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EVALUATING FLEXURE OF THE MANDIBLE ON OPENING AS CAPTURED BY INTRAORAL SCANNERS

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A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Orthodontics in the School of Dentistry.

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ABSTRACT

Josiah M. Rich: Evaluating Flexure of the Mandible on Opening as Captured by Intraoral Scanners (Under the direction of Tung Nguyen)

Aims: The mandible flexes on opening, constricting the width in the transverse dimension. Digital intraoral scanners require the patients' mandible to approach maximum opening during capture. This study compares positional changes of teeth as captured by intraoral scans, alginate impressions, and Cone Beam Computed Tomography (CBCT). **Methods**: Thirty subjects had alginate impressions, intraoral scans and CBCT scans taken. Digital surface models (STL) were generated for each method, superimposed and total mean surface errors of the teeth were calculated. **Results**: The mean error was greatest at the molars. Error of open alginate to CBCT scan was 0.440mm±0.146, closed alginate to CBCT was 0.428mm±0.124, and intraoral scan to CBCT was 0.337mm±0.154 all at the molar region. Intraoral scans captured less mandibular flexure than alginate impressions and can be used for any purpose previously done with alginate.

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LIST OF ABBREVIATIONS

3D	Three dimensional
ANOVA	Analysis of variance
CBCT	Cone-beam computed tomography
CT	Computed tomography
GPa	Gigapascal
PDL	Periodontal ligament
PVS	Polyvinyl siloxane
SD	Standard deviation

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A REVIEW OF THE LITERATURE

Flexure of Bones

Osseous structures in the body are not fully rigid and can behave dynamically under certain conditions that require limited flexure. Bone density has been shown to be affected by genetic as well as environmental factors (diet and skeletal loading).[1] Specific to skeletal loading, it has long been recognized that exercise which increases loading has effects on size, shape, mechanical strength, and bone density.[2] Although there is a limit to how much flexure can occur in human cortical bone before fatigue,[3] it is recognized that high strain rates with high peak forces increase bone formation more than a large number of low-force repetitions.[4] Frost hypothesized that under repetitive, dynamic flexural strain, lamellar bone surfaces drift in the concave-tending direction, leading to adaptation in shape to better handle the flexure.[5]

Flexure of the Mandible

The mandible is a unique bone in that each of the bilateral craniomandibular articulations can operate independently, though movement on one side affects the other due to the symphysis traversing the midline. The complex nature of this ginglymoarthrodial joint (it can hinge as well as glide) make it an area interest to dentists, orthodontist, prosthodontist and radiologists.[6] There is marked variation in size and shape of the condyle and ramus of the mandible due to variation in development, as well as compensatory remodeling to adapt to malocclusion, trauma, or other developmental anomalies.[7] The mandible has been described as horse shoe, or 'U' shape and can be considered a curved beam with either unilateral or bilateral forces acting on it.[8] The temporomandibular joint is loaded more heavily during jaw opening than closing.[9] The pair of lateral pterygoid muscles are primarily responsible for the opening and protrusive movement of the mandible. When the mouth opens, these pterygoid muscles pull the head and neck of the condyle medially, causing flexure to the mandible. Secondary muscles responsible for medial force on the condyle include the mylohyoid, platysa and superior constrictor muscles.[8]

Fischman used photographic comparison to explain that the contraction of lateral pterygoid muscles results in a sagittal movement of the posterior segments, presumably by flexure near the symphysis of the mandible.[10] The magnitude of flexure varies greatly between individuals and in many is so minimal that it is often overlooked as having no clinical significance.[8] Hylander suggested that one pattern of jaw deformation in the mandible was symphyseal bending connected with medial convergence on opening.[8, 11-13] He also suggested at least four unique patterns of flexure for the mandible on opening and mastication, of which he postulated that medial flexure on opening had the highest magnitude.[11] This medial mandibular flexure appears to be minimal when there is no protrusive movement and opening is less than 20mm.[12] There appears to be great variation in the amount of medial flexure of the mandible on opening, though a stronger musculature has been associated with larger flexure of the mandible.[8] It has been hypothesized that over time the degree of flexure can lead to morphological changes to the bone that can be used to indicate gender.[14] Anthropologists and forensic scientists find this particularly interesting, though there is a wide range of variation in the amount of flexure, and investigators are not in agreement over the strength of correlation between the degree of flexure and gender of the subject.[14-18]

