

**Accuracy of Bolton Anterior and Overall Ratios on ClinCheck® Software in
the Crowded Dentition**

By

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A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial
fulfillment of the requirements for the degree of

MASTER OF DENTISTRY

(Orthodontics)

Division of Orthodontics

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Abstract

Introduction:

The purpose of this study is to investigate the reliability of ClinCheck® Software on predicted mesiodistal tooth widths, assess the accuracy of Bolton ratios at 2 time points and whether crowding has any influence on Bolton ratios.

Methods:

Overall and anterior Bolton ratios were calculated for 29 patients with 5 to 8mm of crowding and undergone Invisalign treatment at a private orthodontic clinic in Canada. To evaluate the Bolton ratios, the mesiodistal widths were manually measured using an electronic caliper on 3D printed casts pre-treatment (T1) and at the last refinement scan (T2) as well as via ClinCheck® Software.

Results:

There are statistically significant differences in Bolton ratios between manual measurements and ClinCheck® Software for T1 overall ratio ($p < .001$), T2 anterior ratio ($p < .001$) and T2 overall ratio ($p = .016$, 1% of difference). Manual measurements indicate that crowding does not affect Bolton anterior ($p = .172$) and overall ratios ($p = .938$), however ClinCheck® measurements indicate that there are statistically significant differences in the anterior ($p = .05$) and overall ($p < .001$) Bolton ratios when crowding is involved ($\pm 1\%$). Tooth width measurements assessed by ClinCheck® Software tends to provide larger tooth widths compared with manual measurements.

Although the overall reliability of tooth width measurements delivered by the ClinCheck® Software was excellent (ICC 0.994) the reliability of the Bolton ratios is uncertain with wide confidence intervals (0.267 – 0.949).

Conclusions:

Tooth width measurements assessed by the ClinCheck® Software are accurate and clinically acceptable when measuring individual teeth, except for first molars in both arches. ClinCheck® Software shows questionable reliability when Bolton ratios are estimated. Crowding does not influence Bolton ratios when calipers are used whereas ClinCheck® indicates there are statistically significant but in all probability not clinically relevant differences in ratios when crowding is present.

Acknowledgements

I would like to express my deepest appreciation to my committee: Dr. William Wiltshire, Dr. Milos Lekic and Dr. Sylvia Todescan. Thank you for your all your guidance and support throughout this project. It was such a privilege working with you and I am forever grateful for your time and mentorship.

To my wonderful parents and my brother – thank you for your unconditional love.

I would like to thank my husband, Tim. Thank you for your love, strength, support and always encouraging me to chase my dreams. I am so lucky to have you in my life and I could not have done it without you.

Thank you to my co-residents for these unforgettable memories that I will cherish for a lifetime. It has been a pleasure sharing this experience with you all.

Special thanks to Sandra Munoz-Costa and Egon Munoz for their help with the 3D printing of the dental models.

I would like to acknowledge Loring Chuchmach for his wonderful help with the statistical analysis of the data.

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1. Introduction

Meticulous treatment planning in orthodontics is crucial to ensure a beautiful and successful end result. In order to achieve good interdigitation with optimal esthetics and occlusion an orthodontist must be able to recognize tooth size discrepancies within the maxillary and mandibular arch and plan accordingly. To address inter-arch tooth size discrepancies a few methods have been proposed: interproximal reduction, finishing with open spaces in the anterior region for composite build ups and accepting a non-class I buccal segment finish (Proffit *et al.*, 2019). The use of tooth width measurements and a Bolton analysis can be used to detect tooth-size discrepancies (Crosby & Charles, 1989).

The Bolton analysis was established by Wayne Bolton in 1958. He studied 55 cases of “excellent occlusion” to investigate the relationship between the mesiodistal widths of maxillary and mandibular teeth in an ideal occlusion (Bolton, 1958; Bolton 1962). Bolton established a ratio by measuring the mesiodistal widths from the canine to canine of the maxillary and mandibular anterior teeth and termed it the “anterior ratio” and calculated this value to be 77.2% (+/- 1.65).

Sum mandibular 3-3 X 100 = Anterior ratio

Sum maxillary 3-3

The term “overall ratio” is the ratio from measuring the mesiodistal widths from the first molar to the first molar of the mandibular teeth and maxillary teeth and the ratio was determined to be 91.3 (+/- 1.91).

Sum mandibular 6-6 X 100 = Overall ratio

Sum maxillary 6-6

Bolton anterior and overall ratios has become the standard in evaluating inter-arch tooth size discrepancies.

Traditionally, tooth width measurements are obtained from using plaster study casts and calipers. With advances in digital dentistry, there is a recent trend toward using digital study models as opposed to using traditional plaster study models to obtain tooth measurements. With recent technological advances, 3D printing technology has allowed for a more digital workflow in dentistry and has reduced the need of the traditional way of obtaining study models. The main advantages of obtaining 3D models compared with conventional plaster models are its benefits in efficiency, ease of use, longevity (no risk of physical damage) and storage space such that it doesn't require physical space (Hazeveld et al, 2014). Digital model systems have been found to be just as reliable with high accuracy and reproducibility as compared with conventional plaster models (Rossini *et al.*, 2016). In recent years there have been many digital model software programs with applications that can measure tooth widths and Bolton ratios to aid in orthodontic treatment planning. However, it is still important to validate the accuracy and reliability of the tooth widths as estimated by these software programs.

With the rising popularity of Invisalign® in recent years, Align Technology is considered the leading manufacturer of clear aligners. Invisalign is accompanied by ClinCheck® Pro software which provides estimations of the mesiodistal widths and Bolton ratios in millimeters to 2

decimal places of all permanent teeth except the second and third molars. The accuracy of these estimations has not been confirmed (Shailendran *et al.*, 2022).

When crowding is present the ideal interproximal contact points may sometimes be estimated and this estimation can introduce variations in the measurements of the teeth (Shellhart *et al.*, 1995). In a study, it was observed that Bolton anterior ratio was significantly higher when lower incisal crowding is present compared to the group with good alignment (Nordeval *et al.*, 1975). Therefore, the analysis in tooth-size discrepancy in crowded cases may have more limited reliability.

Factors that may significantly impact accuracy measurements when using calipers to measure tooth widths on physical models are inadequate access in a crowded dentition, challenges in identifying mesial and distal landmarks due to unusual interproximal tooth anatomy, and inconsistencies in applying the measurement protocol (Hunter 1960, Shellhart, 1995).

This research will assess the reliability of the mesiodistal tooth widths predicted by ClinCheck[®] software compared to those measured using digital calipers, investigate the accuracy of ClinCheck[®] Software on Bolton ratios and whether crowding has any influence on overall and anterior Bolton ratios.

2. LITERATURE REVIEW

2.1 History of studies regarding tooth size discrepancy

Tooth size discrepancy is defined as a disproportion among the sizes of individual teeth (Proffit, 2019). In order to achieve ideal interdigitation of teeth, the upper and lower teeth must be proportional in size. The topic of tooth size was pioneered by G.V Black who first formally investigated the mesio-distal widths of human teeth and published tables of mean values (Black, 1906). The mean dimensions found in Black's study are still important references used (Bolton, 1958).

In 1923, Young examined the combined mesiodistal width of the incisors, canines and premolars of the maxillary and mandibular arch in two orthodontic patients. It was found that the difference in tooth widths may have affected the overbite such that the overbite is shallow when the mandibular teeth are larger relative to the maxillary teeth and the overbite is deeper when the mandibular teeth are smaller relative to the maxillary teeth (Young, 1923).

Tooth size discrepancy being an etiological factor was not given much consideration until Ballard compared discrepancies between teeth of opposite sides of the dental arch. He discovered that 90% of the 500 cases in his study showed at least 0.25mm of left-right discrepancy in one or more pairs of teeth with more than 80% having discrepancies of 0.5mm or greater. To resolve the discrepancy Ballard suggested interproximal reduction of teeth to balance out the asymmetries (Ballard, 1944).

In 1949, Neff measured the mesiodistal widths of the maxillary and mandibular anterior teeth in 200 subjects. He developed the ratio termed “the anterior coefficient” and this is calculated by dividing the sum of the widths of the mandibular anterior teeth into the sum of the maxillary anterior teeth. The range was 1.17 to 1.41. He suggested that the “ideal anterior coefficient” ranged between 1.20 – 1.22 which would produce a 20 percent overbite. A higher anterior coefficient will produce a deeper overbite (Neff, 1949).

Steadman looked at formulating a method to determine overbite and overjet relationship to the size difference between upper and lower anterior teeth. He proposed that the interincisal angulation and the canine relationship are two additional factors that will influence the overjet and overbite relationship (Steadman, 1949).

Wheeler, one of the main investigators of dental anatomy published a textbook of dental anatomy and physiology which was viewed as ideal dimensions of teeth that could be used for carving teeth and creating an ideal occlusal setup (Wheeler, 1940).

2.2 Bolton’s Study on Anterior and Overall ratios

The Bolton analysis was established by Wayne Bolton in 1958. Bolton evaluated 55 cases of “excellent occlusion” to investigate the relationship between the mesiodistal widths of maxillary and mandibular teeth in an ideal occlusion. Most of these cases were treated orthodontically with no extractions. Of the 55 cases, 44 cases were orthodontically treated and 11 were untreated. The cases selected were from the orthodontic department of the University of Washington and from

ten different private practices. A three-inch needle-pointed dividers were used to measure the mesiodistal diameter of all teeth except for the second and third molars.

To calculate the “anterior ratio” the sum of the mesiodistal width of the mandibular canine to contralateral canine was divided by the sum of the mesiodistal width of the maxillary canine to contralateral canine. To calculate the “overall ratio” the sum of the mesiodistal width of mandibular first molar to contralateral first molar was divided by the sum of the mesiodistal width of the maxillary first molar to contralateral first molar. Bolton discovered the anterior and overall ratios were consistent across his study sample. His findings for the anterior ratio were 77.2%, with a standard deviation of 1.65 and a coefficient of variation of 2.14%. As for the overall ratio, his findings were 91.3%, standard deviation of 1.91 with a coefficient of variation of 2.09%. He found the simplicity of the analysis was so quickly and easily carried out that it could be used as a diagnostic tool in predicting the outcome of orthodontic cases. An anterior ratio greater than one standard deviation (1.65) from the average of 77.2% would indicate excess mandibular tooth mass in the anterior region whereas, an anterior ratio less than one standard deviation from the average would indicate excess maxillary anterior tooth mass. Both outcomes would affect proper incisal coupling if the buccal segments were placed in a class I molar relationship. An overall ratio greater or less than one standard deviation (1.91) from the average of 91.3% would indicate non-ideal posterior interdigitation and overbite-overjet relationship without interproximal reduction, extractions or build-ups.

Another conclusion Bolton found were the results of the tooth size data published by Black and Ballard were closely related to the results he found. Additionally, he used the mesiodistal widths

from Wheeler's textbook of dental anatomy which were viewed as ideal tooth dimensions and calculated the anterior and overall ratio to be 77.8 and 91.4, respectively. These values were closely related to the results found in his own study. Bolton emphasized the importance of considering premolar sizes on an individual basis prior to making the final decision on extraction cases. Lastly, the degree of overbite in his study of 55 excellent occlusion had a wide range of variability ranging from 11.8% to 53.9%. He was unable to find a statistically significant coefficient of correlation between overbite and the "anterior coefficient" when comparing to Neff's study on the effect of tooth size on overbite (Bolton, 1958).

In 1962, Bolton published a follow up article on the clinical application of tooth size analysis. The article focused on the use of anterior and overall ratios in predicting various extraction patterns. Bolton applied the ratios using hypothetical examples and assessed different combinations of extraction patterns to produce the best results. The combinations used included four premolars, impacted canines, mandibular premolars, one mandibular incisor, peg laterals or combination of premolars and lateral incisors. Bolton also discovered extreme labial inclination of incisors and incisors with thick labiolingual thickness are clinical features that may disrupt the anterior ratio. Bolton concluded calculating the anterior and overall ratios is quick and simple and can be used as a diagnostic tool and can eliminate the need for a diagnostic setup (Bolton, 1962).

Figure 2.2: An Analysis Sheet for Calculating Overall and Anterior Bolton Ratio

Analysis of Tooth Size Discrepancies

OVERALL RATIO

$$\frac{\text{Sum mandibular "12" mm.}}{\text{Sum maxillary "12" mm.}} = \frac{\quad}{\quad} \times 100 = \frac{\quad}{\quad} \% \quad \text{Overall ratio}$$

Mean 91.3 = 0.26
S.D. (n) 1.91
Range 87.5 - 94.8

Max. "12"	Mand. "12"	Max. "12"	Mand. "12"	Max. "12"	Mand. "12"
86	77.6	94	85.8	103	94.0
86	78.6	95	86.7	104	95.0
87	79.4	96	87.6	105	95.9
88	80.3	97	88.6	106	96.8
89	81.3	98	89.5	107	97.8
90	82.1	99	90.4	108	98.6
91	83.1	100	91.3	109	99.5
92	84.0	101	92.2	110	100.4
93	84.9	102	93.1		

PATIENT ANALYSIS

If the overall ratio exceeds 91.3 the discrepancy is in excessive mandibular arch length. In above chart locate the patient's maxillary "12" measurement and opposite it is the correct mandibular measurement. The difference between the actual and correct mandibular measurement is the amount of excessive mandibular arch length.

If overall ratio is less than 91.3:

$$\frac{\text{actual mand. "12"}}{\text{actual max. "12"}} - \frac{\text{correct mand. "12"}}{\text{correct max. "12"}} = \frac{\text{excess mand. "12"}}{\text{excess max. "12"}}$$

ANTERIOR RATIO

$$\frac{\text{Sum mandibular "6" mm.}}{\text{Sum maxillary "6" mm.}} = \frac{\quad}{\quad} \times 100 = \frac{\quad}{\quad} \% \quad \text{Anterior ratio}$$

Mean 77.2 = 0.22
S.D. (n) 1.66
Range 74.5 - 80.4

Max. "6"	Mand. "6"	Max. "6"	Mand. "6"	Max. "6"	Mand. "6"
40.0	30.9	45.5	35.1	50.5	39.0
40.5	31.3	46.0	35.5	51.0	39.4
41.0	31.7	46.5	35.9	51.5	39.8
41.5	32.0	47.0	36.3	52.0	40.1
42.0	32.4	47.5	36.7	52.5	40.5
42.5	32.8	48.0	37.1	53.0	40.9
43.0	33.2	48.5	37.4	53.5	41.3
43.5	33.6	49.0	37.8	54.0	41.7
44.0	34.0	49.5	38.2	54.5	42.1
44.5	34.4	50.0	38.6	55.0	42.5
45.0	34.7				

PATIENT ANALYSIS

If anterior ratio exceeds 77.2:

$$\frac{\text{actual mand. "6"}}{\text{actual max. "6"}} - \frac{\text{correct mand. "6"}}{\text{correct max. "6"}} = \frac{\text{excess mand. "6"}}{\text{excess max. "6"}}$$

(Bolton, 1958)

2.3 Andrew's Six Keys – Defining a Normal Occlusion

Andrews defined the “six keys to normal occlusion” are:

1. Molar relationship. The distal surface of the distobuccal cusp of the upper first permanent molar occludes with the mesial surface of the mesiobuccal cusp of the lower second molar. The upper first molar's mesiodistal cusp should occlude in the groove between the middle and mesial cusps of the lower first molar.

