas of orthodontic principles. Second Edition, St. Louis: Mosby Year Book, 1993.

69. Barcoma E, Shroff B, Best AM, Shoff MC, Lindauer SJ; Interproximal reduction of teeth: Differences in perspective between orthodontists and dentists. Angle Orthod. 2015;85(5):820–825.

70. Nelson, SJ.. Wheeler's Dental Anatomy, Physiology and Occlusion. United Kingdom, Elsevier Health Sciences, 2009.

71. Sheikholeslam A, Möller E, Lous I. Pain,Tenderness And Strength Of Human Mandibular Elevators. Scand J Dent Res 1980; 88: 60-6.

72. Sheikholeslam A, Möller E, Lous I. Postural and Maximal Activity in Elevators of the Mandible Before and After Treatment of Functional Disorders. Scand J Dent Res 1982; 90:37-46

73. Raoul G, Rowlerson A, Sciote J, Codaccioni E, Stevens L, Maurage CA, et al. Masseter myosin heavy chain composition varies with mandibular asymmetry. J Craniofac Surg. 2011; 22:1093–8.

74. Eckardt L, Harzer W. Facial structure and functional findings in patients with progressive muscular dystrophy (Duchenne) Am J Orthod Dentofacial Orthop. 1996; 110:185–90.

75. Sciote JJ, Raoul G, Ferri J, Close J, Horton MJ, Rowlerson A. Masseter function and skeletal malocclusion. Rev Stomatol Chir Maxillofac Chir Orale. 2013;114(2):79-85.

76. Othman SA, Harradine NW. Tooth-size discrepancy and Bolton's ratios: a literature review. J Orthod. 2006 Mar;33(1):45-5.

77. Nguyen T, Jackson T. 3D technologies for precision in orthodontics. Semin Orthod. 2018; 24:386-392.

78. Miyazaki T, Hota Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dent Mater J. 2009; 28(1):44-56.

79. Al Mortadi N, Eggbeer D, Lewis J, Williams RJ. CAD/CAM/AM applications in the manufacture of dental appliances. Am J Orthod Dentof Orthop. 2012; 142: 727-733

80. Hack, G.D.; Patzelt, S.B.M. Evaluation of the Accuracy of Six Intraoral Scanning Devices: An in-vitro Investigation. ADA Prof. Prod. Rev. 2015; 10: 1–5.

81. Zimmermann, M.; Ender, A.; Mehl, A. Local accuracy of actual intraoral scanning systems for single-tooth preparations in vitro. J. Am. Dent. Assoc. 2019; 151: 127–135.

82. Boeddinghaus M., Breloer ES, Rehmann P, Wöstmann B. Accuracy of single-tooth restorations based on intraoral digital and conventional impressions in patients. Clin. Oral Investig. 2015; 19: 2027–2034.

APPENDIX A

FIGURES

Figure 1. Summary of Materials and Methods.

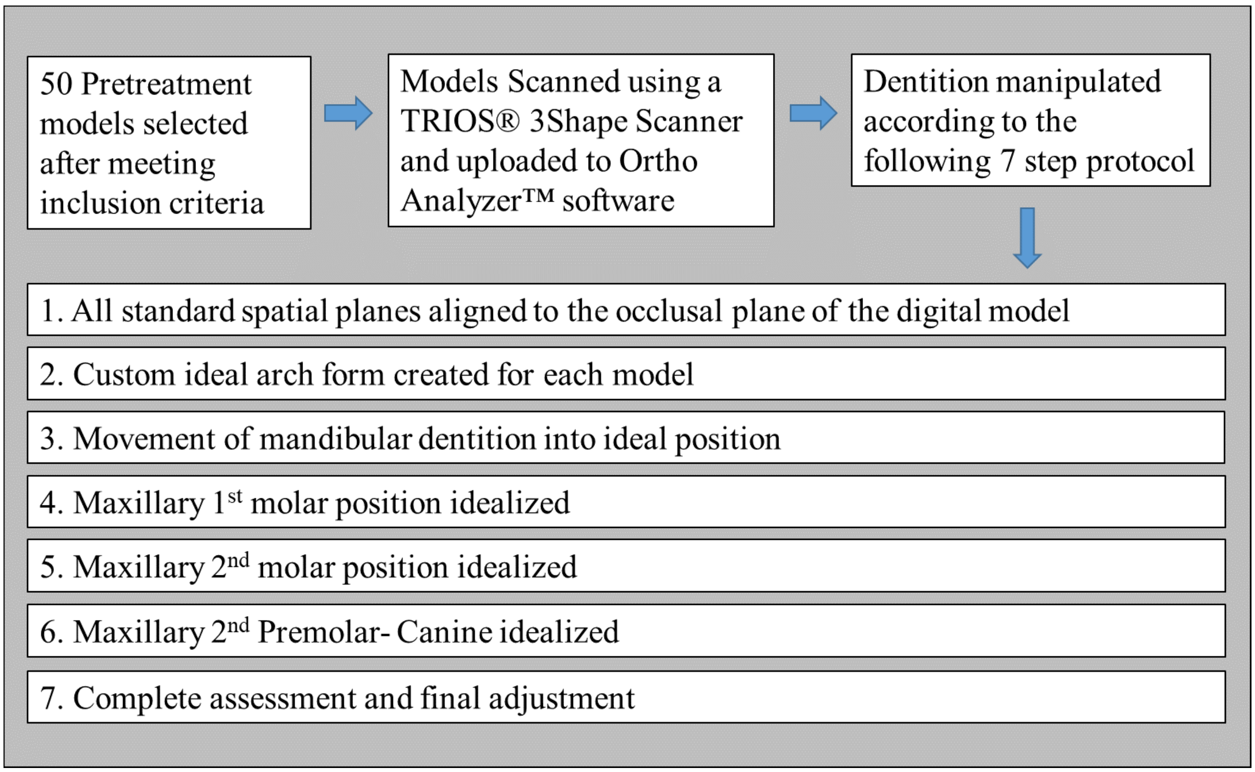


Figure 2. Manipulation protocol: Step one- All standard planes were aligned to the occlusal plane of the digital models.