As early as 1996, anthropologists in South Africa were using the mandibular ramus flexure as a morphologic indicator of sexual dimorphism, with a reported predictive accuracy of 99%.[14] However, anthropologists from Kansas seeking to replicate the study found accuracy for males to be only 91.3% and 56.4% for females.[15] Several years later, researchers using panoramic radiographs to assess flexure of the posterior border of the mandibular ramus were in agreement only 64-73% of the time and concluded that this was not a reliable indicator of gender.[19] Koreans using 3D mandible models and discriminant analysis for multiple variables, found that multivariate analysis could predict sex determination with accuracy as high as 88.8% and was acceptable for use in forensic science and law.[17] In an all-female study, measurements on thirty-five lead to a conclusion that the mandibular arch width decreases at the most open position compared with rest position, though no statistically significant differences were seen.[16] A unique study from India found significant correlation between median mandibular flexure on mouth opening and face type.[18] Subjects with brachyfacial type showed more median mandibular flexure than those with dolichofacial type. Additionally, subjects with lower gonial angle, smaller symphysis, and larger mandibular length seem to display more mandibular flexure.[8]

Despite the controversy surrounding the amount of flexure and whether it is correlated to face type or gender, medial mandibular flexure exists and has been known to cause problems if ignored when doing dental work in the mandible. Nowhere is there more concern about the magnitude and side effects of transverse flexure of the mandible than in the prosthodontic literature.

Impact of Mandibular Flexure in Prosthodontic Rehabilitation

Full-mouth prosthodontic rehabilitation often requires long-span fixed prosthesis, which are commonly attached to implants. These fixed prosthesis are made out of porcelain, acrylic, or zirconia for their strength and esthetic properties, and can be thought of as completely rigid structures. Young's modulus of elasticity of cortical bone (10-20 GPa) compared with tetragonal zirconia polycrystals (210 GPa) and grade IV titanium used for implants or implant connectors (100 GPa) shows that these restorative materials are five to ten times more rigid than the supporting cortical bone.[13] Unlike the periodontal ligament (PDL) of teeth, osseointegrated implants are fused directly to the bone and do not have any ligament that can be compressed to allow for temporary flexure. If the mandible flexes, but the mandibular prosthesis cannot, it puts the strain of flexure on the bone-implant junction and can lead to failure over time, or migrate through the bone and exit the cortical plate. It has been shown that frameworks made from more elastic materials (such as palladium-gold) are much better at reducing stress at the terminal implant, though these materials are more costly and have other esthetic compromises.[8]

For as long as implants have been used in dentistry, the causes of implant failure have been studied. Bending moments of force have been considered undesirable as they place force in a suboptimal direction and can lead to abutment breakage or implant screw loosening.[20] Mandibular flexure of the bone caused by opening can lead to stress on fully implant borne prosthetic components, one study showing a relative displacement of 420µm and a force of 16 N between implants.[21] Over time, this amount of force predisposes the patient to implant and/or prosthesis failure. This problem is not limited to full arch reconstruction. Unilateral loading also shows strain on the bone-implants interface as the mandible flexes.[22]

Many problems relating to prosthetic rehabilitation have been linked to medial mandibular flexure, including distortion of full arch impressions, poor fit of fixed and removable prothesis, pain during function, fracture of implant components, loosening of cemented prothesis, and resorption around implants.[23] Implant-to-natural-tooth fixed partial dentures show other problems. Many natural tooth abutments in implant-to-natural-tooth fixed protheses show intrusion over time, which may be attributed to mandibular flexion and torsion.[24] Factors contributing to the degree of flexure have been suggested in the literature and include age, bone density, muscle strength, structure of the cancellous bone, and shape of the mandible.[23]