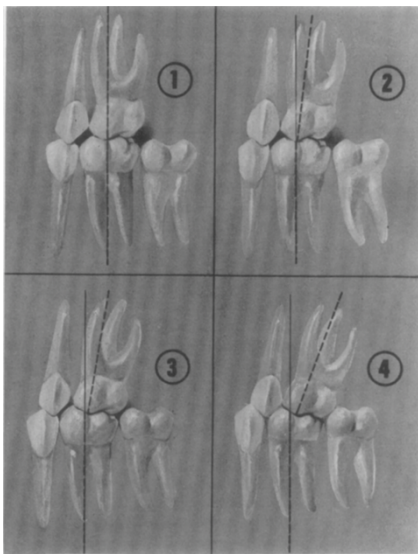


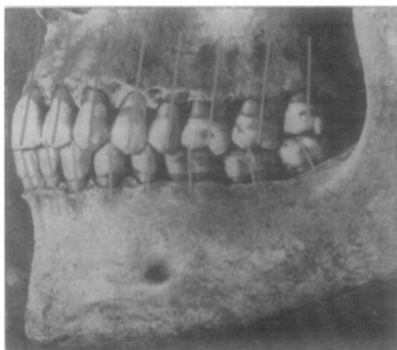
Figure 2.3.1: Molar Relationships

- 1) Improper molar relationship
- 2) Improved molar relationship
- 3) More improved molar relationship
- 4) Proper molar relationship

(Andrews, 1972)

2. Crown angulation, mesiodistal tip. The gingival portion of all crowns are positioned more distal than the incisal portion. The degree of crown tip of the incisors determines the amount of mesiodistal space it occupies. Therefore, the degree of crown angulation can have a significant effect on the posterior occlusion as well as anterior esthetics.

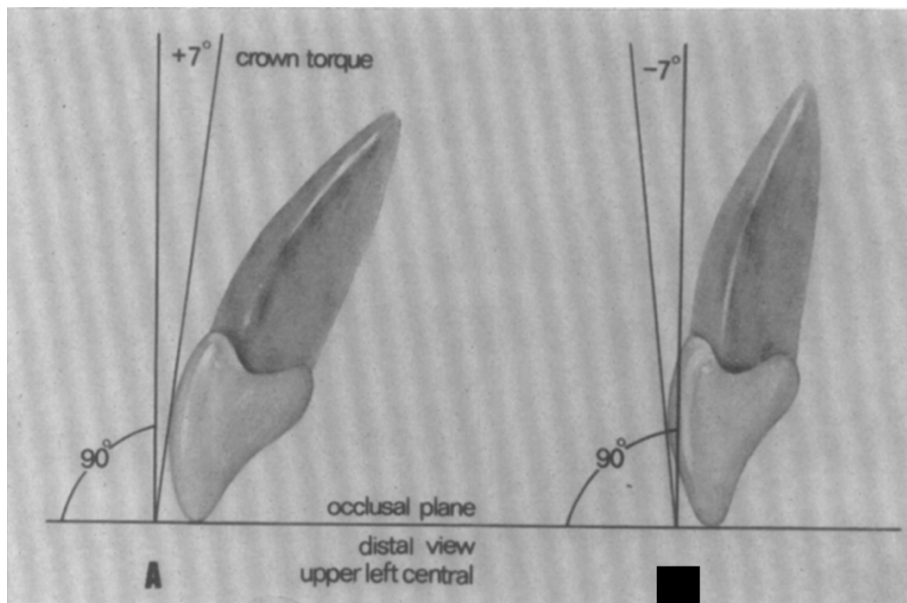
Figure 2.3.2: Crown Angulation/Tip



(Andrews, 1972)

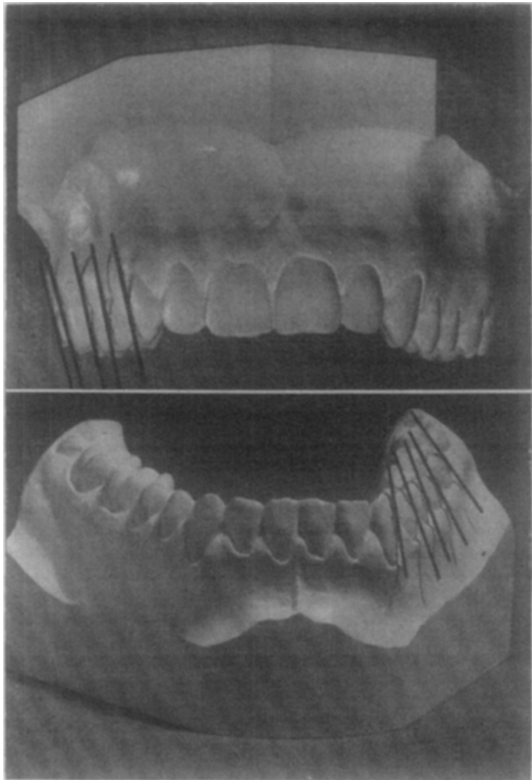
3. Labiolingual crown inclination. Refers to the labiolingual inclination of the long axis of the crown and not the inclination of the long axis of the tooth.
- Anterior teeth (central and lateral incisors) should have sufficient crown inclination to prevent overeruption of the incisors and allow for proper distal positioning of the contact points of the upper teeth in their relationship to the lower teeth to allow for proper occlusion of the posterior dentition.
 - Upper posterior teeth (canines through molars) show a constant lingual crown inclination from the canines through to the premolars and becomes slightly more pronounced in the molars.
 - Lower posterior teeth (canines through molars) show progressive lingual crown inclination and increases from the canines through to the second molars

Figure 2.3.3: Anterior Crown Labiolingual Inclination



(Andrews, 1972)

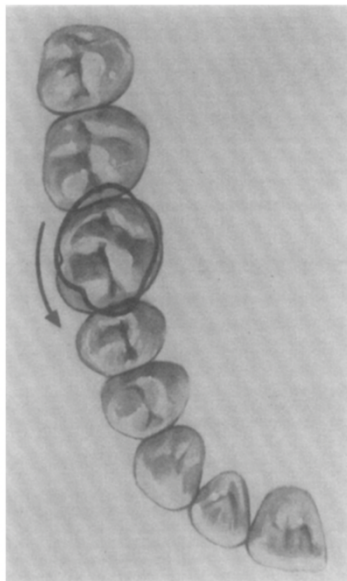
Figure 2.3.4: Posterior Crown Buccolingual Inclination



(Andrews, 1972)

4. Rotations. Teeth should have no rotations. A rotated molar occupies more space which would disrupt normal occlusion.

Figure 2.3.5: Rotations – rotated molar occupied greater mesiodistal space

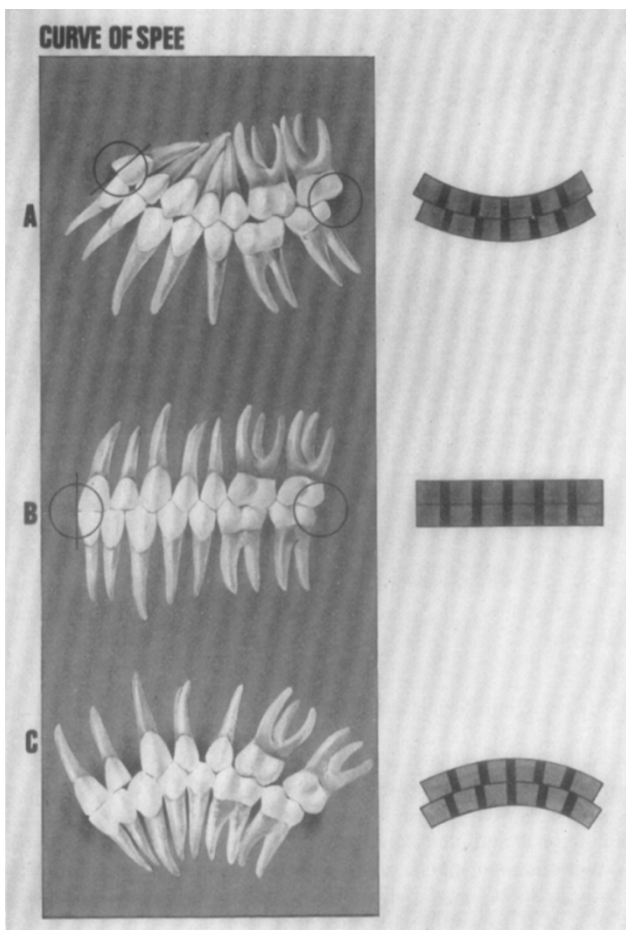


(Andrews, 1972)

5. Tight contacts. Teeth should have no spaces presents and the contacts are tight in absence of tooth size discrepancies.

6. Occlusal plane. The curve of Spee should be generally flat or with a slight curve and is most receptive to normal occlusion. A deep curve of Spee results in less space for the upper dentition whereas a reverse curve of Spee results in excessive space in the upper teeth.

Figure 2.3.6: Curve of Spee



A. A deep curve of Spee results in a more confined area for upper teeth and spillage of upper teeth mesially and distally

B. A flat curve of Spee which is desirable for normal occlusion

C. A reverse curve of Spee results in excessive room for the upper teeth

(Andrews, 1972)

2.4 Variables that can affect anterior and overall Bolton ratios

The Bolton analysis has become a widely accepted diagnostic tool for orthodontists around the world. However, it must be noted that in Bolton's original sample of 55 subjects did not take into account variables such as gender, ethnicity, malocclusion, effect of labiolingual thickness and crowding. These variables in Bolton's original sample were not specified (Bolton, 1958). Therefore, a potential for selection bias could exist.

2.4.1 Gender

In 1972, Lavelle found tooth sizes were larger in males compared to females, even though the difference was minimal being less than 1% (Lavelle 1972). Richardson and Malhotra sampled 162 African Americans with an equal male and female distribution and found the mesio-distal crown dimensions in the maxillary and mandibular arches were greater in males than females. While the anterior and overall ratios for the maxillary and mandibular arch were similar for both genders (Richardson *et al.*, 1975).

Smith *et al.* sampled 180 subjects, that were grouped African American, Hispanic and Caucasians and each group included 30 males and 30 females. They observed that the males in the African American and Hispanic study groups had a higher overall ratio than Bolton's original ratio, whereas the overall ratio for females in these two populations were similar to Bolton's original ratio. The overall ratio for Caucasian males found in this study were significantly higher than the published Bolton ratio which led Smith *et al.* to conclude that Bolton ratios are only valid for Caucasian females (Smith *et al.*, 2000). However, the differences between males and females were small, 0.7% for overall ratio and 0.6% for anterior ratio which is much less than 1

standard deviation from Bolton's mean (Othman *et al.*, 2006).

Uysal *et al.* did a study based on 150 Turkish subjects with normal occlusion and 560 Turkish patients with malocclusions. They found there was no sexual dimorphism in Bolton ratios for subjects with malocclusion but a statistically significant difference was found for males and females in the overall ratio for normal occlusion (Uysal *et al.*, 2005).

While some studies found tooth size is affected by gender, majority of the studies have concluded there are no differences in Bolton anterior and overall ratio between males and females. If a difference was found it was small and clinically insignificant.

Table 2.4.1: Summary of Studies on TSD - Statistically Significant for Sex, Malocclusion and Ethnicity

Author	Country	Gender Difference	Malocclusion differences	Racial/Ethnicity
Sperry <i>et al.</i>	USA		Yes	
Crosby & Alexander	USA		No	
Nie & Lin	China	No	Yes	
Araujo & Souki	Brazil	No	Yes	
Ta <i>et al.</i>	China		Yes	
Alkofide & Hashim	Saudi Arabia		Yes	
Liano <i>et al.</i>	Italy		No	
Uysal <i>et al.</i>	Turkey		No	
Lavelle	USA	Yes		Yes
Richardson & Malhotra	USA	No		
Al-Tamimi & Hashim	Saudi Arabia	No		
Smith <i>et al.</i>	USA	Yes		Yes

(Othman & Harradine, 2006)

2.4.2 Ethnicity

Bolton's original sample did not provide any information regarding different ethnicities and relating Bolton's original sample to different ethnic backgrounds is an area of ongoing research. Lavelle studied tooth size and Bolton ratios in Caucasians, Africans and Asians living in Britain and concluded that the overall and anterior ratios for British Africans were higher than those for

the Caucasian sample, whereas the ratios for the Asian population were found to be in between the two (Lavelle, 1972).

Smith *et al.* while looking at the inter-arch tooth-size relationship from 3 different populations, found that Africans displayed overall ratios that were significantly higher than that of Caucasians due to their larger posterior mandibular teeth. Smith *et al.* also observed the lack of differences in the overall ratio between Hispanics and Africans deceiving because there were significant differences found between the anterior and overall ratio. They found the larger anterior mandibular teeth for the Hispanic study group were counterbalanced by the larger posterior mandibular teeth for the African group which led to similar ratios for the two groups. Lastly, there were no significant differences when looking at the anterior and overall ratios between the Hispanic and Caucasians. However, the Hispanic group displayed consistently larger maxillary and mandibular tooth widths (Smith *et al.*, 2000).

In 2005, Uysal and Sari looked at the tooth size discrepancy in 150 Turkish subjects to compare to Bolton's original sample. They discovered a discrepancy in the overall ratio was found in 18% of their Turkish study sample and anterior ratios that were 2 standard deviations from Bolton's mean in 21.3% of their sample. They concluded that population specific standards are necessary for clinical assessments (Uysal & Sari, 2005). Similarly, Santoro *et al.*, examined 54 Dominican Americans to compare to Bolton's sample and found that 28% of their subjects displayed an anterior tooth size discrepancy and 11% showed an overall tooth size discrepancy that were clinically and statistically significant and fell 2 standard deviations from the Bolton mean

amount (Santoro *et al.*, 2000). A summary of some of the studies looking at tooth size discrepancies in different ethnicities can be seen in Table 2.4.1.

Some authors observed that the anterior and overall ratios for their population specific sample were similar to Bolton's original values. In 1991 Lew and Keng examined anterior ratio of 85 Singaporean Chinese and found their sample were compared favourably to Bolton's values even though they had wider maxillary lateral incisors and narrower maxillary central incisors (Lew & Kang, 1991). Moon *et al.* also found Bolton's original overall and anterior ratios were compared favourably to 58 Filipino patients living in Canada (Moon *et al.*, 2023). Hashim *et al.*, also looked at the overall and anterior Bolton ratio among a sample of 100 Qatari population and found no statistically significant difference in the overall ratio but a significant difference was seen in the anterior ratio (Hashim *et al.*, 2017).