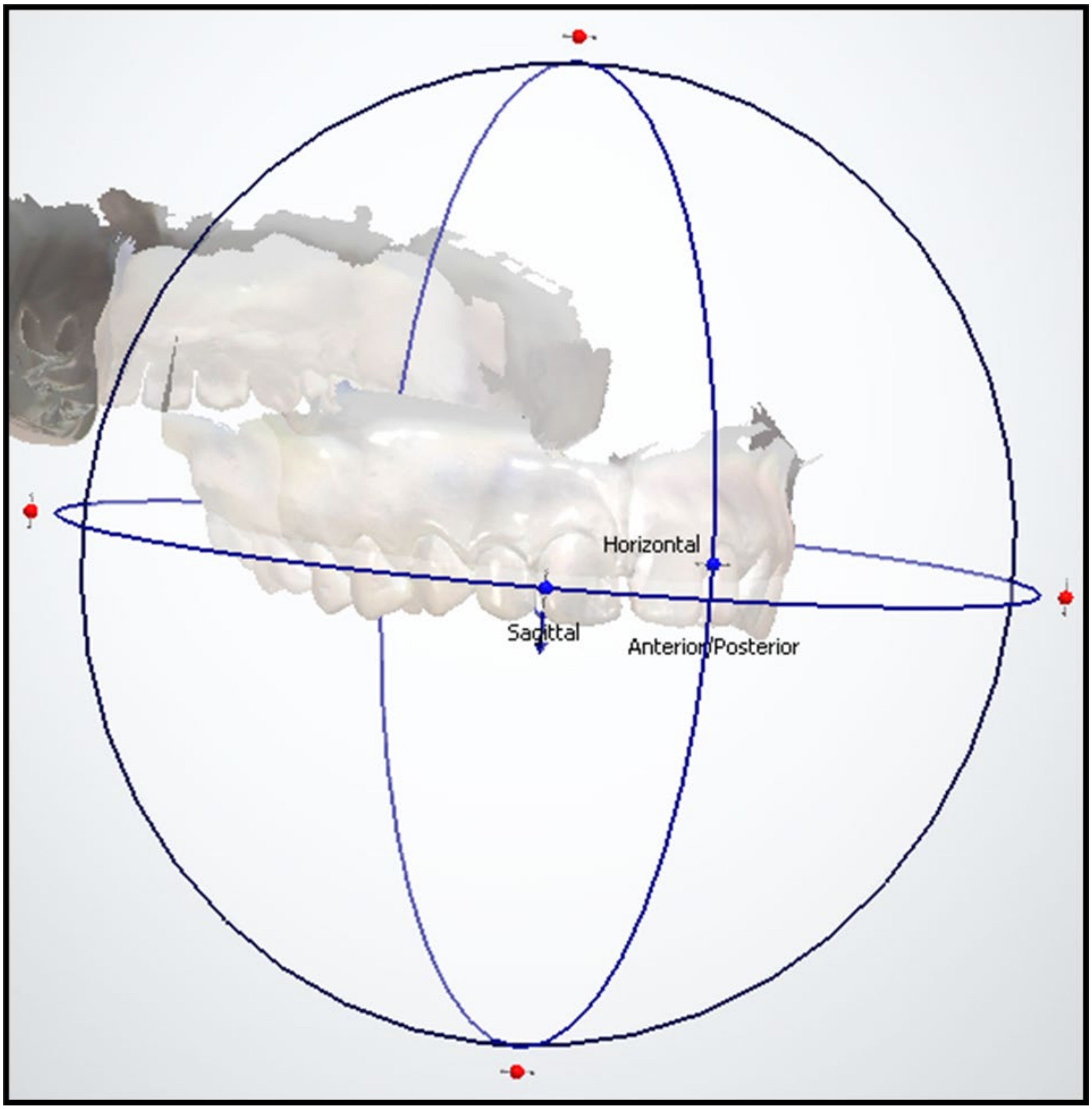


Figure 3. Manipulation protocol: Step two- Custom mandibular arch form (A) created for every digital model. Arch form was parabolic in nature and based on the original mandibular inter-canine width. The maxillary arch (B) was copied directly from the mandibular arch form.

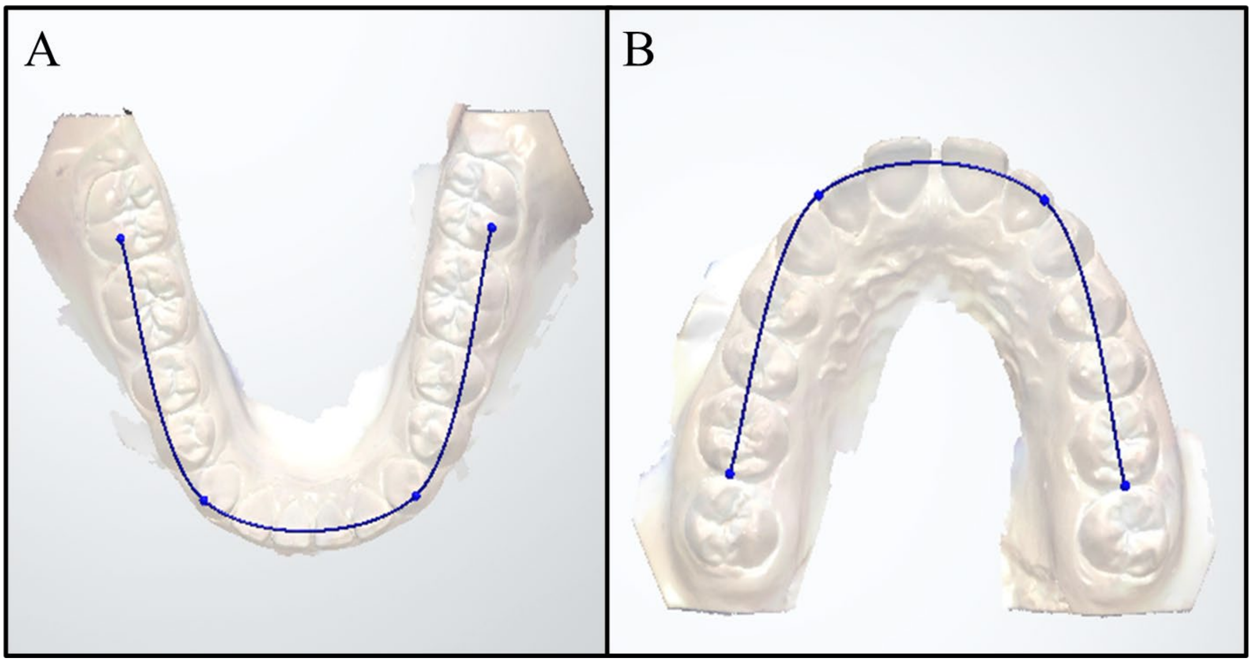


Figure 4. Manipulation protocol: Step three- Idealization of the mandibular dentition. Achieved by: Levelling the curves of Wilson and Spee until they are mild to none (A,C), Removing rotations (B), and achieving ideal interdental and inter-occlusal contacts (0<Contact≤0.05)(A,B).