Several recommendations have been made to reduce the impact of medial mandibular flexure. Related to prosthesis design, many clinicians agree that a split prosthesis design is preferable to a full arch, rigid connector.[8, 13, 23, 25, 26] These split-framework designs are suggested to restore more natural functional condition to the mandible, although there are limited long term follow up studies to confirm this.[8, 26] The number of implants and material used for the superstructure supported by the implants can pathologically limit the natural flexure of the mandible during function.[25] Other recommendations include non-rigid connectors and distal cantilevers.[13, 23, 25] Overdentures that used a flexible rubber “O’ring” showed reduced stress on the implant and prosthetic components, which lead to a higher success rate after 10 years than a rigid bar.[25]

Despite all the research that has been done, consensus is that mandibular flexure on the implant-bone interface is not fully understood and more research is needed.[22] While complication with full arch rehabilitation involving implants can occur due to mandibular flexure, it is nearly impossible to predict for which patients this will occur to an extent that it is problematic. In a study involving 129 patients and 766 implants who underwent full mouth/full arch rehabilitation using the All-on-Four™ protocol, there were no implant failures at 200 days in the mandible, and only 4 implant failures in the maxilla (100% and 99.1% success rates, respectively).[27] Though this study does not provide long term clinical outcomes, it shows high success rates initially even with rigid, full arch, implant supported prosthesis. It is notable that the All-on-Four™ protocol advocates for placing the most posterior implant no further than the mental foramina, which helps reduce the amount of flexure experienced by the splinted implants.[8]

It is nearly unanimously agreed upon that impressions should be taken as close to physiological rest position as possible.[10, 13, 23] All impressions require some degree of mouth opening, but this should be limited as much as possible. If the impression is captured when the mouth is open wide, the dental units will be positioned more lingually than when at rest.[8] The material used for these impressions can also influence the accuracy of capturing the geometry and morphology of the hard and soft tissues of the mandible as well as the dental units.

Traditional Dental Impression Materials

For decades alginate (irreversible hydrocolloid) impression material was considered to have as much dimensional accuracy as any other material on the market at the time, and as such was the most ubiquitous material used in dentistry to create casts of oral hard and soft tissue.[28] Though considered highly technique sensitive, alginate impressions were used for the most detailed of prosthetic procedures.[28, 29] Polyvinyl siloxane (PVS) materials later surged in popularity for their long term dimensional stability (no time limit between taking the impression and pouring the cast), low and high viscosity options, and greater accuracy, though working time was less and interaction with latex rendered the materials useless.[30, 31] PVS became the material of choice for most impressions related to restorative dentistry. Though newer 'extended-pour' alginate materials provided more dimensional stability prior to being poured,[32, 33] alginate materials were known to have less accuracy and stability, which only got worse with increased storage time of the powder.[34] Nevertheless, for the purpose of full arch initial and final records in orthodontics, the properties of alginate impressions remained fully acceptable.[32]

Digital Intraoral Scanners

As technology has sought to replace analog artifacts with their digital equivalents over the past few decades, dentistry undergone a similar evolution that has replaced many traditional methods and materials with new workflows and armamentarium for a computer driven era. Specifically, intraoral scanners have developed to be accurate enough for many prosthetic and restorative dental procedures.[35, 36] While traditional PVS or alginate impressions are still widely used due to familiarly, less expensive short-term economics and some limitations of the digital intraoral scanners, there is no question dentistry will move toward using intraoral scanners with more frequency in the future.