2.4.3 Malocclusion

Many studies have investigated whether malocclusion has any effect on the tooth size discrepancy. Lavalle observed the overall ratio were the greatest in Class I and least in Class III for maxillary dentition while the overall ratios were in the middle for Class II division 1 and 2 cases. He suspected that tooth size may play a role in the etiology of malocclusion (Lavalle, 1972).

Sperry *et al.* studied tooth-size discrepancy in 78 subjects with Angle Class III malocclusion and compared his findings with 26 subjects with Class I and 26 subjects with Class II malocclusion. They found Class III subjects showed greater mandibular tooth excess than the Class I and II

groups (Sperry *et al.*, 1977).

In another study, Crosby and Alexander observed 109 subjects and categorized them into Class I, Class II Div 1, Class II Div 2 and surgical Class II to identify any tooth size discrepancies in anterior and overall Bolton ratios among the different malocclusions however, this study did not include any Class III subjects. The results of the study showed no statistically significant differences in the malocclusion group but 22.9% of the patients had an anterior Bolton that fell 2 standard deviations outside of Bolton's mean (Crosby & Alexander, 1989).

Nie and Lin also did a study on Bolton ratios among different malocclusion groups and found similar differences. Their study consisted of 360 Chinese subjects and the data was analyzed according to their Angle classifications I, II, and III as well as according to their skeletal type. They concluded that the higher ratios were associated with Class III malocclusions and the lower ratios were associated with Class II malocclusions. They suggest that tooth size discrepancy between maxillary and mandibular teeth may be one of the important factors in the cause of malocclusion especially in Class II and Class III malocclusions (Nie & Lin, 1999). Ta *et al.*, also found statistically significant trend to larger ratios in Class III patients (Ta *et al.*, 2001).

Araujo and Souki also looked at the correlation between anterior tooth size discrepancy and Angle Class I, II and III malocclusions in a sample of 300 Brazilian subjects. The main conclusion was individuals with Angle Class I and III show greater prevalence of tooth size discrepancies than individuals with Class II. Lastly, the mean anterior tooth size discrepancy for

Angle Class III subjects were significantly higher than for Class I and Class II subjects (Araujo & Souki, 2003).

2.4.4 Effect of labiolingual thickness on Bolton ratios

In Bolton's 1962 paper, it was discovered that extreme labial inclination of incisors and incisors with thick labiolingual thickness are clinical features that may affect the occlusion and an ideal anterior ratio. Bolton suggested a greater maxillary anterior sum would be needed or in extreme cases, enameloplasty of marginal ridges of maxillary incisors may be necessary in order to achieve proper overjet relationship (Bolton, 1962).

In 1998, Rudolph *et al.* tested the use of tooth thickness in predicting intermaxillary tooth size discrepancy. This study consisted 44 subjects with varying labiolingual thickness with an ideal overbite and Class I canine occlusion. They concluded as the labiolingual tooth thickness increases, the ideal anterior ratio decreases. Considering how tooth thickness affects the anterior ratio, they created two formulas to help better predict the ideal anterior ratio. One formula is applied when the thickness is greater than 2.75mm while the other is used when the thickness is less than 2.75mm. Predicting the tooth size discrepancies were more accurate when using the new formula than when only using the Bolton analysis (Rudolph *et al.*, 1998).

Beygelman *et al.*, had similar conclusions where they found maxillary incisor thickness does affect the occlusion and anterior ratios. In their sample of 50 subjects, they concluded the anterior ratio can range anywhere from 0.70-0.79 based on the thickness of the incisors. Their

findings from the simulations suggest the ideal tooth thickness is about 2mm. If the maxillary incisor thickness is greater than 2mm, it could lead to Class II molar and canine relationship. Based on their findings they recommended the use of thickness-adjusted anterior ratio to more accurately predict the anterior tooth size that is necessary to achieve proper occlusion (Beygelman *et al.*, 2019).

2.4.5 Crowding

Crowding is one of the most common malocclusions. When crowding is present the ideal interproximal contact points may sometimes be estimated and this estimation can introduce variations in the measurements of teeth. Thus, the analysis in tooth size discrepancy when crowding is present may have limited reliability (Shellhart *et al.*, 1995).

Nordeval *et al.* observed that the Bolton anterior ratio was significantly higher when lower incisal crowding is present compared to the group with good alignment (Nordeval *et al.*, 1975). Similarly, when Shellhart *et al.* looked at the reliability of Bolton ratios when crowding is involved, they found there is a clinically significant measurement error when there is at least 3mm of crowding present (Shellhart *et al.*, 1995).

Bernabe *et al.* compared tooth width ratios in crowded and noncrowded dental arches and concluded statistical but no clinical differences (less than one mm) were found between crowded and non-crowded dentition (Bernabe *et al.*, 2004).

2.5 Management of Tooth Size Discrepancy

The importance of recognizing tooth size discrepancy is crucial to ensure a beautiful successful end result with good interdigitation and optimal esthetics. To address inter-arch tooth size discrepancies a few methods have been proposed. Interproximal reduction is used when the discrepancy is caused by excess in tooth size. Whereas when the problem is associated with tooth size deficiency, opening spaces between some teeth may be necessary for composite build ups. Fields proposed that 2 to 2.5mm of enamel stripping from the mesial of canine to the mesial of canine is the upper limit to interproximal reduction in the anterior teeth (Fields, 1981). Proffit suggested the width of the lower incisor can be reduced up to 0.5mm on each side without going through the interproximal enamel (Proffit, 2015).

Proffit also proposed for more generalized small deficiencies, it can be masked by altering the incisor position. Uprighting the upper incisors (lingual crown torque) can help mask larger upper incisors while adding buccal crown torque to can help compensate for smaller upper incisors. Other methods can include finishing orthodontic treatment with mildly excessive overbite or overjet or adding slight distal root tip to increase the mesiodistal width of the maxillary incisors. However, this plan may have some esthetic limitations (Proffit, 2015., Fields, 1981).

2.6 Prevalence of tooth size discrepancy and threshold for clinically significant TSD

The prevalence of tooth size discrepancy has been debated over numerous studies and results are still inconclusive. Proffit states approximately 5% of the population has some sort of tooth size discrepancy (Proffit, 2015).

In 1989, Crosby and Alexander did a study on 109 subjects with varying malocclusions and found 22.9% of the sample had an anterior tooth size discrepancy and the anterior ratio was greater than 2 standard deviations from the Bolton mean. There was a greater percentage of patients with anterior tooth size discrepancy than with an overall tooth size discrepancy (Crosby & Alexander, 1989). Similar findings were seen in a study conducted by Freeman *et al.* when they looked at 157 orthodontic subjects. The subjects consisted of 115 Caucasians, 27 Africans, and 15 patients of other ethnic origin. They found that there was an equal chance of the overall discrepancy being an excess in the maxilla or in the mandible whereas the anterior discrepancy was nearly twice as likely to be an excess in the mandible (19.7%) than an excess in the maxilla (10.8%). Another conclusion they found was 30.6% of their sample presented with significant anterior tooth size discrepancy while 13.5% has significant overall tooth size discrepancy (Freeman *et al.*, 1996). A summary of different studies and prevalence of tooth size discrepancy can be found below.

Table 2.6.1: Studies on the Prevalence of Anterior and Overall Tooth Size Discrepancies

Author	Population	Sample Size	% Anterior TSD	% Overall TSD
Crosby & Alexander	Orthodontic	109	22.9	-
Freeman <i>et al.</i>	Orthodontic	157	30.6	13.5
Santoro <i>et al.</i>	Orthodontic	54	28.0	11.0
Araujo & Souki	Orthodontic	300	22.7	-
Bernabe <i>et al.</i>	School	200	20.5	5.4
Othman et al.	Orthodontic	150	17.4	5.4

(Othman & Harradine, 2007)

Proffit states that a tooth size discrepancy of less than 1.5 mm is rarely significant but larger discrepancies can affect achieving the ideal occlusion. Proffit used 2mm of tooth size discrepancy as a general guideline from the Bolton analysis as the threshold for clinical significance (Proffit, 2015). However, Proffit did not specify whether the 1.5mm to 2.0 mm is applied only to the anterior ratio, overall ratio or both.

Originally Bolton had suggested a ratio greater than 1 SD from his reported mean would indicate diagnostic consideration (Bolton, 1958). However, more recently a clinically significant tooth width ratio discrepancy has been defined as 2 SD outside of Bolton's published mean ratio (Crosby & Alexander, 1989., Freeman *et al.*, 1996., Santoro et al., 2000., Endo *et al.*, 2009)

In 2004, Bernabe *et al.*, used Proffit's recommended 1.5mm cut off in their sample of 200 subjects and found 32.5% of the sample had clinically significant anterior ratios and 36.5% had clinically significant overall ratios. If they used 2 SD outside of Bolton's published means then 20.5% would have clinically significant anterior ratio and 5.4% would have clinically significant overall ratios. They concluded that a 2 SD range from Boltons mean underestimates the prevalence of clinically significant anterior and total tooth width ratios (Bernabe *et al.*, 2004).

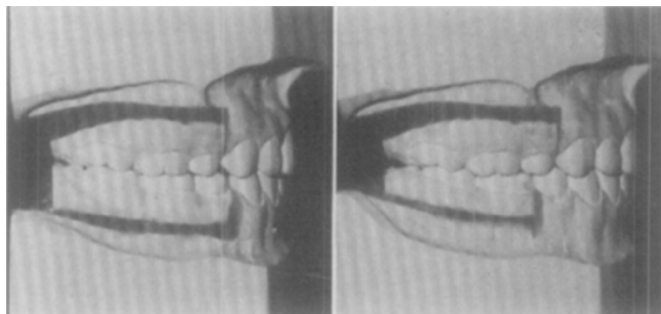
Othman and Harradine found that tooth size discrepancies are better expressed in terms of millimeters that are required for correction and recommended a threshold of 2 mm (Othman & Harradine, 2007).

Similarly Endo *et al.*, also looked at the threshold for clinically significant tooth size discrepancy and concluded that ratios outside 2 SDs from the mean and 2mm are recommendable as appropriate threshold for clinical significance (Endo *et al.*, 2009).

2.7 Effect of Four Premolar Extractions on the Bolton Overall Ratio

In 1962, Bolton published a follow up article and looked at the use of anterior and overall ratios in predicting various extraction patterns. He explored the effects of four premolar extractions on the overall ratio and discovered that the overall ratio would decrease by approximately 2%, usually from 91.0+ to 89.0%, if equal sized premolars were extracted from the upper and lower arches. If the lower premolars being extracted are greater in mesiodistal width than the upper premolars then the overall ratio would decrease by almost 4%. Bolton suggested that the additional tooth mass removed in the mandibular posterior segment allows for the mandibular molars to mesialize. Mesialization of the mandibular molars places the molars in a slightly super class I relationship in which the distal cusp of the maxillary first molar occludes between the mandibular first and second molars which is a key finding in orthodontic stability. He cautioned that this was a finding and should be not be used as a recommendation for extractions of four premolars (Bolton, 1962).

Figure 2.7 An occlusal set up after removal of the first premolars of equal size and after removal of upper first premolars and lower second premolars



(Bolton, 1962)

Endo *et al.* looked at premolar extractions on the Bolton overall ratios in 198 Japanese subjects with four different extraction combinations (1) all first premolars (2) all second premolars (3) maxillary first and mandibular second premolars and (4) maxillary second and mandibular first premolars. They concluded that overall ratios decreased in every malocclusion group after extraction of any combination of premolars but decreases in overall ratio were more significant in group 2 and 4 (Endo *et al.*, 2010). Tong *et al.* also had similar findings where high overall ratios could change to normal overall ratios with either extraction of all second premolars or extraction of maxillary second premolar and mandibular first premolars (Tong *et al.*, 2004). Their findings showed that orthodontists should consider that overall ratios might decrease and normal and clinically significant tooth size discrepancies could change mutually after extractions (Endo *et al.*, 2010).

In 2021, Mongilio *et al.* looked at the effect of 4 first premolar extractions on 55 patients with Class I occlusion and ideal anterior and overall Bolton ratios. They found there was an average of 1.1mm of net residual space between the mandibular second premolars and first molars. They concluded that complete space closure cannot be accomplished without interproximal reduction in the maxillary arch or build ups in the mandibular arch (Mongilio *et al.*, 2021).

2.8 Methods of measuring tooth size discrepancy

2.8.1 Visual assessment

Proffit proposed a quick way to check for anterior tooth size discrepancy is by comparing the size of the upper and lower lateral incisors and to check for posterior tooth size discrepancy is by comparing the size of the upper and lower second premolars. An anterior tooth size discrepancy

is likely to exist if the upper lateral incisor is smaller than the lower lateral incisor whereas a posterior tooth size discrepancy is expected if the size of the upper and lower second premolars are different (Proffit *et al*, 2019).

However, Othman and Harradine claims that “eyeballing” the study models is an unreliable method of assessing tooth size discrepancy. They found that simple visual assessment missed more than half of the cases with a significant tooth size discrepancy greater than 2mm (Othman & Harradine, 2007).

2.8.2 Accuracy of tooth widths and Bolton ratio reported by the ClinCheck® software

Shailendran *et al.* studied the accuracy and reliability of tooth widths and Bolton ratios measured by the ClinCheck® Pro software. They found that on average ClinCheck® Pro underestimates tooth widths by 0.36mm except for the first molars which was underestimated by about 0.9mm. Thus, ClinCheck® Pro systematically underestimates tooth widths when compared to digital calipers and this discrepancy progressively worsens as you move distally towards the posterior dentition. The underestimation of tooth widths in the ClinCheck® Pro software could be due to inefficiency in capturing the interproximal contact areas. Align Technology also uses proprietary mathematical shape assumptions when defining the interproximal anatomy which could contribute to inaccuracies in the aligner measurements (Shailendran *et al.*, 2022).

A conclusion from their study was ClinCheck® Pro only shows moderate reliability for both anterior and overall Bolton ratios and would mean, if solely relying on ClinCheck® Bolton ratio,

could lead to irreversible and unnecessary interproximal reductions or missing existing tooth size discrepancies (Shailendran *et al.*, 2022).

Adobes Martin *et al.* looked at the reliability of tooth width measurements delivered by ClinCheck Pro software on digital study casts and similar to Shailendran *et al.*'s study. However, they found that ClinCheck[®] Pro software consistently provided larger widths compared with the manual method. They concluded the tooth width measurements delivered by ClinCheck[®] Pro are considered to be accurate and clinically acceptable except for molars. They also found the software does not use the original Bolton formula for tooth discrepancy assessment therefore the anterior and overall Bolton ratios made available by the software is not accurate and clinically acceptable especially in the case of mandibular excess (Adobes Martin *et al.*, 2022).