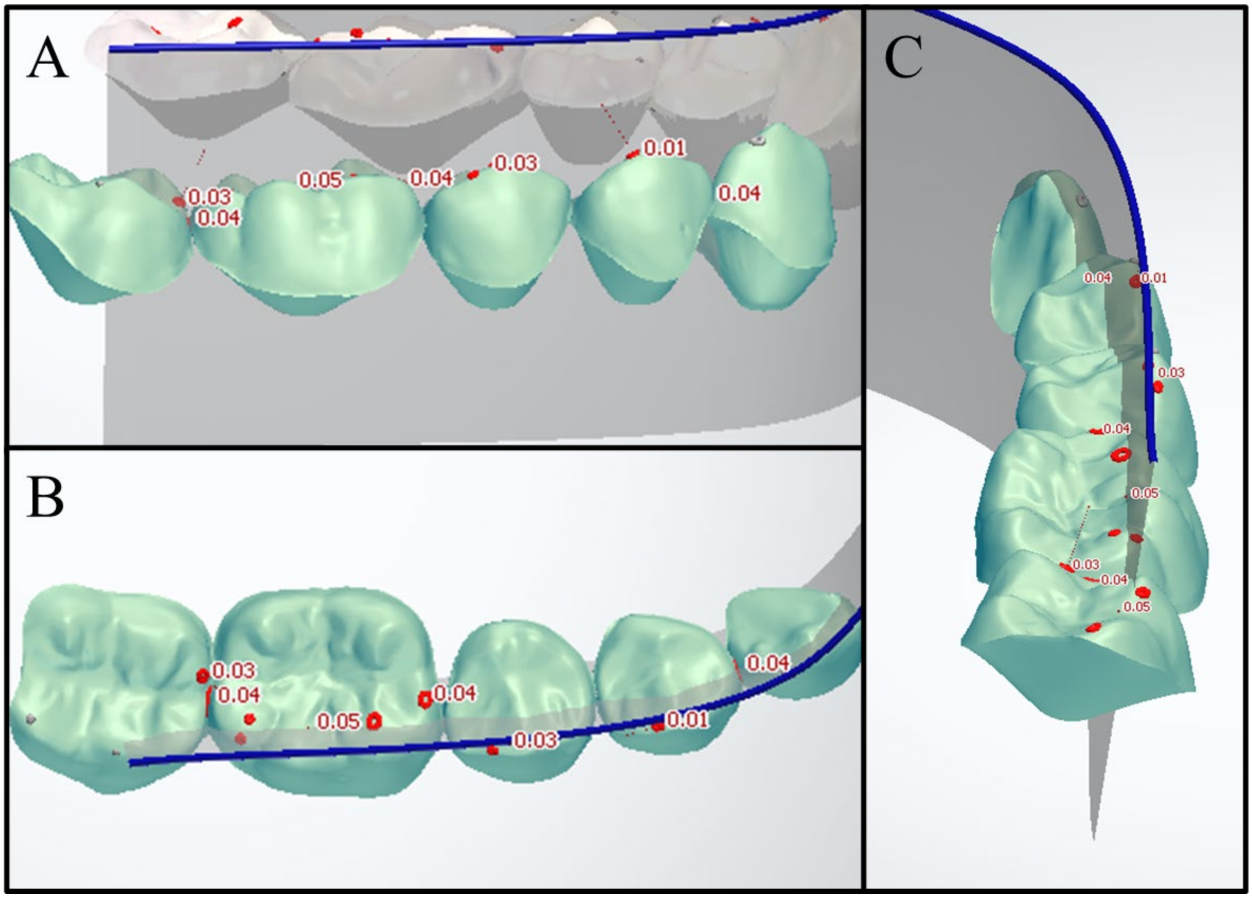


Figure 5. Manipulation protocol: Steps four and five- Maxillary 1st and 2nd molar idealized. The mesiobuccal cusp of the maxillary 1st molar was made to rest in the groove between the mandibular mesial and middle cusps (A). The 1st molar had to have at least four ideal occlusal contacts shared between the mandibular 1st and 2nd molar (B). The maxillary 2nd molar mesiobuccal cusp had to rest between the mesial and distobuccal cusps of the lower 2nd molar (C) and share at least two ideal occlusal contacts (D).