While these intraoral scanners are gaining popularity, the literature to validate their accuracy or reliability is both limited and dated.[37] Manufacturers of these products claim the intraoral scanners will ‘streamline’ efficiency in the practice[38] and that the technology is so accurate it will improve the fit of appliances.[39] The reality, however is that technology is changing so fast that by the time studies are done to validate manufacturer’s claims, the unit has been replaced by a newer model and the original is no longer even available for purchase.[38] Studies have been done using techniques to fabricate digital models from either 3D scan of plaster models, or 3D radiographic scans of impressions.[40, 41] Using a bench-top scanner to digitize plaster models showed reliability similar to traditional stone models that were poured soon after being taken.[42] One study displayed less variability in virtual measurements on digital models than the corresponding measurements on plaster.[32] Cone-beam computed tomography (CBCT) scans of alginate impressions and intraoral scans were used to create digital models and compared against traditional stone models. Findings indicate that tooth-width measurements did not differ significantly between the three methods.[41] One novel approach captured a PVS inter-occlusal record to get a more detailed model of the occlusal surfaces of teeth and a record of the biting relationship between arches, and was then scanned using a bench-top scanner. When compared to the control of stone models acquired using alginate, the difference was less than 0.1mm, showing high accuracy and efficient capture time, though the technique still required impression material intraorally.[43]

Intraoral scanners use proprietary software specific to each company to acquire and generate the 3D models.[44] Scanning accuracy can be affected by the level of diffuse or specular reflection of the surface material.[43] In vitro comparison of four popular intraoral scanners available in 2014 showed significant differences between coating and non-coating systems, as well as errors and deviations specific to parallel confocal microscopy and laser triangulation techniques respectively.[44] Using intraoral scanners to scan models extra orally has historically shown higher accuracy than using those same scanners intraorally, likely due to some of the challenges (saliva, tongue, limited space) of the oral environment.[40]

Full arch intraoral scans present some unique challenges. Unlike traditional alginate or PVS impressions which capture the full arch all at once, intraoral scanners slowly piece together each captured section. The proprietary additive algorithm is unique to each scanner and may vary in accuracy. This means that any small errors in tooth position that are captured on one side of the arch will be magnified as the algorithm continues to add to the errant captured area. In addition, any slight movement of dental units within the PDL space during capture can throw off the final rendered scan as well. The prosthodontic literature is aware of the added complexities in full arch scans compared with single unit scans. Four intraoral scanners were compared with a desktop scanner (reference) for full arch scans of 14 abutments, and concluded that inaccuracies of the scans may lead to inaccuracies of the final restorations.[45] The differences between scans were statistically significant and tended to show more inaccuracy in the horizontal plane further away from the point of the start of the scan. This reinforces the hypothesis that small errors lead to bigger errors as more data is built further away from the starting point. Of note is that all scans were done bench-top, outside the mouth for this study.[45] In 2016 a similar study was done, once again using intraoral scanners on the bench-top, concluding that the accuracy of intraoral scanners was sufficient for prosthesis of up to 4 units in length, but not accurate enough for full arch scans.[36] The limitations of full arch intraoral scans are compounded further when adding flexure of the mandibular bone to the equation.

Intraoral Scanners and Flexure of the Mandible

It has been well established that the mandibular bone flexes in shape as muscles contract during protrusive movements and opening of the mouth.[8, 12, 13, 22] This change in shape of the jaws affects the position of teeth during opening and is of concern for rigid prosthesis designs for restorative treatments. Traditional impression materials (PVS and alginate) capturing the lower arch allow the mandible to be placed into or near physiologic rest position. The technique of having the jaw as close to fully closed as possible, limited only by the impression material and the tray, has been recommended by many as a way to limit the amount of osseous flexure of the mandible that would be captured by the impression.[10, 13, 23] The literature is quite blunt that if an impression is taken with the lower jaw wide open, the lower teeth will be recorded in a position more lingually than when at rest.[8] Intraoral scanners have gained popularity as a replacement for traditional dental impressions and are capable of creating digital models of the dental arches without the use of alginate or PVS. These scanners, however, require the patient to have their mouth open reasonably wide, at least while teeth in the posterior region are being captured.

Intraoral scanning technology currently employed by all devices on the market in 2017 make use of a wand that captures small areas of the dentition in three dimensions at a time. The wand is moved around the mouth to capture all areas, and software stitches together the 3D snapshots of each area to make the digital model. The algorithm responsible for this is proprietary to each company and variations exist between techniques used. Current studies suggest significant error in full arch scans that limit their use for long span units of fixed prosthesis restorative work.[36, 45] By the nature of the software, any small errors lead to larger discrepancies as the software builds a three-dimensional model on any incorrect data it previously captured. This may or may not be clinically relevant. Teeth can move temporarily within the periodontal ligament space as well, possibly leading to inaccuracies with how the final scan compares with the physical position of the teeth. As stated previously, the mandible flexes when the mouth is open wide. The size of the capture wand necessitates a wide open mouth to scan the posterior teeth. This almost certainly means that these dental units will be captured by the scanner in their position of flexure within the mandible.