2.8.3 Methods of Measuring Tooth Width for Bolton ratios

The traditional method of measuring tooth widths involved manually measuring mesio-distal widths of teeth on dental casts via the use of needle pointed dividers or a Boley gauge (Othman & Harradine, 2006). Shellhart *et al.*, studied the reliability of the Bolton analysis when using these two instruments and the effect of crowding on tooth size discrepancies. They found clinically significant measurement errors when there is at least 3mm of crowding, which could lead clinicians to consider evaluating tooth size discrepancies after crowding has been unraveled (Shellhart *et al.*, 1995).

With recent technological advances there has been a trend in using digital impressions and study models as an alternative method for obtaining study models. Tomassetti *et al.* compared manual

measurements with Vernier callipers to 3 different computerized casts (Quickhat Image Pro, OrthoCad and Hamilton Arch Tooth System) and found that computerized methods are much more time efficient as compared to manual hand measurements with calipers. They concluded that QuickCeph yielded the fastest results while Vernier callipers were the slowest. However, QuickCeph gave results which gave the greatest mean discrepancy from Vernier callipers and also the least correlated with the results from the Vernier calipers. Although no statistically significant differences were found between the methods, a clinically significant difference (>1.5mm) were present for each method which led them to question whether digital methods are as accurate as the traditional methods (Tomassetti *et al.*, 2001).

Zilberman *et al.* tested the accuracy of conventional measuring methods using calipers and virtual computerized models such as OrthoCad. Their findings were measurements with digital calipers on plaster models produced the most accurate and reproducible results. While OrthoCad measurements showed a high accuracy and reproducibility, it was inferior to measurements done on plaster models with digital calipers. Overall, they concluded OrthoCad's accuracy is clinically acceptable and believes 3D virtual models will someday become the standard for orthodontic use (Zilberman *et al.*, 2003).

Since then, a systematic review conducted by Fleming *et al.*, found orthodontic measurements with digital models were comparable to measurements taken from plaster models. They suggested that the use of digital models could be used as an alternative to conventional methods on plaster models (Fleming *et al.*, 2011). Similarly, in a systematic review by Rossini *et al.* concluded that digital models are as reliable as traditional plaster models with high accuracy,

reliability and reproducibility which led them to suggest that digital models could be considered the new gold standard for orthodontic purposes (Rossini *et al.*, 2016).

Regardless of the different methods available, there are still limitations with both manual (digital caliper) and digital model methods. The accuracy of tooth widths measured with these two methods is very dependent on the dentition replication process and the accuracy and the consistency of the measuring tools.

2.8.4 Plaster models Vs. digital models

The traditional way of obtaining study models is by alginate impressions and plaster casts. With recent technological advances, 3D printing technology has allowed for a more digital workflow in dentistry and has reduced the need of the traditional way of obtaining study models. The main advantages of obtaining 3D models compared with conventional plaster models are its benefits in efficiency, ease of use, longevity (no risk of physical damage) and storage space such that it doesn't require physical space (Hazeveld *et al.*, 2014).

There have been many studies looking at whether virtual models captured by the scanner are as accurate as the traditional plaster models. In 2013, Akyalcin *et al* evaluated the accuracy of 3D digital models acquired from a chairside scanner (Cadent iTero scanner from Align Technology, San Jose, Calif) and a cone-beam computed tomography (CS 9300 unit Carestream Health, Atlanta, Ga) measurements on 60 dry skulls. They concluded measurements from the iTero models demonstrated near perfect agreement with the caliper measurements while CBCT measurements has a moderate to high level of agreement. In conclusion they found CBCT scans

and iTero models produced interchangeable results with manual measurements and therefore suggest that both methods are sufficient for use in orthodontic diagnosis and treatment planning (Akyalcin *et al.*, 2013).

Hazeveld *et al.* looked at the accuracy and reproducibility of dental models reconstructed from digital data and converted into physical models using 3 rapid prototyping techniques: digital light processing, jetted photopolymer and 3D printing. Linear measurements between plaster models and rapid prototyping models were compared. In their study when they compared the mesiodistal widths they found the absolute differences ranged from 0.00 to 1.24mm in the anterior region and from 0.03 to 2.26 in the overall and thus they believe the replica models in this study were usable for the Bolton analysis. They concluded that all replicas are accurate enough and might be used interchangeably with plaster models and may be appropriate for selected applications in orthodontics (Hazeveld *et al.*, 2014). A similar trend was seen by Bowes *et al.*, who showed that mandibular incisor measurements are accurate and reliable across both manual caliper method and using the digital model system (Bowes *et al.*, 2017).

In 2017, Koretsi *et al* observed that orthodontic model analysis with digital calipers are comparable between plaster and printed dental models. They took 48 plaster models that were digitized with orthoXscan (Dentaurum) and printed with Objet30 Dental Prime (Stratasys) and concluded that plaster casts and models obtained from orthoXscan and printed by Objet20 Dental Prime can be interchangeably used for clinical purposes in orthodontics (Koretsi *et al.*, 2017).

3. Purpose

The purpose of this study was:

1. To assess the reliability of the mesiodistal tooth widths predicted by ClinCheck[®] Software and compare to those measured using digital calipers.
2. To assess the accuracy of Bolton ratios given by Invisalign's ClinCheck[®] software at two different time points.
3. To determine whether crowding has any influence on the anterior and overall Bolton ratios.

4. Null Hypothesis

1. The mesiodistal tooth widths as predicted by the ClinCheck® Software are not reliable in comparison to those measured manually using the digital caliper.
2. There is no statistically significant difference between the anterior and overall Bolton ratios determined by ClinCheck® software when measuring tooth widths at two time points.
3. There is no statistically significant difference between the anterior and overall Bolton ratios in crowded cases before treatment and at the last refinement scan

5. Materials and Methods

5.1 Ethics

Ethics approval was obtained from the Bannatyne Human Research Board (BHREB) prior to the commencement of this retrospective study. Provisional approval was received on January 31st, 2024 and a final certificate of approval was received on June 24, 2024.

5.2 Methods

All patients that underwent Invisalign treatment had their mouth digitally scanned with an iTero Element scanner (Align Technology, Orchard Parkway, San Jose, CA, USA) with additional aligner refinement iTero scans throughout their treatment. Pre-treatment and last refinement STeroLithography (STL) format were downloaded with permanent teeth erupted from right to the left first molar in both jaws and 3D printed models using Die and Model 2 acrylic on the Sprint Ray Pro95S 3D machine.

To evaluate Bolton ratios, the mesiodistal tooth widths of every tooth from the first right molar to the first left molar in each jaw was recorded by measuring the greatest distance between physiological contact points on the proximal surfaces. Measurements were manually measured with a fine tip electronic caliper (OrthoPli #0400-EEP) accurate to 0.01mm on 3D printed model's pre-treatment (T1) and at the last refinement scan (T2) by a primary and a secondary investigator and compared to the Bolton ratios as predicted by the ClinCheck[®] Software. The secondary investigator was calibrated by the primary investigator in the measurement technique, the light source was standardized and the digital caliper was zeroed between every tooth measurement.

5.3 Sample Selection

Potential study participants from Children's Dental World were contacted by the front reception via phone to ask for consent regarding the use of their records by the principal investigator.

Overall and anterior Bolton ratios were calculated for 29 patients with 5 to 8 mm of crowding in the anterior and/or whole (overall) maxillary and mandibular arch who have undergone non-extraction Invisalign treatment and no interproximal reduction at a private orthodontic clinic (Children's Dental World). All 29 patients had completed orthodontic treatment and will have their pre-treatment iTero records (T1) and last refinement iTero record (T2) once all the crowding has unravelled.

Inclusion criteria

The orthodontic digital casts at two time points (T1 and T2) that are included in the sample satisfied the following criteria:

1. 5mm – 8mm crowding in Mx and Md arch overall
2. Permanent dentition present from 16 to 26 and 36 to 46
3. No interproximal reduction preformed during treatment
4. No congenitally missing teeth
5. No interproximal caries or restorations
6. No permanent teeth extracted during treatment
7. Patients underwent clear aligner (Invisalign) treatment and their teeth were digitally scanned with the iTero scanner at two time points

Exclusion criteria

1. Congenitally missing teeth
2. Interproximal reduction
3. Interproximal restorations or caries
4. Peg lateral incisors

5.4 Anterior and overall Bolton ratio calculations

Using the formula for the Bolton “overall ratio” and “anterior ratio” the data from the measurements obtained from measuring casts using a digital caliper can be calculated.

The formula is as follows:

$$\text{Overall ratio} = \frac{\text{Sum of mesiodistal tooth widths of mandibular 6-6}}{\text{Sum of mesiodistal tooth widths of maxillary 6-6}} \times 100$$

$$\text{Anterior ratio} = \frac{\text{Sum of mesiodistal tooth widths of mandibular 3-3}}{\text{Sum of mesiodistal tooth widths of maxillary 3-3}} \times 100$$

5.5 Assessment of Intra- and Inter-examiner reliability

Intra-examiner reliability was assessed by remeasuring 50% of the sample by the primary investigator and was done 2 weeks after completion of the initial measurements to prevent recall bias.

To assess for the inter-examiner reliability, 20% of the sample was randomly selected by the secondary investigator, Dr. Tim Tse (licensed physician in Winnipeg, MB). The secondary investigator was calibrated by the primary investigator on the use of the digital caliper.

Lastly, the overall and anterior Bolton ratios was evaluated using the mesiodistal tooth widths acquired from the patients Invisalign ClinCheck[®] and compared to the ratios that were calculated using the measurements obtained from measuring 3D casts using a digital caliper.

5.6 Statistical Test

Paired T tests were used to compare the accuracy of ClinCheck[®] estimated tooth widths and Bolton ratios tested on 29 patients measured from 2 time points (T1 – initial scan and T2 – last refinement scan). They will also be used to determine the accuracy of ClinCheck[®] predicted anterior and overall Bolton ratios compared to manual measurements using a digital caliper. The p-value was considered significant for $\alpha < 0.05$.

Intraclass correlation coefficient (ICC) analyses were used to determine intra-rater reliability and inter-rater reliability between the primary and secondary investigators. This was also used to determine the reliability of ClinCheck[®] Bolton ratios.

ICC values can be judged by:

- Values less than 0.5 indicated poor reliability
- Values between 0.5 and 0.75 indicated moderate reliability
- Values between 0.75 and 0.9 showed good reliability
- Values greater than 0.90 reflected excellent reliability.

6. Results

6.1 Intra-Rater and Inter-Rater Reliability of Each Tooth and Bolton Ratios

6.1.1 Intra-Rater and Inter-Rater Reliability for Each Tooth at Pre-Treatment (T1)

- There was **excellent** intra-rater reliability for measuring each tooth (ICC = 1.000).
- There was **excellent** inter-rater reliability between the primary investigator (PI) and secondary investigator for measuring each tooth (ICC = 0.999).
- There was **excellent** reliability for ClinCheck® measurements compared to those measured by the primary investigator (ICC = 0.993).

Table 6.1.1: Intra/Interrater reliability of each tooth – Pre-Treatment (T1)

Comparisons	ICC	95% CI
PI vs self (n=360)	1.000	1.000, 1.000
PI vs Second Investigator (n=696)	0.999	0.999, 0.999
PI vs ClinCheck® Software (n=696)	0.993	0.990, 0.995

6.1.2. Intra-Rater and Inter-Rater Reliability for Each Tooth at Last Refinement (T2)

- There was **excellent** intra-rater reliability for measuring each tooth (ICC = 0.999).
- There was **excellent** inter-rater reliability between the primary and secondary investigator for measuring each tooth (ICC = 0.999).
- There was **excellent** reliability for ClinCheck® measurements compared to those measured by the primary investigator (ICC = 0.994).

Table 6.1.2: Intra/Interrater reliability of each tooth – Last Refinement (T2)

Comparisons	ICC	95% CI
PI vs self (n=336)	0.999	0.998, 0.999
PI vs Second Investigator (n=696)	0.999	0.999, 0.999
PI vs ClinCheck® Software (n=696)	0.994	0.991, 0.996

6.1.3. Intra-Rater and Inter-Rater Reliability of Ratios – Pre-Treatment (T1)

Anterior Ratios:

- There was **excellent** intra-rater reliability for calculating the anterior Bolton ratios (ICC = 0.975).
- There was **excellent** inter-rater reliability between the primary and secondary investigator for calculating anterior Bolton ratios (ICC = 0.941) but wide 95% confidence interval (0.389-0.984).
- There was **excellent** reliability for anterior Bolton ratios given by ClinCheck® compared to those calculated by the primary investigator (ICC = 0.922).

Overall Ratios:

- There was **excellent** intra-rater reliability for calculating the overall Bolton ratios (ICC = 0.958).
- There was **excellent** inter-rater reliability between the primary and secondary investigator for calculating the overall Bolton ratios (ICC = 0.970).

- There was **good** reliability for overall Bolton ratios given by ClinCheck[®] compared to those calculated by the primary investigator (ICC = 0.848) but wide 95% confidence interval (0.267-0.949).

Table 6.1.3: Intra/Interrater reliability of ratios – Pre-Treatment (T1)

Comparisons	ICC	95% CI
PI vs self (Anterior) (n=15)	0.975	0.927, 0.991
PI vs Second Investigator (Anterior) (n=29)	0.941	0.389, 0.984
PI vs ClinCheck [®] Software (Anterior) (n=29)	0.922	0.835, 0.964
PI vs self (Overall) (n=15)	0.958	0.879, 0.986
PI vs Second Investigator (Overall) (n=29)	0.970	0.936, 0.986
PI vs ClinCheck [®] Software (Overall) (n=29)	0.848	0.267, 0.949

6.1.4. Intra-Rater and Inter-Rater Reliability of Ratios – Last Refinement (T2)

Anterior Ratios:

- There was **excellent** intra-rater reliability for calculating the anterior Bolton ratios (ICC = 0.984).
- There was **excellent** inter-rater reliability between the primary and secondary investigator for calculating the anterior Bolton ratios (ICC = 0.913).
- There was **good** reliability for anterior Bolton ratios given by ClinCheck[®] compared to those calculated by the primary investigator (ICC = 0.887) but wide 95% confidence interval (0.577-0.958).

Overall Ratios:

- There was **excellent** intra-rater reliability for calculating the overall Bolton ratios (ICC = 0.979).
- There was **excellent** inter-rater reliability between the primary and secondary investigator for calculating the overall Bolton ratios (ICC = 0.948).
- There was **good** reliability for overall Bolton ratios given by ClinCheck[®] compared to those calculated by the primary investigator (ICC = 0.888).