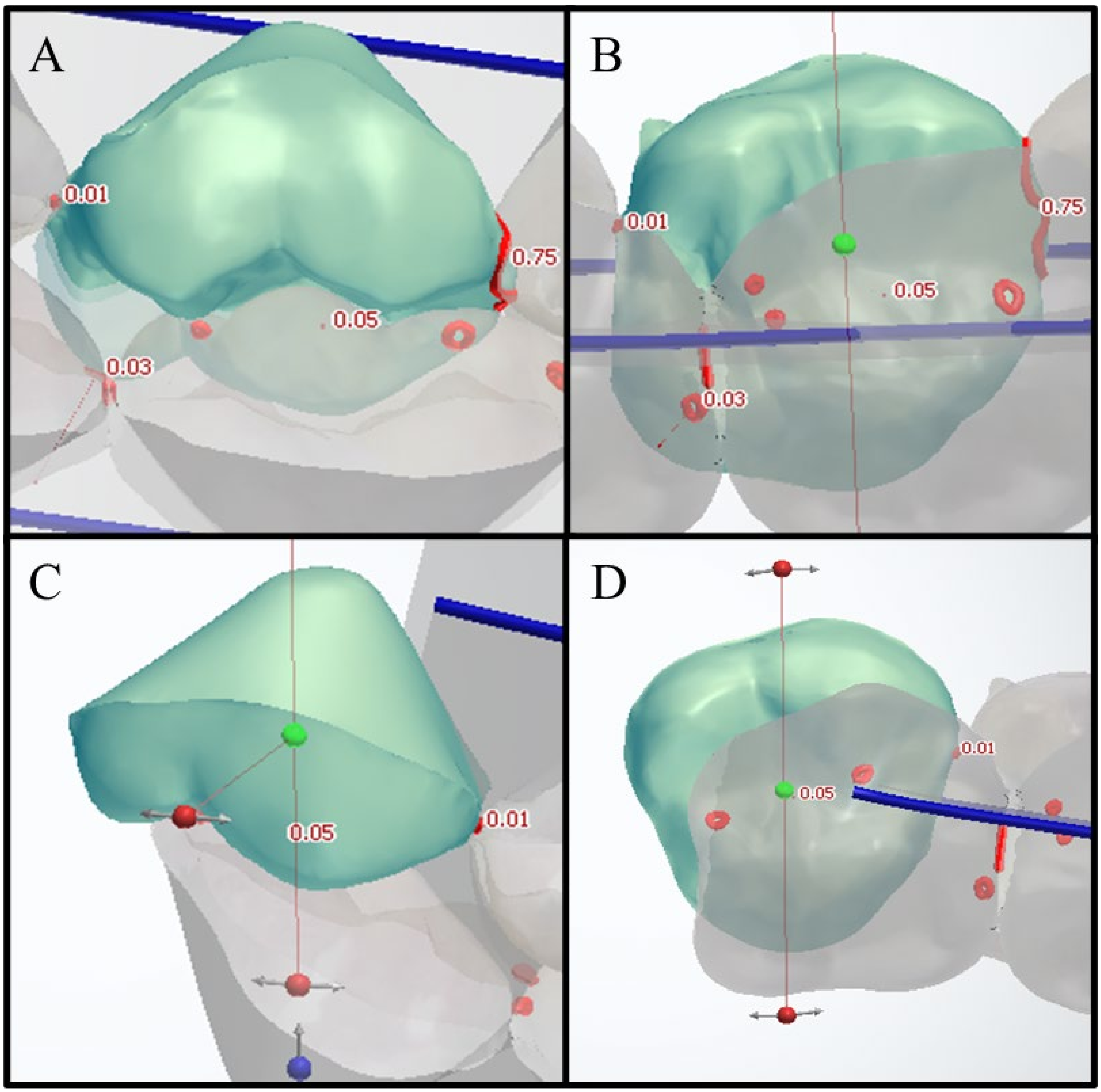


Figure 6. Manipulation protocol: Step six- The maxillary 2nd premolar through the canine were then to meet the following criteria: their buccal cusp tips rest in their opposing embrasure (A), they share at least two ideal contacts with their opposers and have no rotations (B).

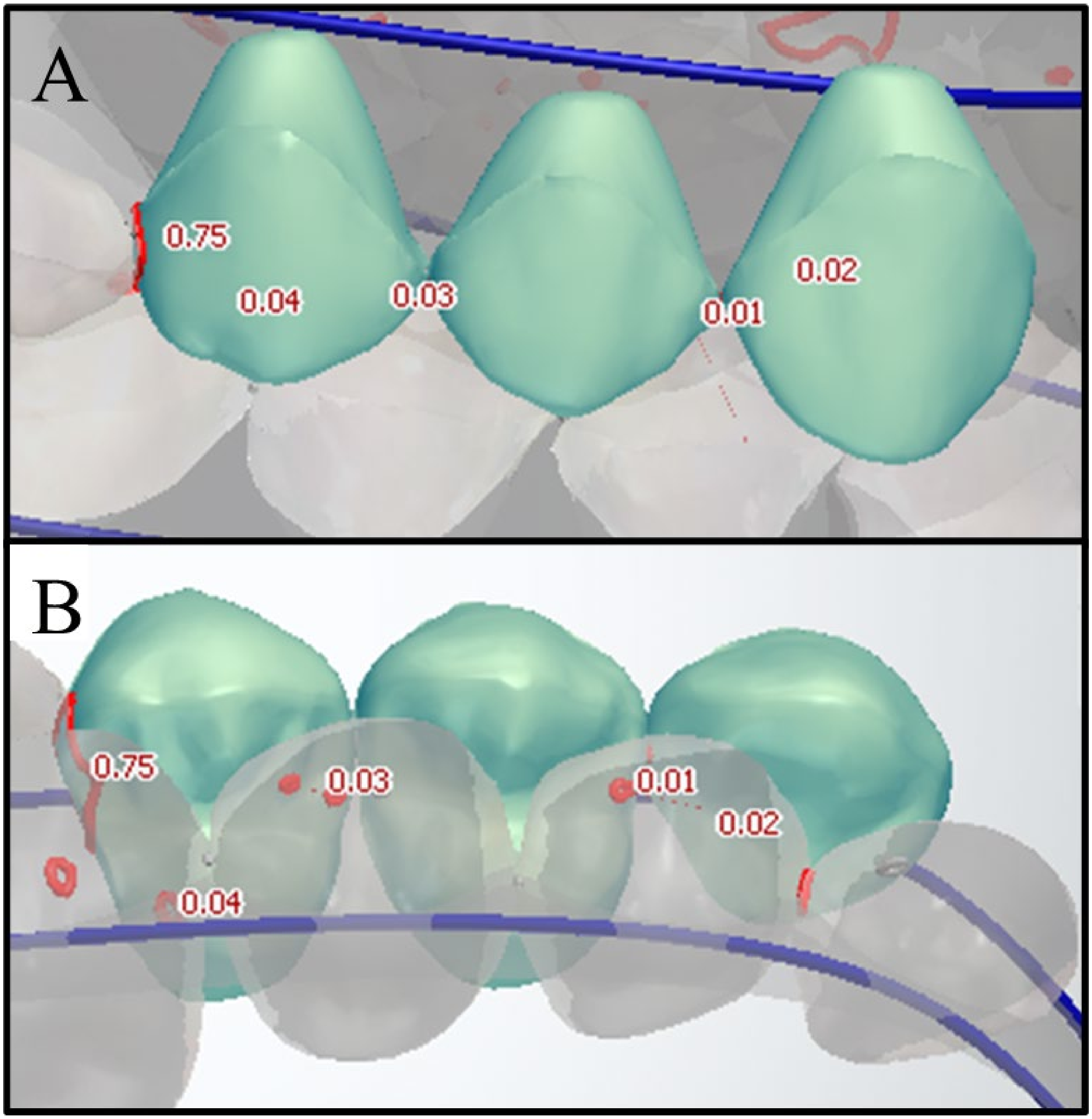


Figure 7. Manipulation protocol: Step seven- Final Inspection. The entire posterior segment on each side is inspected to determine that the criteria listed in the previous figures were met (A,B). Any overlap of greater than 0.05mm or spacing, was recorded as a discrepancy. A discrepancy can be seen here between the 1st molar and 2nd premolar contact (C).