Cone Beam Computed Tomography: the Gold Standard

Three dimensional radiographic imaging has been used in dentistry for numerous applications, and the reliability and accuracy of Cone Beam Computed Tomography (CBCT) has been validated.[46, 47] Unlike the spiral (or sometimes called helical) computed tomography used commonly in medicine, the cone beam is able to capture a larger volume of information with less radiation exposure to the patient.[48]

Cone beams have been used as a replacement for taking stone models of teeth with mixed success. When using a machine with a voxel size of 280µm, investigators found no statistically differences comparing measurements on the CBCT volume and the physical teeth using calipers.[49] However, when multiple measurements were added together, it was observed that the CBCT values were slight underestimates of the actual size of the dental units. A similar study validated linear measurement accuracy on skulls compared with their CBCT measurements.[50] When compared with a coordinate measuring machine, CBCT volumes showed nearly perfect intra-reliability correlation coefficient (though the voxel size of the machine used in the study was never reported).[51] Mean linear accuracy was less than 300µm for measurements of simulated osseous lesions tested with a unit capable of 200µm voxel size.[46]

Examining teeth specifically, CBCT volumes at 200µm were compared with a MicroCT (bench top, spiral CT unit) capable of 7µm voxel resolution.[52] Results showed that the CBCT models of teeth were slightly larger than the MicroCT unit, which was attributed to increased voxel size of the CBCT unit. The investigators concluded that this may or may not be accurate enough, depending on the clinical situation. Accuracy of CBCT continues to be validated across multiple units between 200µm and 300µm voxel size, with correlation coefficients 0.995 to 1.0 comparing cone beam measurements with digital caliper measurements.[47] At this point in time, CBCT remains the gold standard for virtually measuring areas that are not possible to physically measure.[46, 47, 52]

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Introduction

The mandible is a unique bone in that each of its bilateral craniomandibular articulations can operate relatively independently, with movement on one side of the jaw requiring only a minimal balancing movement on the contralateral side. Further, the mandible is an osseous structure capable flexure in response to muscle pull during function. Interestingly, the temporomandibular joint is loaded more heavily during jaw opening than closing from medial pull predominantly from the lateral pterygoid muscles, resulting in greater medial flexure of the bone during opening.[9] [8]

The magnitude of flexure varies greatly between individuals.[8] Hylander suggested the predominant pattern of jaw deformation was symphyseal bending and medial convergence on opening.[8, 11-13] This medial mandibular flexure appears to be minimal when there is no protrusive movement and when opening is less than 20mm.[12] Importantly, this type of flexure has been linked to complications of dental treatment, including fracture of fixed restorations in the mandible.

Full-mouth rehabilitation using long span fixed protheses of porcelain, acrylic, or zirconia have been reported to cause problems due to flexure of the mandible. Young's modulus of elasticity of cortical bone (10-20 GPa), compared with tetragonal zirconia polycrystals (210 GPa) and grade IV titanium used for implants or implant connectors (100 GPa), shows that these restorative materials are five to ten times more rigid than the supporting cortical bone.[13] If the mandible flexes but the mandibular prosthesis cannot, it puts the strain of flexure on the bone-abutment junction and can lead to failure over time.