Table 6.1.4: Intra/Interrater reliability of ratios – Last Refinement (T2)

Comparisons	ICC	95% CI
PI vs self (Anterior) (n=15)	0.984	0.948, 0.995
PI vs Second Investigator (Anterior) (n=29)	0.913	0.746, 0.964
PI vs ClinCheck [®] Software (Anterior) (n=29)	0.887	0.577, 0.958
PI vs self (Overall) (n=15)	0.979	0.934, 0.993
PI vs Second Investigator (Overall) (n=29)	0.948	0.890, 0.975
PI vs ClinCheck [®] Software (Overall) (n=29)	0.888	0.735, 0.950

6.2 Comparison of Hand Measured Vs. ClinCheck® Software Bolton Ratios

6.2.1 Comparison of Hand Measured Ratios Vs. ClinCheck Software Ratios

- Table 6.2.1 below indicates that the hand measured vs ClinCheck® software measurements are significantly different for the pre-treatment overall ratio ($p<.001$), last refinement anterior ratio ($p<.001$) and last refinement overall ratio ($p=.016$).

Table 6.2.1: Comparisons of Hand Measured Ratios vs ClinCheck® Software ratios

	Hand Measurement	Software Measurement	t(df) p-value
Pre Treatment Anterior Ratio	77.999 (2.007)	78.107 (2.076)	-0.526(28), $p=.603$
Pre Treatment Overall Ratio	91.715 (1.807)	90.734 (1.780)	5.25 (28), $p<.001$
Last Refinement Anterior Ratio	77.641 (1.586)	78.362 (1.940)	-4.13(28), $p<.001$
Last Refinement Overall Ratio	91.698 (1.503)	91.266 (1.578)	2.56 (28). $p=.016$

*Paired t test used (Mean, SD shown)

6.2.2 Comparison Between Pre Treatment and Last Refinement Ratios for Primary Investigator Hand Measurements

- Table 6.2.2 below shows the hand measurements indicate there are no significant differences between T1 (p=.172) and T2 (p=.938) anterior and overall ratios.

Table 6.2.2: T1 and T2 – PI hand measurements

	Pre Treatment	Last Refinement	t(df) p=value
Anterior Ratio	77.999 (2.007)	77.641 (1.586)	t(28) = 1.40, p=.172
Overall Ratio	91.715 (1.807)	91.698 (1.503)	t(28) = .079, p=.938

*Paired t test used (Mean, SD shown)

6.2.3. Comparison Between Pre Treatment and Last Refinement Ratios for ClinCheck® Software

- Table 6.2.3 below shows the ClinCheck® measurements indicate there are significant differences between T1 (p=.05) and T2 (p<.001) anterior and overall ratios.

Table 6.2.3: T1 and T2 – ClinCheck® Software

	Pre Treatment	Last Refinement	t(df) p=value
Anterior Ratio	78.107 (2.076)	78.362 (1.940)	t(28) = -2.04, p=.05
Overall Ratio	90.734 (1.780)	91.266 (1.578)	t(28) = -4.88, p<.001

*Paired t test used (Mean, SD shown)

6.3: Inter-rater Reliability Split by Tooth Number

6.3.1 Inter-rater reliability split by tooth number for PI vs Self (Pre & Last Refinement)

- There was good to **excellent** intra-rater reliability for measuring each tooth (ICC = 0.867 to 0.997).
- While the point estimate is high for the last refinement scan for tooth #26, the confidence intervals suggest the true ICC could be as low as 0.600 or as high as 0.957. The possibility of a true level of agreement could be only moderate for tooth #26.

Table 6.3.1: Inter-rater reliability split by tooth number – PI vs Self (Pre & Last Refinement)

Tooth Number	Pre-Treatment (T1)			Last Refinement (T2)		
	ICC	95% CI		ICC	95% CI	
11	0.992	0.977	0.997	0.993	0.889	0.998
12	0.977	0.932	0.992	0.996	0.984	0.999
13	0.995	0.986	0.998	0.992	0.976	0.997
14	0.993	0.981	0.998	0.989	0.600	0.998
15	0.997	0.993	0.999	0.991	0.972	0.997
16	0.997	0.992	0.999	0.985	0.953	0.995
21	0.986	0.957	0.995	0.996	0.954	0.999
22	0.991	0.974	0.997	0.991	0.972	0.997
23	0.995	0.985	0.998	0.988	0.964	0.996
24	0.990	0.971	0.997	0.983	0.866	0.996
25	0.993	0.980	0.998	0.989	0.966	0.996
26	0.997	0.978	0.999	0.867	0.600	0.957
31	0.989	0.955	0.996	0.979	0.836	0.995
32	0.984	0.952	0.995	0.991	0.940	0.998
33	0.992	0.977	0.997	0.993	0.893	0.998
34	0.995	0.985	0.999	0.995	0.984	0.998
35	0.996	0.988	0.999	0.990	0.969	0.997
36	0.998	0.995	0.999	0.988	0.908	0.997
41	0.987	0.961	0.995	0.979	0.934	0.993
42	0.993	0.979	0.998	0.991	0.961	0.997
43	0.996	0.988	0.999	0.991	0.969	0.997
44	0.997	0.992	0.999	0.992	0.972	0.997
45	0.996	0.987	0.998	0.987	0.959	0.996
46	0.996	0.988	0.999	0.971	0.708	0.993

6.3.2. Inter-rater reliability split by tooth number for the primary investigator vs secondary investigator (Pre & Last Refinement)

- There was good to **excellent** intra-rater reliability between the primary investigator and secondary investigator for measuring each tooth. (ICC = 0.960 to 0.994)

Table 6.3.2: Inter-rater reliability split by tooth number – PI vs Second Investigator (Pre and Refinement)

Tooth Number	T1			T2		
	ICC	95% CI		ICC	95% CI	
11	0.988	0.766	0.997	0.986	0.970	0.993
12	0.990	0.980	0.995	0.986	0.969	0.993
13	0.990	0.978	0.995	0.990	0.975	0.996
14	0.987	0.965	0.994	0.986	0.965	0.994
15	0.984	0.965	0.993	0.987	0.973	0.994
16	0.990	0.971	0.996	0.986	0.950	0.995
21	0.988	0.835	0.997	0.990	0.966	0.996
22	0.992	0.983	0.996	0.987	0.973	0.994
23	0.991	0.981	0.996	0.991	0.981	0.996
24	0.991	0.980	0.996	0.990	0.979	0.995
25	0.990	0.978	0.995	0.994	0.984	0.997
26	0.982	0.929	0.993	0.965	0.925	0.983
31	0.986	0.965	0.994	0.956	0.872	0.982
32	0.991	0.981	0.996	0.986	0.970	0.993
33	0.995	0.988	0.998	0.986	0.970	0.993
34	0.991	0.981	0.996	0.991	0.981	0.996
35	0.987	0.972	0.994	0.991	0.981	0.996
36	0.988	0.955	0.995	0.989	0.964	0.996
41	0.988	0.968	0.995	0.960	0.907	0.982
42	0.987	0.972	0.994	0.985	0.968	0.993
43	0.989	0.971	0.995	0.990	0.978	0.995
44	0.985	0.967	0.993	0.990	0.979	0.995
45	0.988	0.964	0.995	0.991	0.981	0.996
46	0.983	0.949	0.993	0.982	0.913	0.994

6.3.3. Inter-rater reliability split by tooth number for the primary investigator vs ClinCheck® (Pre & Last Refinement)

- There was poor to moderate intra-rater reliability between the primary investigator and ClinCheck® for Pre-treatment tooth #16 (ICC = 0.491, 95% CI, -0.135-0.827), #26 (ICC = 0.582, 95% CI, -0.144-0.873), Last refinement tooth #16 (ICC = 0.581, 95% CI, -0.166-0.870) and #26 (ICC=0.628, 95% CI, -0.206-0.855)
- While the ICC is good to excellent for pre-treatment tooth #46 (ICC = 0.939, 95% CI, 0.591-0.981) and #36 (ICC = 0.918, 95% CI, 0.498-0.974)) and last refinement tooth #46 (ICC = 0.926, 95% CI, 0.339-0.979) and #36 (ICC = 0.899, 95% CI, 0.042-0.973) the confidence intervals indicate the true ICC could be quite low for these teeth.

Table 6.3.3: Inter-rater reliability split by tooth number – PI vs ClinCheck® (Pre and Last Refinement)

Tooth Number	T1			T2		
	ICC	95% CI		ICC	95% CI	
11	0.978	0.955	0.990	0.984	0.967	0.993
12	0.975	0.947	0.988	0.983	0.953	0.993
13	0.980	0.958	0.991	0.991	0.981	0.996
14	0.969	0.935	0.986	0.983	0.953	0.993
15	0.975	0.948	0.988	0.965	0.694	0.989
16	0.491	-0.135	0.827	0.581	-0.166	0.870
21	0.973	0.943	0.987	0.984	0.966	0.992
22	0.986	0.970	0.993	0.972	0.941	0.987
23	0.982	0.961	0.991	0.985	0.967	0.993
24	0.982	0.961	0.992	0.972	0.902	0.989
25	0.962	0.919	0.982	0.976	0.948	0.989
26	0.582	-0.144	0.873	0.628	-0.206	0.855
31	0.941	0.874	0.972	0.968	0.932	0.985
32	0.972	0.939	0.987	0.978	0.948	0.990
33	0.972	0.940	0.987	0.972	0.940	0.987
34	0.981	0.958	0.991	0.978	0.954	0.990
35	0.971	0.908	0.989	0.961	0.269	0.991
36	0.918	0.498	0.974	0.899	0.042	0.973
41	0.940	0.874	0.972	0.957	0.906	0.980
42	0.967	0.930	0.985	0.979	0.950	0.991
43	0.985	0.966	0.993	0.957	0.884	0.982
44	0.990	0.979	0.995	0.976	0.950	0.989
45	0.973	0.928	0.988	0.947	0.773	0.981
46	0.939	0.591	0.981	0.926	0.339	0.979

6.4 Hand measured and ClinCheck® Values on Maxillary and Mandibular First Molars

6.4.1. Pre-treatment measurement differences for hand measured and Clincheck® values on the maxillary and mandibular first molar teeth

- Table 6.4.1 shows ClinCheck® measurements are consistently larger than hand measurements when looking at all first molars with the greatest difference seen in tooth #16 and #26. Significant differences were found for all first molars (P<.001).

Table 6.4.1: Pre-treatment measurement differences for Hand and ClinCheck® values

Tooth number	Hand (n=29)	ClinCheck (n=29)	Difference (mm)	T (p-value)
16	10.73 (.53)	11.57 (.50)	+0.84	-13.63 (<.001)
26	10.73 (.51)	11.49 (.57)	+0.76	-13.05 (<.001)
36	11.59 (.50)	11.79 (.50)	+0.20	-5.26 (<.001)
46	11.61 (.49)	11.78 (.53)	+0.17	-5.29 (<.001)

*Mean/SD shown, paired t test used

6.4.2. Last refinement measurement differences for hand measured and Clincheck® values on the maxillary and mandibular first molar teeth

- Table 6.4.2 shows ClinCheck® measurements are consistently larger than hand measurements when looking at all first molars with the greatest difference seen in tooth #16 and #26. Significant differences were found for all first molars (P<.001).

Table 6.4.2: Last refinement measurement difference for Hand and ClinCheck® values

Tooth number	Hand (n=29)	ClinCheck (n=29)	Difference (mm)	T (p-value)
16	10.70 (.45)	11.39 (.54)	+0.69	-11.92 (<.001)
26	10.74 (.49)	11.36 (.53)	+0.62	-10.00 (<.001)
36	11.53 (.47)	11.78 (.49)	+0.25	-7.53 (<.001)
46	11.58 (.47)	11.79 (.50)	+0.21	-6.32 (<.001)

*Mean/SD shown, paired t test used

6.4.3. Summary of Pre-treatment measurement differences for hand measured and Clincheck®

values

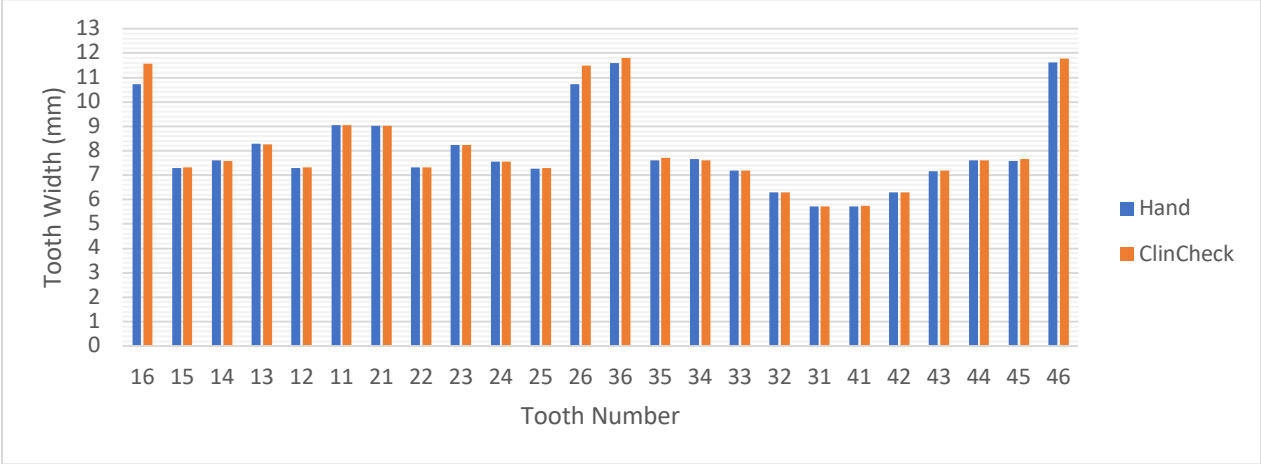
- Table 6.4.3 and figure 6.4.3 shows ClinCheck® measurements are consistently larger than hand measurements with the values getting progressively larger moving posteriorly. The greatest difference is seen in tooth #16 (+0.84mm) and #26 (+0.76mm).