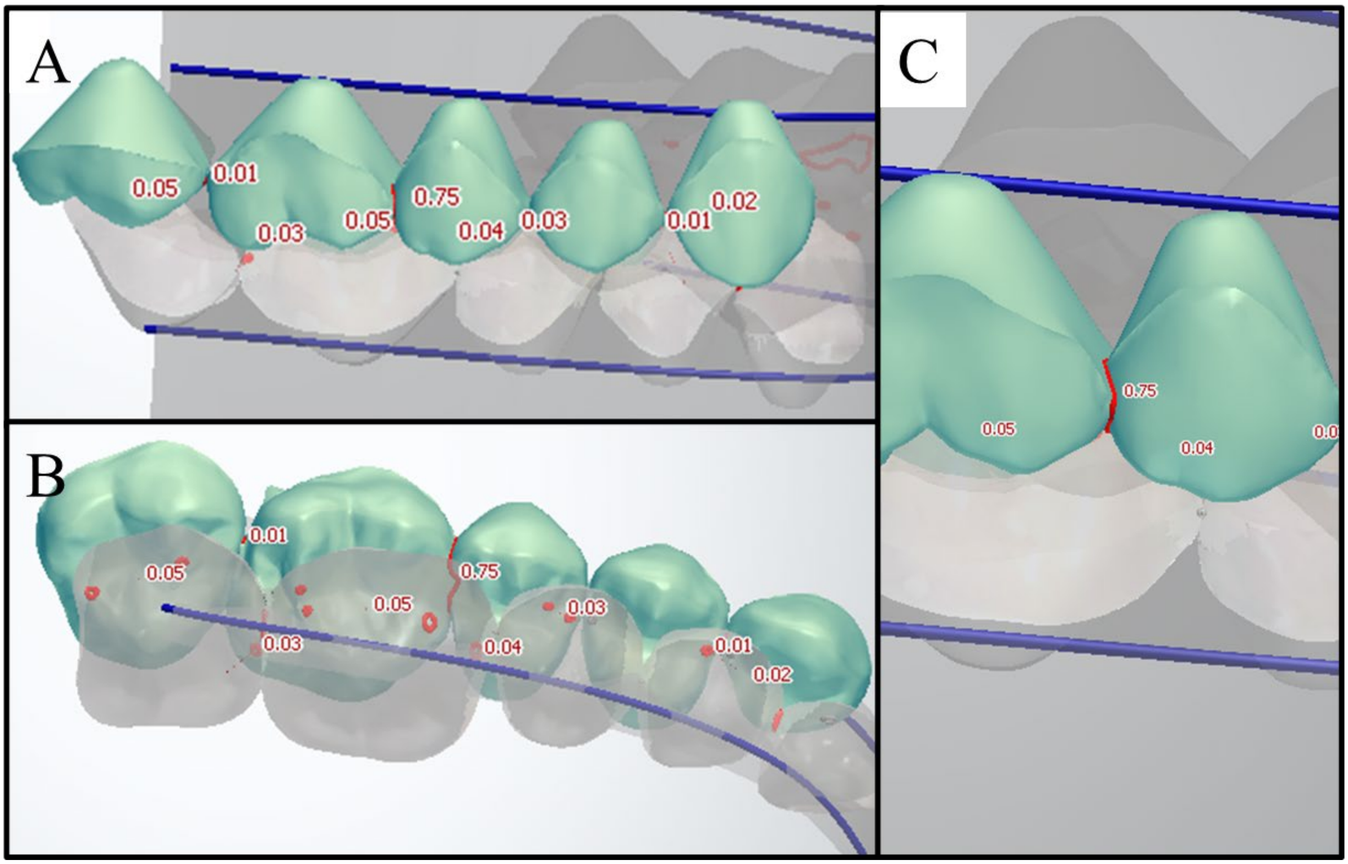


Figure 8. The number of discrepancies at each contact point- Any contact not shown had no discrepancies. The maxillary 2nd premolar- 1st molar contact had the greatest number of discrepancies.

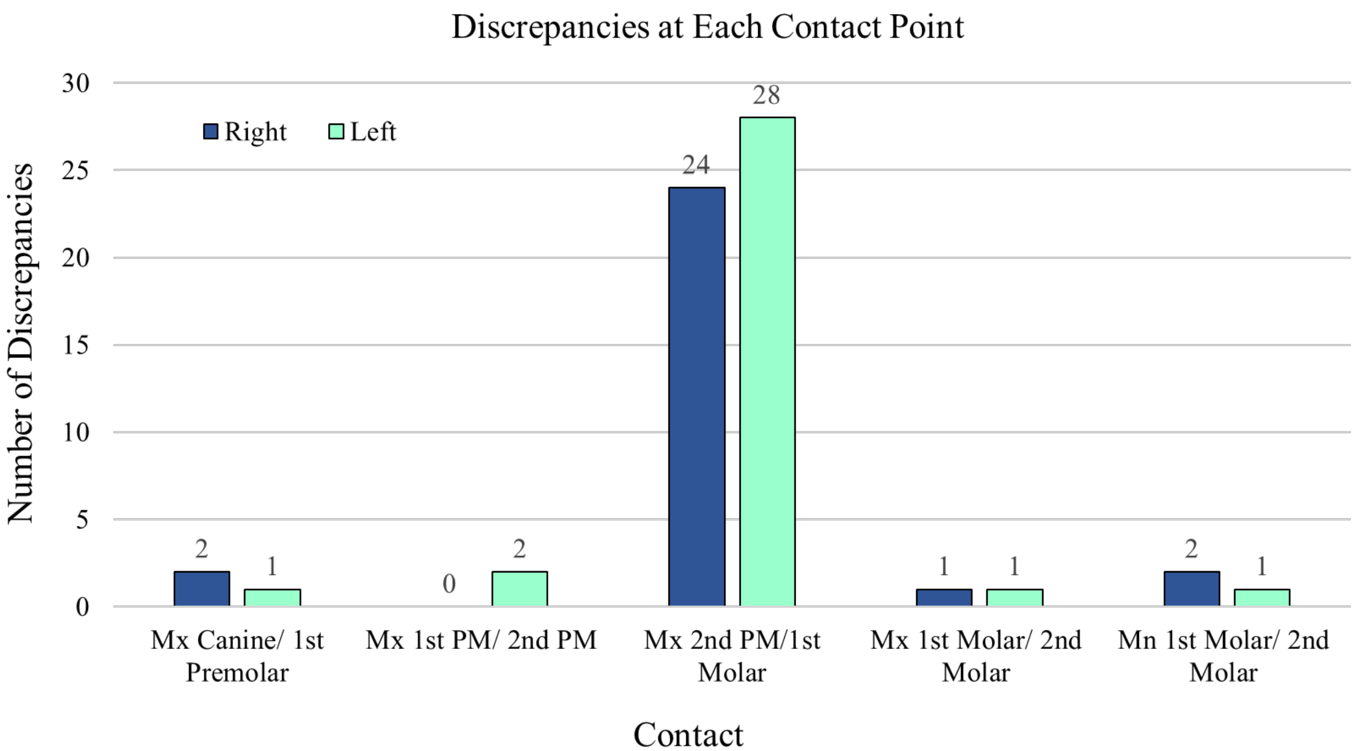


Figure 9. Discrepancy Contribution- Of the 62 contact discrepancies detected, 84% of these discrepancies were due to a discrepancy between a maxillary 2nd premolar and 1st molar. 8% were due to a discrepancy between molars. 5% were due to a discrepancy between 1st and 2nd premolars. 3% were due to a discrepancy between the canine and 1st premolar.