It is nearly unanimously agreed upon that impressions should be taken as close to physiological rest position as possible to limit distortion caused by medial mandibular flexure.[10, 13, 23] If an impression is captured when the mouth is open wide enough, the posterior dental units may be positioned more lingually than when at rest.[8]

For decades, alginate (irreversible hydrocolloid) impression materials were used ubiquitously in dentistry to create casts of oral hard and soft tissue.[28] Polyvinyl siloxane (PVS) materials later surged in popularity for their long term dimensional stability, variable viscosity options, and greater accuracy.[30, 31] PVS became the material of choice for most impressions related to restorative dentistry since alginate materials were known to have less accuracy and stability.[34] For the purpose of full arch initial and final records in orthodontics, however, the properties of alginate impressions have remained acceptable.[32]

Cone Beam Computed Tomography (CBCT) has been validated in dentistry for both reliability and accuracy.[46, 47] When using a machine with a voxel size of 280µm, investigators found no statistically significant differences comparing measurements on the CBCT volume and the physical teeth using calipers.[49] When compared with a coordinate measuring machine, CBCT volumes showed nearly perfect intra-reliability correlation coefficient.[51] Accuracy of CBCT continues to be validated across multiple units between 200µm and 300µm voxel size, with correlation coefficients 0.995 to 1.0 comparing cone beam measurements with digital caliper measurements.[47] CBCT remains the gold standard for virtually measuring surfaces that are not possible to physically measure, such the location of lower teeth in a fully closed, non-flexing mandible.[46, 47, 52]

Over the past decade, intraoral scanners have developed to be accurate enough for many prosthetic and restorative dental procedures.[35, 36] Though these intraoral scanners are gaining popularity, the literature to validate their accuracy or reliability is limited.[37] Scanning accuracy can be affected by the level of diffuse or specular reflection of the surface material.[43] An *in vitro* comparison of four popular intraoral scanners available in 2014 showed significant differences between coating and non-coating systems, as well as errors and deviations specific to parallel confocal microscopy and laser triangulation techniques respectively.[44]

Full arch intraoral scans present some unique challenges. Unlike traditional alginate or PVS impressions which capture the full arch all at once, intraoral scanners slowly piece together each captured section. The proprietary additive algorithm unique to each scanner may vary in accuracy.[44] Small errors in tooth position that are captured on one side of the arch will be magnified as the algorithm continues to add to the distorted area. In 2016, a study concluded that the accuracy of intraoral scanners was sufficient for prosthesis of up to four units in length, but not accurate enough for full arch scans.[36]

This additive distortion effect might be amplified if an intraoral scanner requires the patient to have their mouth open reasonably wide and medial mandibular flexure results. Compared to a rest position, the mandibular teeth might be captured in a more lingually tipped position during the scan, and the intra- and interarch relationships of the teeth might be significantly inaccurate as recorded.

To date, no data exist that evaluate the effect of mandibular flexure on the accuracy of full arch intraoral scanning technology. If the mouth opening required to capture an intraoral scan significantly decreases the accuracy of the scan that is captured, then diagnosis, treatment planning, post-treatment assessment and any lab work fabricated using such records might be compromised and lead to less optimal treatment outcomes in dentistry and orthodontics.

The current study undertook two aims: 1) Compare closed mouth alginate impressions with open mouth alginate impressions to determine whether the alginate material was sensitive enough to capture any additional flexure of the mandibular bone on opening rather than when closed, and 2) Compare flexure of the mandible as captured by alginate impressions (both open mouth and closed mouth) and intraoral scans with a CBCT volume of the teeth in the closed position.

Methods

This study had Biomedical IRB approval from the University of North Carolina at Chapel Hill. Thirty consecutive participants (18 female, 12 male; average age 28.5y, range 22-38y) were recruited from the University of North Carolina School of Dentistry based on inclusion criteria of a full dentition and no history of trauma or orthognathic surgery to the mandible. Participants were excluded if they failed to meet inclusion criteria or reported any history of taking drugs known to significantly alter bone metabolism.