Table 6.4.3: Summary of Mean Tooth Widths and Difference - Pre-Treatment (T1)

Tooth number	Hand (n=29)	ClinCheck Pre (n=29)	Difference (mm)
16	10.73 (.50)	11.57 (.50)	+0.84
15	7.29 (.50)	7.31 (.47)	+0.02
14	7.60 (.49)	7.57 (.47)	-0.02
13	8.29 (.53)	8.25 (.54)	-0.03
12	7.29 (.44)	7.32 (.46)	+0.03
11	9.04 (.47)	9.06 (.49)	+0.03
21	9.03 (.48)	9.03 (.48)	+0.01
22	7.31 (.50)	7.31 (.52)	-0.01
23	8.23 (.51)	8.24 (.51)	+0.01
24	7.55 (.48)	7.55 (.46)	0
25	7.26 (.52)	7.30 (.44)	+0.03
26	10.73 (.51)	11.49 (.57)	+0.76
36	11.59 (.50)	11.79 (.50)	+0.20
35	7.61 (.52)	7.70 (.47)	+0.09
34	7.66 (.51)	7.61 (.52)	-0.05
33	7.18 (.49)	7.18 (.53)	-0.01
32	6.29 (.43)	6.30 (.39)	0
31	5.73 (.32)	5.73 (.31)	0
41	5.72 (.30)	5.74 (.29)	+0.03
42	6.29 (.37)	6.29 (.37)	0
43	7.15 (.51)	7.20 (.57)	+0.05
44	7.62 (.51)	7.60 (.51)	-0.02
45	7.58 (.50)	7.66 (.50)	+0.08
46	11.61 (.49)	11.78 (.53)	+0.17

*Mean/SD shown

Figure 6.4.3: Mean tooth widths for Hand measurements and ClinCheck Software (T1)



6.4.4. Summary of Last Refinement measurement differences for hand measured and Clincheck® values

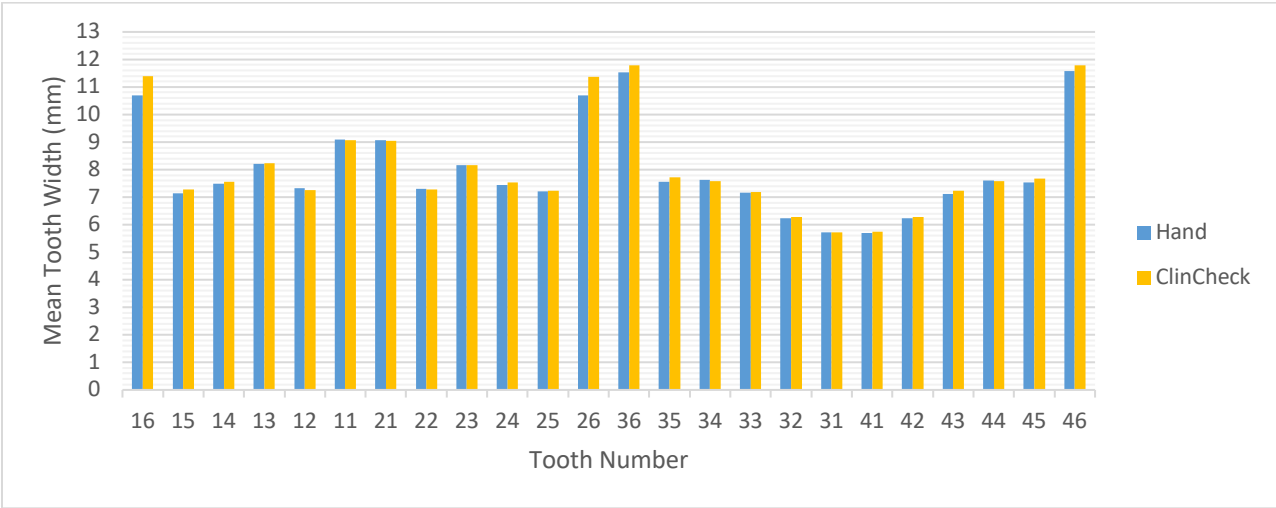
- Table 6.4.4 and figure 6.4.4 shows ClinCheck® measurements are consistently larger than hand measurements with the values getting progressively larger moving posteriorly. The greatest difference is seen in tooth #16 (+0.69mm) and #26 (+0.62mm).

Table 6.4.4: Summary of Mean Tooth Widths and Difference - Last Refinement (T2)

Tooth number	Hand Measure Post(n=29)	ClinCheck Measure Pre (n=29)	Difference (mm)
16	10.70 (.45)	11.39 (.54)	+0.69
15	7.15 (.48)	7.28 (.47)	+0.13
14	7.49 (.46)	7.55 (.48)	+0.06
13	8.21 (.57)	8.22 (.54)	+0.02
12	7.32 (.51)	7.26 (.46)	-0.1
11	9.08 (.49)	9.07 (.51)	0
21	9.07 (.47)	9.05 (.47)	0
22	7.31 (.52)	7.28 (.49)	0
23	8.17 (.56)	8.17 (.52)	0
24	7.44 (.47)	7.53 (.47)	+0.09
25	7.20 (.47)	7.24 (.44)	+0.04
26	10.70 (.49)	11.36 (.53)	+0.62
36	11.53 (.47)	11.78 (.49)	+0.25
35	7.56 (.48)	7.71 (.46)	+0.16
34	7.62 (.48)	7.58 (.53)	0
33	7.17 (.55)	7.18 (.56)	+0.02
32	6.24 (.41)	6.29 (.41)	+0.05
31	5.71 (.30)	5.72 (.30)	+0.01
41	5.70 (.28)	5.74 (.30)	+0.04
42	6.24 (.40)	6.29 (.39)	+0.05
43	7.11 (.54)	7.23 (.61)	+0.11
44	7.61 (.50)	7.57 (.47)	0
45	7.53 (.48)	7.67 (.49)	+0.14
46	11.58 (.47)	11.79 (.50)	+0.2

*Mean/SD shown

Figure 6.4.4: Mean tooth widths for Hand measurements and ClinCheck® Software (T2)



7. Discussion

7.1. Reliability of ClinCheck® mesiodistal tooth widths

Invisalign is the most widely used aligner system on the market but the accuracy of their tooth width and Bolton ratio measurements remains unproven by an independent investigation (Shailendren *et al.*, 2022). In this study, hand measured mesiodistal tooth widths were compared the tooth widths provided by the ClinCheck® software split by tooth number and found excellent reliability for all the teeth except for the maxillary first molars. The maxillary first molars showed poor to moderate reliability at two different time points while the mandibular first molars had wide 95% confidence intervals. Table 6.4.3 and 6.4.4 shows that the ClinCheck® measurements are consistently larger than the hand measured values with the greatest difference seen in tooth #16 (+0.83mm) and #26 (+0.76mm) for pre-treatment values and #16 (+0.69mm) and #26(+0.62mm) for last refinement values with the greatest difference being for the pre-treatment measurements.

Shailendren *et al.* suggested ClinCheck® software progressively underestimated tooth widths and the discrepancy progressively worsens as you move posteriorly. They suggested that the software's measurement inaccuracies were due to challenges in accurately capturing the interproximal contact areas with a digital scanner. Additionally, Align Technology utilizes patented algorithms and shape assumptions which attempts to reconstruct the anatomy of interproximal areas (Shailendren *et al.*, 2022). Whereas, in a study by Adobe Martins *et al.*, they found that ClinCheck® software provided larger tooth widths compared to hand measurements (Adobes Martin *et al.*, 2022). The values found in this study shows that ClinCheck® software

overestimates the values and are seen to be larger than the hand measured values with the tooth widths progressively getting larger as you move posteriorly.

Andrew's six keys of defining a normal occlusion suggested that a rotated molar occupies a greater mesio-distal space may explain Clincheck® pre-treatment upper molar measurements are larger than in the last refinement measurements (Pre-treatment #16 = 11.57 / #26 = 11.49, Refinement #16 = 11.39 / #26 = 11.36) the mean difference being 0.18mm for #16 and 0.13mm for #26. We are not aware of how the ClinCheck® software operates and the tools it uses to measure the mesio-distal widths but with the difference seen between manual measurements and software measurements it could be due to a variation in how the software measures the mesiodistal width such that the software may not be able to accurately determine where the mesiodistal contact point of each tooth is located. Adobes Martin *et al.* suggested maxillary first molars may be inaccurate on the ClinCheck® software due to their trapezoidal shape where the maximum width is not in line with the contact points. A rotated trapezoidal upper molar when interpreted on the ClinCheck® software could result in larger measurements and thus result in misinterpreting and diagnosing an overall Bolton ratio (Adobes Martin *et al.*, 2022). Lastly, the shape of the anatomical structure being measured could also affect the point identification such as it is more difficult to precisely identify a point located on a curved anatomical structure than a point located at the edge of an anatomical structure (Koretsi *et al.*, 2018).

The excellent ICC for the anterior tooth widths in both hand measurements and on the ClinCheck® software could be due to the incisors having a more regular shape where the maximum width is in line with the contact points. This corresponds to other studies who showed

that mandibular incisor measurements are accurate and reliable across both manual caliper method and using the digital model system (Bowes *et al.*, 2017; Koretsi *et al.*, 2018; Adobes Martin *et al.*, 2022).

7.2. Accuracy of Bolton ratios

Although there was an excellent Intraclass Correlation (ICC) for the anterior and overall Bolton ratio at 2 different time points, the wide confidence intervals show that the reliability for the Bolton ratios given by ClinCheck® may be questionable.

It is difficult to distinguish whether the discrepancies in the measurements are due to human errors made by the primary investigator or due to inaccuracies within the ClinCheck® software. Based off of the study by Shailendren *et al* and Adobes Martin *et al* in 2022 that looked at the inaccuracies in the ClinCheck® software as well as numerous studies that found clinically insignificant differences between hand measurements on 3D digital models and the traditional method of using digital calipers on plaster cast it can be inferred that the ClinCheck® software may contain some inaccuracies. (Zillberman *et al.*, 2003; Paredes *et al.*, 2006; Rossini *et al.*, 2016; Bowes *et al.*, 2017; Koretsi *et al*, 2017; Shailendren *et al.*, 2022; Adobes Martin *et al.*, 2022) Therefore, ClinCheck® Bolton ratios should be interpreted with caution. Instead of relying solely on ClinCheck® Bolton ratios, clinicians should use their clinical judgement when planning and performing IPR or composite build ups.

Another possibility regarding the inaccuracy of the Bolton ratios may be that ClinCheck® software may not use the same formula proposed by Bolton in 1962. Adobes Martin *et al.* looked

at the Bolton ratios provided by the software and compared it with the one calculated with the original Bolton formula on the tooth width measurements provided by the software and found the software does not use the original Bolton formula to assess for tooth size discrepancies.

Although they found clinically significant differences in the anterior and overall Bolton made by the ClinCheck® software the difference was found to be 2mm and differences of up to 2mm is considered clinically acceptable (Adobes Martin *et al*, 2022; Othman *et al.*, 2006; Bowes *et al.*, 2020). They concluded the anterior and overall Bolton ratios on the ClinCheck® software are not accurate but the difference is still considered clinically acceptable especially in the case of mandibular excess (Adobes Martin *et al*, 2022).

Lastly, when comparing hand measurements with ClinCheck® Bolton ratios, only the pre-treatment anterior Bolton ratio showed no significant difference and that could be due to random error. Even though the results showed a statistically significant difference for pre-treatment overall ratio, last refinement anterior and overall ratio, the difference is only found to be $\pm 1\%$ and the difference would in all probability not be clinically relevant.

7.3. Effects of crowding on Anterior and Overall Ratios

In this study crowding shows no significant differences in both the anterior ($p=.172$) and overall ($p=.938$) ratios at two timepoints. This is based on the excellent intra and inter-rater reliability of the tooth width measurements and it can be assumed that the anterior and overall ratios for T1 and T2 are accurate.

However, Shellhart's study showed clinically significant measurement errors in +3mm of crowding (Shellhart *et al.*, 1995). This assumption was based on findings from a Boley gauge and a needle pointed divider and should be re-evaluated with more modern digital techniques.

ClinCheck® Software shows that there are statistically significant differences when crowding is present between the anterior ($p=.05$) and overall ($p<.001$) ratios. However, the difference is only $\pm 1\%$ and the difference would likely not be clinically relevant.

7.4. Factors Affecting Inter-rater reliability

In this study there was excellent inter-rater reliability between the primary investigator and the secondary investigator for measuring each tooth and when computing the pre-treatment overall ratio and last refinement anterior and overall ratio but the inter-rater reliability had a wide confidence interval for calculating the pre-treatment anterior ratio. The inter-rater reliability may have been influenced by slight individual variations and random measurement errors are more likely to be accentuated during calculations of the anterior Bolton ratio as there are less tooth widths involved in the calculation compared to an overall Bolton ratio.

7.5. Evaluation of the Null Hypothesis

1. The mesiodistal tooth widths as predicted by the ClinCheck® Software are not reliable in comparison to those measured manually using the digital caliper.
 - Reject - the results show the mesiodistal tooth widths as predicted by the ClinCheck® Software compared to those measured manually using a digital caliper had excellent reliability for every tooth (ICC=0.941-0.986) except for the first molars in both arches (ICC=0.491-0.628) where the maxillary first molars showed poor to moderate reliability and the mandibular molars had wide 95% confidence intervals.

2. There is no statistically significant difference between the anterior and overall Bolton ratios determined by ClinCheck® software when measuring tooth widths at two time points.
 - Reject – this study found statistically significant differences for the anterior and overall Bolton ratios given by ClinCheck® software when measuring tooth widths at two time points ($p=0.05$, $p<0.01$). Therefore, the ClinCheck® software shows questionable reliability when Bolton ratios are estimated.

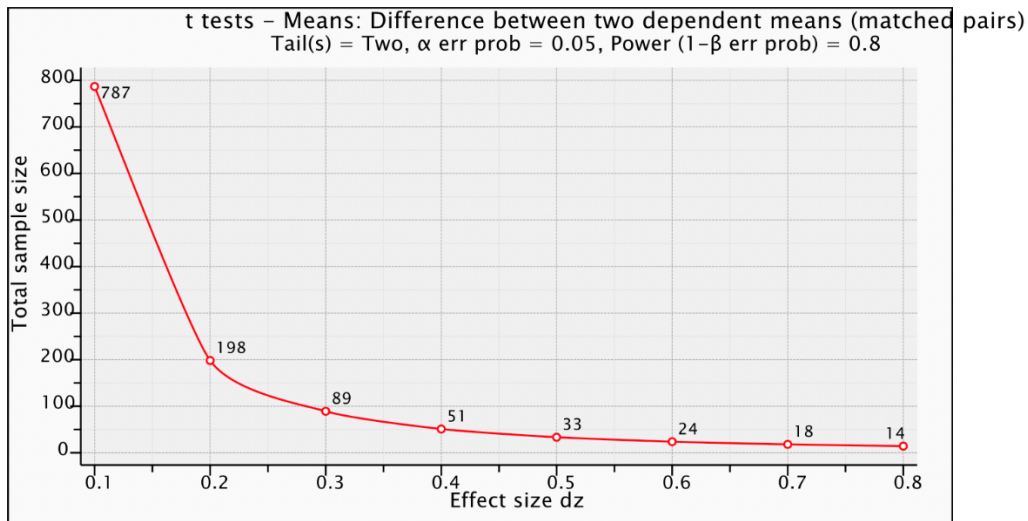
3. There is no statistically significant difference between the anterior and overall Bolton ratios in crowded cases before treatment and at the last refinement scan
 - This can be accepted for hand measured anterior ($p=.172$) and overall ($p=.938$) Bolton ratios however, this null hypothesis can be rejected when assessing the Bolton ratios on the ClinCheck® Software which shows that there are statistically significant differences when crowding is present between the anterior ($p=.05$) and overall ($p<.001$) ratios.