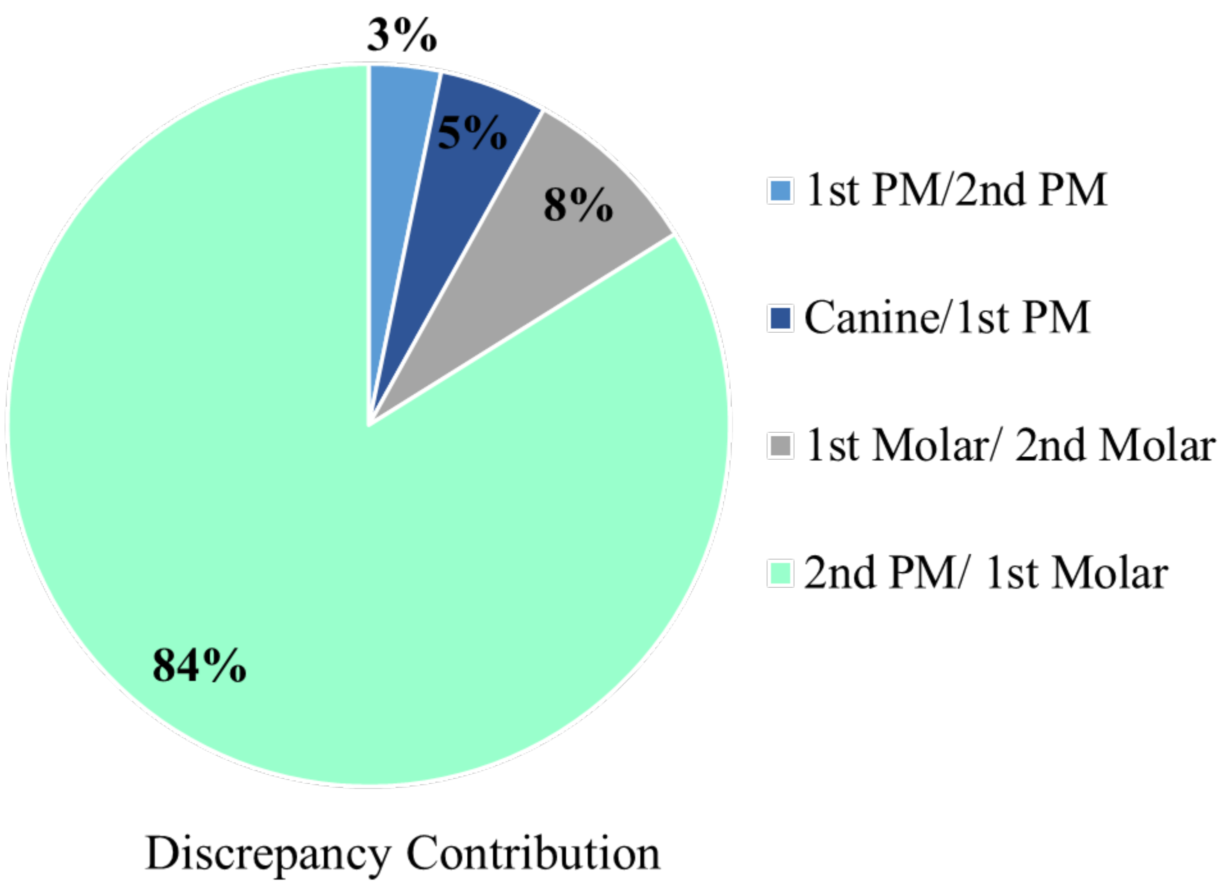


Figure 10. Discrepancies at the 2nd premolar- 1st molar contact.

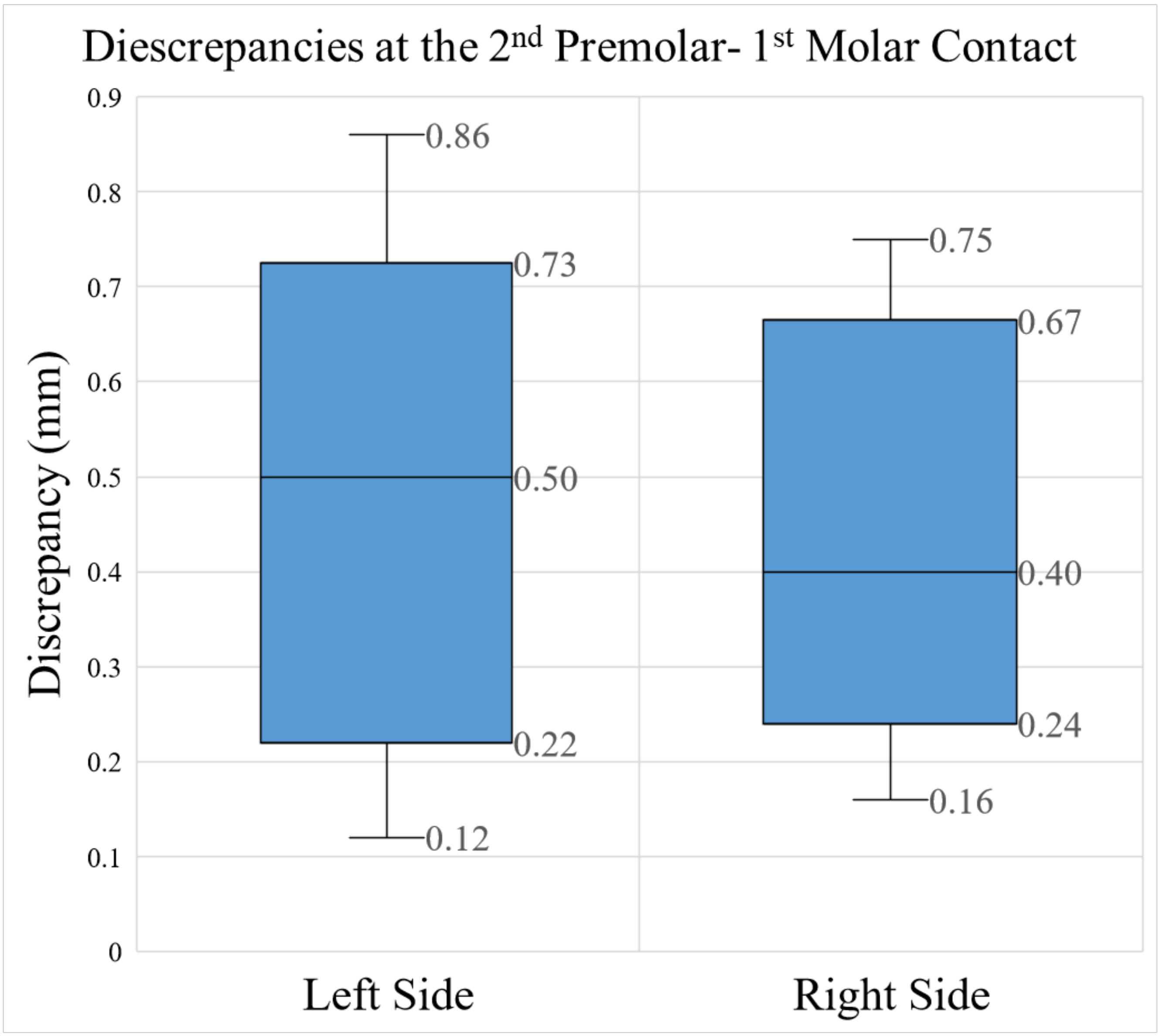


Figure 11. Total discrepancies: Discrepancies only- The sum of the absolute value of all discrepancies on a side. Only individuals that had a total discrepancy were included in this distribution.