However, the difference is only $\pm 1\%$ and the difference would likely not be clinically relevant.

7.6. Study limitations

An important limitation to this study was the study's small sample size. While a sample size of 29 gave sufficient power, a greater sample size would have allowed better statistical analysis to be drawn. A sensitivity test of 29 was on the lower limit on being able to detect a medium effect when using two dependent sample t-tests for comparison. A greater sample size would reduce the margin of error in detecting the important effects and drawing meaningful conclusions.

Figure: 7.6 Effect size according to Different Sample Size



7.7 Clinical Relevance

ClinCheck® Software is considered accurate and clinically acceptable when measuring individual teeth except for permanent first molars in both arches. Align Technology should focus on improving their software's ability to measure posterior dentition.

Instead of relying solely on ClinCheck® Bolton ratios, we should use sensible clinical judgement when planning for IPR or composite build ups.

7.8 Future Studies

1. Using different clinical parameters such as testing tooth width measurements and Bolton Ratios in cases with only Mild crowding (0-3mm), only Moderate crowding (4-7mm) and only severe crowding (8+mm) on pre-treatment and post-treatment records.
2. Comparing tooth width measurements and Bolton ratios on other competing clear aligner systems such as ClearCorrect (Straumann), SureSmile (Dentsply), Solventum (3M), Spark (Ormco) or comparing multiple clear aligner systems to conventional hand measured values.

8. Conclusions

1. Tooth width measurements assessed by the ClinCheck® Software are reliable and clinically acceptable when measuring individual teeth, except for first molars in both arches.
2. ClinCheck® Software shows questionable accuracy when Bolton ratios are estimated.
3. Crowding does not influence Bolton ratios when calipers are used whereas ClinCheck® indicates there are statistically significant but in all probability not clinically relevant differences in ratios when crowding is present.

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10. APPENDIX

10.1 ETHICS APPROVAL



University of Manitoba | Research Ethics and Compliance

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**HEALTH RESEARCH ETHICS BOARD (HREB)
 CERTIFICATE OF FINAL APPROVAL FOR NEW STUDIES
 Delegated Review**

PRINCIPAL INVESTIGATOR: Dr. Anita Lee	INSTITUTION/DEPARTMENT: University of Manitoba and Orthodontic Clinic at Childrens Dental World/Preventive Dental Sciences	ETHICS #: HS26305 (H2024:034)
APPROVAL DATE: June 24, 2024		EXPIRY DATE: June 24, 2025
STUDENT PRINCIPAL INVESTIGATOR SUPERVISOR (if applicable): William Wiltshire		
PROTOCOL NUMBER:	PROJECT OR PROTOCOL TITLE: Accuracy of Bolton Anterior and Overall Ratios on ClinCheck Software in crowded cases before and after treatment	
SPONSORING AGENCIES AND/OR COORDINATING GROUPS: No funding		
Submission Date of Investigator Documents: January 17, 2024 and June 13, 2024		HREB Receipt Date of Documents: January 17, 2024 and June 13, 2024

THE FOLLOWING ARE APPROVED FOR USE:

Document Name	Version (if applicable)	Date
Protocol: Revised protocol along with proposal as outlined in the revised University of Manitoba Bannatyne Campus Research Ethics Board Submission Form for Retrospective Chart or Records Review and Letter of Response dated June 13, 2024		June 12, 2024
Consent and Assent Form(s): RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM (<u>First page of the consent form MUST have institutional UM logo or be placed on UM Letterhead prior to presenting to participants</u>)		June 12, 2024
ASSENT FOR CHILDREN less than 13 years old (<u>First page of the consent form MUST have institutional UM logo or be placed on UM Letterhead prior to presenting to participants</u>)		January 5, 2024
Other: Data Collection/Capture Sheet (undated) Master List (undated)		

CERTIFICATION

The above-named research study/project has been reviewed in a *delegated manner* by the University of Manitoba (UM) Health Research Board (HREB) and was found to be acceptable on ethical grounds for research involving human participants. The study/project and documents listed above was granted final approval by the Chair or Acting Chair, UM HREB.

HREB ATTESTATION

The University of Manitoba (UM) Research Board (HREB) is organized and operates according to Health Canada/ICH Good Clinical Practices, Tri-Council Policy Statement 2, and the applicable laws and regulations of Manitoba. In respect to clinical trials, the HREB complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations of Canada and carries out its functions in a manner consistent with Good Clinical Practices.

A unit of the office of the Vice-President (Research and International)
<https://umanitoba.ca/research/opportunities-support/ethics-compliance/ethics/bannatyne>

10.2 Journal Article and Submission Confirmation

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To: Anita Lee

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Tue 5/13/2025 2:41 PM

Caution! This message was sent from outside the University of Manitoba.

Dear Dr. Lee:

On May 13, 2025, I received your manuscript entitled "Accuracy of Bolton Anterior and Overall Ratios on ClinCheck®; Software in The Crowded Dentition" by authors:

Anita Lee
William Wiltshire
Milos Lekic
Sylvia Todescan

Your manuscript has been assigned the Paper #: 050825-366.

The paper will be sent out to experts who will be asked to assist with the peer review of your manuscript. Please note that the average time for this review is about 8 weeks.

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Thank you for submitting your best work to The Angle Orthodontist.

Sincerely,

Steven J Lindauer
Editor, The Angle Orthodontist

Reply

Forward

Title: Accuracy of Bolton Anterior and Overall Ratios on ClinCheck® Software in The Crowded Dentition

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Accuracy of Bolton Anterior and Overall Ratios on ClinCheck® Software in The Crowded Dentition

ABSTRACT

Objective:

(1) Investigate the reliability of ClinCheck® Software on predicted mesiodistal tooth widths (2) assess the accuracy of Bolton ratios at 2 time points and (3) whether crowding has any influence on Bolton ratios.

Materials and Methods:

Overall and anterior Bolton ratios were calculated for 29 patients with 5 to 8mm of crowding and had undergone Invisalign treatment at a private orthodontic clinic. To evaluate the Bolton ratios, the mesiodistal widths were manually measured (electronic caliper) on 3D printed casts pre-treatment (T1) and at the last refinement scan (T2) as well as via ClinCheck® Software.

Results:

Statistically significant differences found in Bolton Ratios between manual measurements and ClinCheck® Software for the T1 overall ratio ($p < .001$), T2 anterior ratio ($p < .001$) and T2 overall ratio ($p = .016$, 1% of difference). Manual measurements indicate that crowding does not affect Bolton anterior ($p = .172$) and overall ratios ($p = .938$), however ClinCheck® measurements indicate that there are statistically significant differences in the anterior ($p = .05$) and overall ($p < .001$) Bolton ratios when crowding is involved ($\pm 1\%$). Tooth width measurements assessed by ClinCheck® Software tends to provide larger tooth widths compared with manual measurements.

Conclusions:

Tooth width measurements assessed by the ClinCheck® Software are reliable and clinically acceptable when measuring individual teeth, except for first molars in both arches. ClinCheck® Software shows questionable accuracy when Bolton ratios are estimated. Crowding does not influence Bolton ratios when calipers are used whereas ClinCheck® indicates there are statistically significant but in all probability not clinically relevant differences in ratios when crowding is present.

Introduction

Meticulous treatment planning in orthodontics is crucial to ensure a beautiful and successful end result. In order to achieve optimal esthetics and occlusion, an orthodontist must be able to recognize tooth size discrepancies within the maxillary and mandibular arch and treatment plan accordingly. To address inter-arch tooth size discrepancies a few methods have been proposed: interproximal reduction, finishing with open spaces in the anterior region for composite build ups and accepting a non-class I buccal segment finish.¹ The use of tooth width measurements and a Bolton analysis can be used to detect tooth-size discrepancies.²

The Bolton analysis was established by Wayne Bolton in 1958. Bolton studied 55 cases of “excellent occlusion” to investigate the relationship between the mesiodistal widths of maxillary and mandibular teeth in an ideal occlusion.^{3 4} Bolton established a ratio by measuring the mesiodistal widths from the canine to canine of the maxillary and mandibular anterior teeth and termed it the “anterior ratio” and calculated this value to be 77.2% (± 1.65). The term “overall ratio” is the ratio from measuring the mesiodistal widths from the first molar to the first molar of the mandibular teeth and maxillary teeth and the ratio was determined to be 91.3 (± 1.91).^{3,4} Bolton anterior and overall ratio has become the gold standard in evaluating inter-arch tooth size discrepancies.

Traditionally, tooth width measurements are obtained from using plaster study casts and calipers. With advances in digital dentistry, there is a recent trend toward using digital study models as opposed to traditional plaster study models to obtain tooth measurements. With recent technological advances, 3D printing technology has allowed for a more digital workflow in dentistry and has reduced the need of the traditional way of obtaining study models. The main benefits of 3D models over conventional plaster models include increased efficiency, ease of use,

durability (no risk of physical damage) and space-saving storage eliminating the need for physical space.⁵ Digital model systems have been found to be just as reliable with high accuracy and reproducibility as compared with conventional plaster models.⁶ In recent years there have been many digital model software programs with applications that can measure tooth widths and Bolton ratios to aid in orthodontic treatment planning. However, many of these digital software systems have not had the estimations of their tooth widths validated.

With the rising popularity of Invisalign® in recent years, Align Technology is considered the leading manufacturer of clear aligners. Invisalign® is accompanied by ClinCheck® Pro software which provides estimations of the mesiodistal widths and Bolton ratios in millimeters to 2 decimal places of all permanent teeth except the second and third molars. The accuracy of these estimations has not been confirmed.⁷

When crowding is present the ideal interproximal contact points may sometimes be estimated and this estimation can introduce variations in the measurements of the teeth.⁸ It was observed that Bolton anterior ratio was significantly higher when lower incisal crowding is present compared to the group with good alignment.⁹ Therefore, the analysis in tooth-size discrepancy in crowded cases may have more limited reliability.

The purpose of this study was:

4. To investigate the reliability of the mesiodistal tooth widths predicted by the ClinCheck® Software and compare to those measured using digital calipers.
5. To assess the accuracy of Bolton ratios given by Invisalign's ClinCheck® software at two different time points.
6. To determine whether crowding has any influence on the anterior and overall Bolton ratios.

Methods

Overall and anterior Bolton ratios were calculated for **29 patients** from a private orthodontic clinic with pre-treatment iTero records (T1) and last refinement iTero record (T2) once all the crowding has unravelled. To evaluate Bolton ratios, the mesiodistal tooth widths of every tooth from the first right molar to the first left molar in each jaw was recorded by measuring the greatest distance between physiological contact points on the proximal surfaces. Measurements were manually measured with a fine tip electronic caliper (OrthoPli #0400-EEP) accurate to 0.01mm on 3D printed models by a primary and a secondary investigator and compared to the Bolton ratios as predicted by the ClinCheck® Software. Ethics approval was obtained from the university Human Research Ethics Board prior to the commencement of this study.

Inclusion criteria

The orthodontic digital casts at two time points (T1 and T2) that were included in the sample satisfied the following criteria:

8. 5mm – 8mm crowding in Mx and Md arch overall
9. Permanent dentition present from 16 to 26 and 36 to 46
10. No interproximal reduction performed during treatment
11. No congenitally missing teeth
12. No interproximal caries or restorations
13. No permanent teeth extracted during treatment
14. Patients underwent clear aligner (Invisalign) treatment and their teeth were digitally scanned with the iTero scanner at two time points

Exclusion criteria

5. Congenitally missing teeth
6. Interproximal reduction
7. Interproximal restorations or caries
8. Peg lateral incisors

Anterior and Overall Bolton Ratio Calculations

Using the formula for the Bolton “overall ratio” and “anterior ratio” the data from the measurements obtained from measuring casts using a digital caliper were calculated.

The formula is as follows:

$$\text{Overall ratio} = \frac{\text{Sum of mesiodistal tooth widths of mandibular 6-6}}{\text{Sum of mesiodistal tooth widths of maxillary 6-6}} \times 100$$

$$\text{Anterior ratio} = \frac{\text{Sum of mesiodistal tooth widths of mandibular 3-3}}{\text{Sum of mesiodistal tooth widths of maxillary 3-3}} \times 100$$

Assessment of Intra- and Inter-examiner Reliability

Intra-examiner reliability was assessed by remeasuring 50% of the sample by the primary investigator and was done 2 weeks after completion of the initial measurements to prevent recall bias.

To assess for the inter-examiner reliability, 20% of the sample was randomly selected by the secondary investigator. The secondary investigator was calibrated by the primary investigator on the use of the digital caliper.

Lastly, the overall and anterior Bolton ratios was evaluated using the mesiodistal tooth widths acquired from the patients Invisalign ClinCheck® and compared to the ratios that were calculated using the measurements obtained from measuring 3D casts using a digital caliper.

Statistical Tests

Paired T tests were used to compare the accuracy of ClinCheck® estimated tooth widths and Bolton ratios tested on 29 patients measured from 2 time points (T1 – initial scan and T2 – last refinement scan). They were also used to determine the accuracy of ClinCheck® predicted anterior and overall Bolton ratios compared to manual measurements using a digital caliper. The p-value was considered significant for $\alpha < 0.05$.

Intraclass correlation coefficient (ICC) analyses were used to determine intra-rater reliability and inter-rater reliability between the primary and secondary investigators. This was also used to determine the reliability of ClinCheck® Bolton ratios.

ICC values can be judged by:

- Values less than 0.5 indicated poor reliability
- Values between 0.5 and 0.75 indicated moderate reliability
- Values between 0.75 and 0.9 showed good reliability
- Values greater than 0.90 reflected excellent reliability.

RESULTS

Intra-rater and Inter-rater Reliability of Each Individual Tooth

There was excellent reliability between Intra-rater (ICC = 1.00, ICC = 0.999), inter-rater (ICC=0.999, ICC=0.999) and ClinCheck® Software (ICC=0.993, ICC=0.994) at T1 and T2

Intra-Rater and Inter-Rater Reliability of Anterior and Overall Ratios (T1 and T2)

Anterior Ratios: **excellent** intra-rater (ICC = 0.975, ICC = 0.984), inter-rater (ICC = 0.941, ICC = 0.913) and **T1** ClinCheck® (ICC = 0.922) but only **good** for **T2** with wide 95% CI (0.577 - 0.958)

Overall Ratios: **excellent** intra-rater (ICC = 0.958, ICC = 0.979), inter-rater (ICC = 0.970, ICC = 0.948) and only **good** for **T1** ClinCheck® (ICC = 0.848, ICC = 0.888) but wide 95% CI for **T2** (0.267 - 0.949)

Inter-rater reliability by tooth number for the Hand measurements vs ClinCheck® (T1 and T2)

There was poor to moderate inter-rater reliability for **T1 #16** (ICC = 0.491, 95% CI, -0.135-0.827), **#26** (ICC = 0.582, 95% CI, -0.144-0.873), **T2 #16** (ICC = 0.581, 95% CI, -0.166-0.870) and **#26** (ICC=0.628, 95% CI, -0.206-0.855)

Wide 95% Confidence Interval (CI) for T1 #46 (ICC = 0.939, 95% CI, 0.591-0.981) and **#36** (ICC = 0.918, 95% CI, 0.498-0.974)) and **T2 #46** (ICC = 0.926, 95% CI, 0.339-0.979) and **#36** (ICC = 0.899, 95% CI, 0.042-0.973)

Comparison of Hand Measured Ratios Vs. ClinCheck Software Ratios

Significant differences were found for the pre-treatment overall ratio ($p < .001$), last refinement anterior ratio ($p < .001$), and last refinement overall ratio ($p = .016$) while no significant differences were found for the pre treatment anterior ratio ($p = .603$) as shown in Table 1.