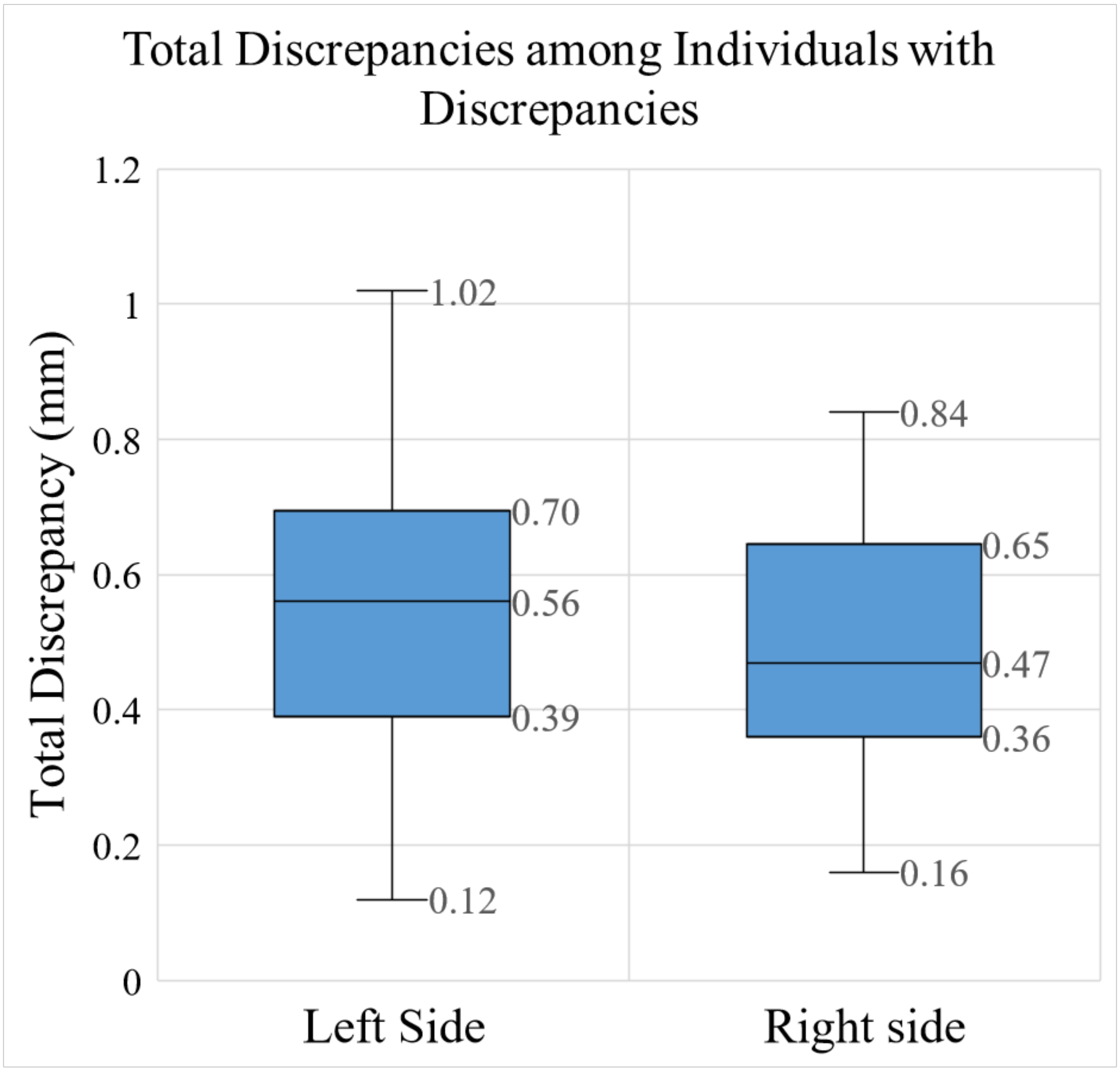


Figure 12. Percentages of sides with various total discrepancies- The percentage of sides evaluated with no total discrepancy (46%), a total discrepancy of <0.5mm (25%), ≥0.5mm but <0.75mm (19%), ≥0.75mm but <1mm (6%), and ≥1mm (4%). 29% of the sides evaluated had total discrepancies ≥0.5mm.

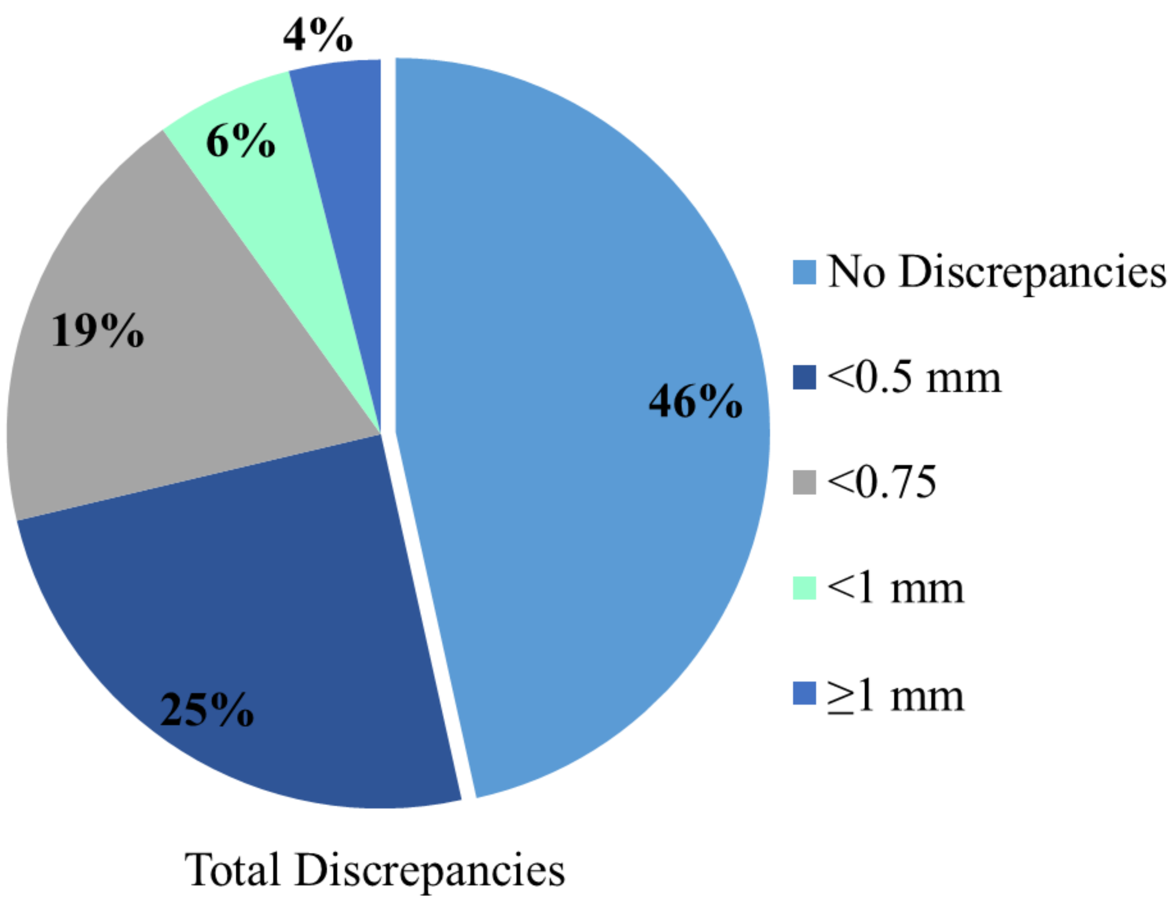
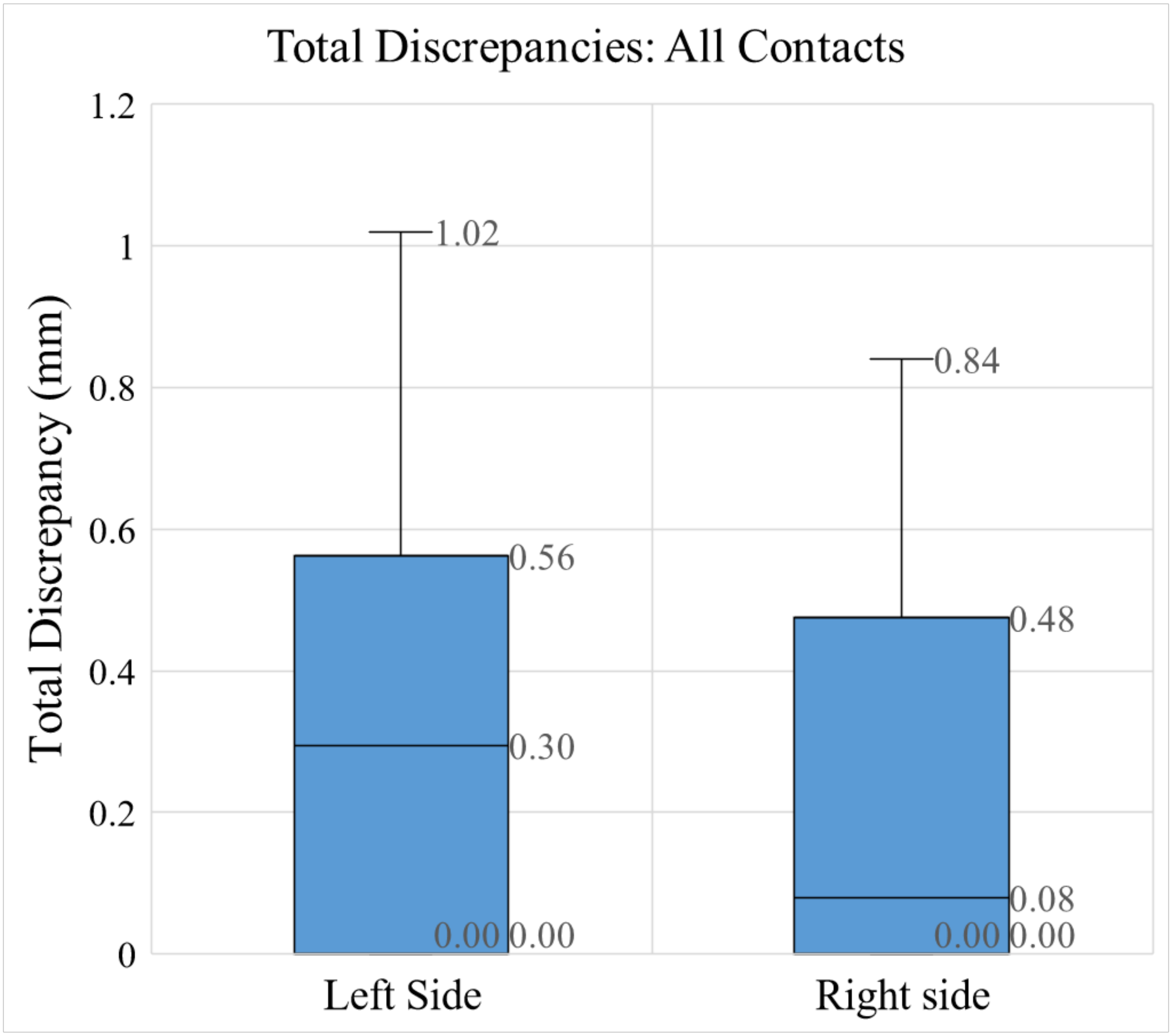


Figure 13. Total Discrepancies: All Contacts- The median and interquartile ranges for the total discrepancies on each side (the sum of the absolute value of all contacts). This includes contacts that had no discrepancy.



APPENDIX B

TABLES

Table 1. Discrepancies at Each Contact Point- (median and interquartile ranges of discrepancies) detected at each contact (mm).

Discrepancies at Each Contact	Left					Right					Difference
	Min	25	50	75	Max	Min	25	50	75	Max	Prob.
Canine-1st PM	0	0	0	0	0.36	0	0	0	0	0.5	0.18
1st PM- 2nd PM	0	0	0	0	0.33	0	0	0	0	0	0.18
2nd PM- 1st Molar	0	0	0	0	0.86	0	0	0	0.4	0.75	0.15
1st Molar- 2nd Molar	-1.29	0	0	0	1.02	-1.01	0	0	0	0.38	0.26
Total Discrepancy	0	0	0.30	0.56	1.78	0	0	0.08	0.48	1.28	0.09

This table includes all contacts, including those without a discrepancy. 50 individuals had both sides manipulated into cusp fossa relationships, representing 50 left, and 50 right sides.