Comparisons Between Pre Treatment and Last Refinement for Hand Measurements

No significant differences were found between T1 and T2 anterior ($p = .172$) and overall ratios ($p = .938$) as shown in Table 2.

Comparisons Between Pre Treatment and Last Refinement for ClinCheck Software

Significant differences were found between T1 and T2 anterior ($p = .05$) and overall ratios ($p < .001$) as shown in Table 3.

Pre-treatment measurement differences for hand measured and Clincheck® values on the maxillary and mandibular first molar teeth

ClinCheck® measurements were consistently larger than hand measurements when looking at all first molars with the greatest difference seen in tooth #16 and #26. Significant differences were found for all first molars ($P < .001$) as shown in Table 4.

Last refinement measurement differences for hand measured and Clincheck® values on the maxillary and mandibular first molar teeth

ClinCheck® measurements were consistently larger than hand measurements when looking at all first molars with the greatest difference seen in tooth #16 and #26. Significant differences were found for all first molars ($P < .001$) as shown in Table 5.

Summary of Pre-treatment and Last Refinement measurement differences for hand and Clincheck® values

ClinCheck® measurements were consistently larger than hand measurements with the values getting progressively larger moving posteriorly for both T1 and T2. The greatest difference is seen in maxillary first molars (#16 (+0.84mm, +0.69mm) and #26 (+0.76mm, +0.62mm) as shown in Table 6 and 7 and figure 1 and 2.

Discussion

Reliability of ClinCheck® mesiodistal tooth widths

In this study when comparing the hand measurements and ClinCheck® measurements, every tooth showed an excellent reliability except for the maxillary 1st molars which showed **poor to moderate** reliability at two time points while the mandibular 1st molars had a wide 95% CI.

Table 4 and table 5 shows that the ClinCheck® measurements are consistently larger than the hand measured values with the greatest difference seen in tooth #16 (+0.83mm) and #26 (+0.76mm) for pre-treatment values and #16 (+0.69mm) and #26(+0.62mm) for the last refinement values with the difference being greater in the pre-treatment measurements.

Shaildendren *et al* suggested that the ClinCheck® software progressively underestimated tooth widths and the discrepancy progressively worsens as you move posteriorly.⁷ The measurement inaccuracies could be due to poor visibility in the posterior area and the software's difficulty in capturing the interproximal areas with the digital scanner. Additionally, Align Technology utilizes patented algorithms and shape assumptions which attempts to reconstruct the anatomy of interproximal areas.⁷ However, in a study by Adobes Martin *et al*, it was found that the ClinCheck® software provided larger tooth widths compared to hand measurements¹⁰ The values found in this study shows that ClinCheck® software overestimates the values and are seen to be larger than the hand measured values. The larger measurements on digital models could be due to the ability to utilize functions such as zooming in or rotating the casts digitally which can help with point positioning. Whereas, when measuring dental casts there could be some difficulty in the caliper tips accessing the contact points of the teeth depending on the bulk of the caliper tips.¹¹

Lastly, we are unaware of how the ClinCheck® software measures the mesio-distal tooth-widths but with the difference seen between manual and software measurements it could be due to the software not being able to accurately locate where the mesiodistal contact point of each tooth is. Adobes Martin *et al* suggested maxillary first molars may be inaccurate on the ClinCheck® software due to their trapezoidal shape where the maximum width is not in line with the contact points. A rotated trapezoidal upper molar when interpreted on the ClinCheck® software could result in larger measurements and thus result in misinterpreting and diagnosing an overall Bolton ratio.¹⁰

Accuracy of Bolton Ratios

Although there was an excellent intraclass correlation (ICC) for the anterior and overall ratio at 2 different time points, the wide confidence intervals show that the reliability for the Bolton ratios given by ClinCheck® may be questionable.

It is difficult to distinguish whether the discrepancies in measurements are due to human error made by the primary investigator or due to inaccuracies within the ClinCheck® software.

Based off of the study by Shailendren *et al* and Adobes Martin *et al* in 2022 that looked at the inaccuracies in the ClinCheck® software as well as numerous studies that found clinically insignificant differences between hand measurements on 3D digital models and the traditional method of using digital calipers on plaster cast it can be inferred that the ClinCheck® software may contain some inaccuracies.^{6,7,10, 12,13,14} Therefore, ClinCheck® Bolton ratios should be interpreted with caution. Instead of relying solely on ClinCheck® Bolton ratios, clinicians should use their clinical judgement when planning and performing IPR or composite build ups.

Another possibility regarding the inaccuracy of the Bolton ratios may be that ClinCheck® software may not use the same formula proposed by Bolton in 1962. Adobes Martin *et al.* looked at the Bolton ratios given by the software and compared it with the one calculated using the original Bolton formula with the tooth width measurements provided by the software and found the software does not use the original Bolton formula for tooth discrepancy assessment.¹⁰ Although clinically significant differences were found in the anterior and overall Bolton ratios provided by the ClinCheck® software the difference was found to be 2mm and the threshold for clinically significant tooth size discrepancies of up to 2mm is considered clinically acceptable.^{11,15,16}

Effects of crowding on Anterior and Overall Bolton Ratios

In this study crowding shows no significant differences in both the anterior ($p=.172$) and overall ($p=.938$) ratios at two timepoints. This is based on the excellent intra and inter-rater reliability of the tooth width measurements and can be assumed the anterior and overall ratios for T1 and T2 are accurate.

However, Shellhart *et al.* study showed clinically significant measurement errors in +3mm of crowding.⁸ This assumption was based on findings from a Boley gauge and a needle pointed divider and should be re-evaluated with more modern digital techniques.

ClinCheck® Software shows that there are statistically significant differences when crowding is present between the anterior ($p=.05$) and overall ($p<.001$) ratios. However, the difference is only $\pm 1\%$ and the difference would in all probability not be clinically relevant.

Conclusions

1. Tooth width measurements assessed by the ClinCheck® Software are reliable and clinically acceptable when measuring individual teeth, except for first molars in both arches.
2. ClinCheck® Software shows questionable accuracy when Bolton ratios are estimated.
3. Crowding does not influence Bolton ratios when calipers are used whereas ClinCheck® indicates there are statistically significant but in all probably not clinically relevant differences in ratios when crowding is present.

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TABLES

Table 1: Comparison of Hand Measured Ratios vs ClinCheck® Software ratios

	Hand Measurement	Software Measurement	t(df) p-value
Pre Treatment Anterior Ratio	77.999 (2.007)	78.107 (2.076)	-0.526(28), p=.603
Pre Treatment Overall Ratio	91.715 (1.807)	90.734 (1.780)	5.25 (28), p<.001
Last Refinement Anterior Ratio	77.641 (1.586)	78.362 (1.940)	-4.13(28), p<.001
Last Refinement Overall Ratio	91.698 (1.503)	91.266 (1.578)	2.56 (28). P=.016

*Paired t test used (Mean, SD shown)

Table 2: T1 and T2 – Primary Investigator hand measurements

	Pre Treatment	Last Refinement	t(df) p=value
Anterior Ratio	77.999 (2.007)	77.641 (1.586)	t(28) = 1.40, p=.172
Overall Ratio	91.715 (1.807)	91.698 (1.503)	t(28) = .079, p=.938

*Paired t test used (Mean, SD shown)

Table 3: T1 and T2 – ClinCheck® Software

	Pre Treatment	Last Refinement	t(df) p=value
Anterior Ratio	78.107 (2.076)	78.362 (1.940)	t(28) = -2.04, p=.05
Overall Ratio	90.734 (1.780)	91.266 (1.578)	t(28) = -4.88, p<.001

*Paired t test used (Mean, SD shown)

Table 4: Pre-treatment measurement differences for Hand and ClinCheck® values

Tooth number	Hand (n=29)	ClinCheck (n=29)	Difference (mm)	T (p-value)
16	10.73 (.53)	11.57 (.50)	+0.84	-13.63 (<.001)
26	10.73 (.51)	11.49 (.57)	+0.76	-13.05 (<.001)
36	11.59 (.50)	11.79 (.50)	+0.20	-5.26 (<.001)
46	11.61 (.49)	11.78 (.53)	+0.17	-5.29 (<.001)

*Mean/SD shown, paired t test used

Table 5: Last refinement measurement difference for Hand and ClinCheck® values

Tooth number	Hand (n=29)	ClinCheck (n=29)	Difference (mm)	T (p-value)
16	10.70 (.45)	11.39 (.54)	+0.69	-11.92 (<.001)
26	10.74 (.49)	11.36 (.53)	+0.62	-10.00 (<.001)
36	11.53 (.47)	11.78 (.49)	+0.25	-7.53 (<.001)
46	11.58 (.47)	11.79 (.50)	+0.21	-6.32 (<.001)

*Mean/SD shown, paired t test used

Table 6: Summary of Mean Tooth Widths and Difference - Pre-Treatment (T1)

Tooth number	Hand (n=29)	ClinCheck Pre (n=29)	Difference (mm)
16	10.73 (.50)	11.57 (.50)	+0.84
15	7.29 (.50)	7.31 (.47)	+0.02
14	7.60 (.49)	7.57 (.47)	-0.02
13	8.29 (.53)	8.25 (.54)	-0.03
12	7.29 (.44)	7.32 (.46)	+0.03
11	9.04 (.47)	9.06 (.49)	+0.03
21	9.03 (.48)	9.03 (.48)	+0.01
22	7.31 (.50)	7.31 (.52)	-0.01
23	8.23 (.51)	8.24 (.51)	+0.01
24	7.55 (.48)	7.55 (.46)	0
25	7.26 (.52)	7.30 (.44)	+0.03
26	10.73 (.51)	11.49 (.57)	+0.76
36	11.59 (.50)	11.79 (.50)	+0.20
35	7.61 (.52)	7.70 (.47)	+0.09
34	7.66 (.51)	7.61 (.52)	-0.05
33	7.18 (.49)	7.18 (.53)	-0.01
32	6.29 (.43)	6.30 (.39)	0
31	5.73 (.32)	5.73 (.31)	0
41	5.72 (.30)	5.74 (.29)	+0.03
42	6.29 (.37)	6.29 (.37)	0
43	7.15 (.51)	7.20 (.57)	+0.05
44	7.62 (.51)	7.60 (.51)	-0.02
45	7.58 (.50)	7.66 (.50)	+0.08
46	11.61 (.49)	11.78 (.53)	+0.17

*Mean/SD shown

Table 7: Summary of Mean Tooth Widths and Difference - Last Refinement (T2)

Tooth number	Hand Measure Post(n=29)	ClinCheck Measure Pre (n=29)	Difference (mm)
16	10.70 (.45)	11.39 (.54)	+0.69
15	7.15 (.48)	7.28 (.47)	+0.13
14	7.49 (.46)	7.55 (.48)	+0.06
13	8.21 (.57)	8.22 (.54)	+0.02
12	7.32 (.51)	7.26 (.46)	-0.1
11	9.08 (.49)	9.07 (.51)	0
21	9.07 (.47)	9.05 (.47)	0
22	7.31 (.52)	7.28 (.49)	0
23	8.17 (.56)	8.17 (.52)	0
24	7.44 (.47)	7.53 (.47)	+0.09
25	7.20 (.47)	7.24 (.44)	+0.04
26	10.70 (.49)	11.36 (.53)	+0.62
36	11.53 (.47)	11.78 (.49)	+0.25
35	7.56 (.48)	7.71 (.46)	+0.16
34	7.62 (.48)	7.58 (.53)	0
33	7.17 (.55)	7.18 (.56)	+0.02
32	6.24 (.41)	6.29 (.41)	+0.05
31	5.71 (.30)	5.72 (.30)	+0.01
41	5.70 (.28)	5.74 (.30)	+0.04
42	6.24 (.40)	6.29 (.39)	+0.05
43	7.11 (.54)	7.23 (.61)	+0.11
44	7.61 (.50)	7.57 (.47)	0
45	7.53 (.48)	7.67 (.49)	+0.14
46	11.58 (.47)	11.79 (.50)	+0.2

*Mean/SD shown

Figure 1: Mean tooth widths for Hand measurements and ClinCheck® Software (T1)

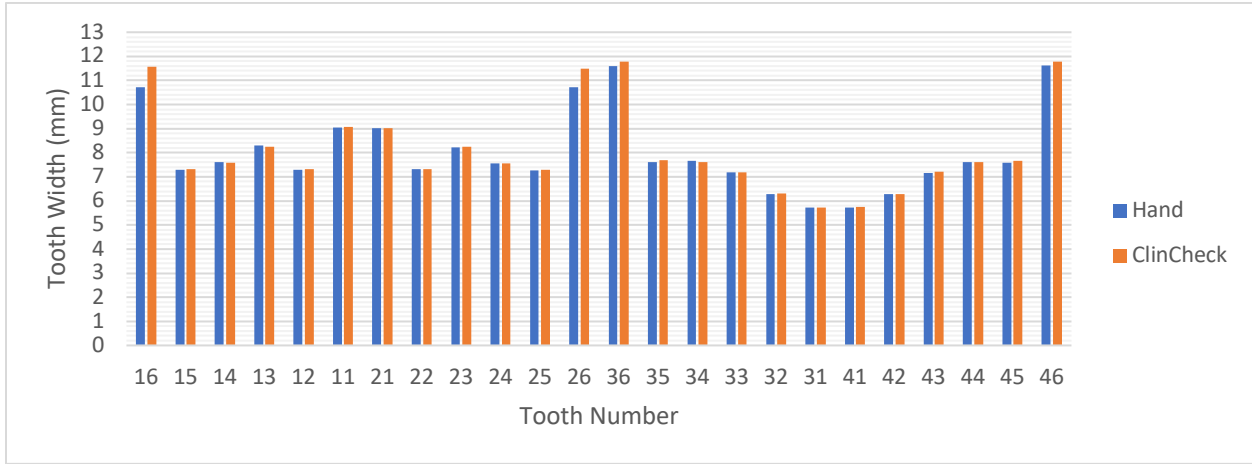


Figure 2: Mean tooth widths for Hand measurements and ClinCheck® Software (T2)