Participants had two alginate impressions taken of their mandibular arch (one with the mouth open as wide as possible, the other nearly fully closed, with the top teeth resting on the top of the impression tray) with Jeltrate Plus™ Fast Set alginate using perforated metal trays to minimize distortion. The impressions were immediately poured in microstone. The participants then had an intraoral scan taken of the lower arch. The first 15 consecutive participants were scanned with the Lythos™ (Ormco™) scanner, and the second 15 consecutive participants were scanned with the Trios® (3Shape) scanner. The Trios® was used instead of the Lythos™ for the second 15 subjects due to Ormco™ discontinuing the product during the investigation. Each participant had a CBCT volume taken using Sirona's Orthophos XG in HD mode with a voxel size of 160 microns. The principle investigator took all impressions, poured all models, and captured all intraoral scans to limit variation in technique. All stone models were scanned with the Ortho Insight 3D® [53] bench top scanner to STL format. Dolphin Imaging Plus™ [54] was used to segment the CBCT scans to isolate the mandibular teeth and then to convert the grey scale voxels to a surface mesh that was exported to STL format. Both the Lythos™ and Trios® softwares allowed for the export of digital scans to open source STL files that could be compared with the STL files acquired using CBCT.

The mesh surfaces of the four impression modalities (Open Alginate, Closed Alginate, Intraoral Scan, CBCT) were automatically registered sequentially in pairs for each participant using open source software Slicer 3D[55] based on Region of Interested based Surface Registration (ROI landmarks were buccal surfaces of canine and first molar crowns. In one case where a first molar had a metal crown, the second molar was used instead).

Error distances between surfaces of the teeth were measured using open source software 3DMeshMetric[56]. Measurements were recorded at the area of greatest difference between the teeth in five specific areas: left molars, left premolars/canine, incisors, right canine/premolars, right molars. The absolute value of each measurement was recorded so that displacement of the teeth, whether labial or lingual in direction, was captured accurately.

Comparisons were taken for the following four sets of 3D surface models: 1) Open Alginate compared with Closed Alginate impressions, 2) Open Alginate impression compared with CBCT, 3) Closed Alginate impression compared with CBCT, and 4) Intraoral Scanner compared with CBCT.

Normality of the data was confirmed using the Kolmogorov-Smirnov test. Consistency of mean measurements between the scans acquired using the Lythos™ and Trios® scanners was confirmed using Welch-Satterthwaite t-tests ($P>0.09$ for all comparisons). Accordingly, all measures acquired using the intraoral scanners were combined into one comprehensive group ("Intraoral Scanners"). Similarly, right and left measurements at each region were averaged, creating three areas of interest: incisors, canine/premolars, and molars.

One sample t-test was run on each data set. Mean difference between the two surfaces, standard deviation, and 95% confidence interval was calculated for each of the four comparisons (Open Alginate vs. Closed Alginate, Open Alginate vs. CBCT, Closed Alginate vs. CBCT, and Intraoral Scanner vs. CBCT). Repeated measures ANOVA was run to compare mean absolute difference across modality groups by tooth region, with a level of statistical significance set at $P=0.05$.

Results

Mean differences in the records acquired using alginate, CBCT, and intraoral scanners are summarized in Tables 1-4. With the Bonferroni correction for multiple comparisons, critical level of significance set to ≤0.004 showed all results to be statistically significant. The mean error difference between surfaces increased from the incisors to the molars for each of the four comparisons that were measured (Open Alginate vs. Closed Alginate, Open Alginate vs. CBCT, Closed Alginate vs. CBCT, and Intraoral Scanner vs. CBCT). The greatest mean difference between surfaces was at the molars for each comparison (Fig. 1). Comparing only the molar regions, the intraoral scan compared with CBCT showed the least difference, less than the open or closed alginate impressions when compared with the CBCT (Fig. 2).

Repeated measures ANOVA compared mean absolute difference across record modality group by tooth region. Statistically significant differences were found at the molar region when comparing the Intraoral Scanner to both the Open and Closed Alginate (P = 0.034 and 0.004, respectively). Statistical significance was found at the canine/premolar region only for the Intraoral Scanner when compared with Closed Alginate (P = 0.013). There were no statistical significance differences comparing any modality groups at the incisor regions.

Discussion

The results comparing Open Alginate with Closed Alginate impressions confirm that more medial flexure of the mandible is captured with the mouth open wide. The discrepancy between the two models increased for more posterior regions, consistent with the pattern of medial mandibular flexure observed in the literature. The greatest discrepancy was at the molars (mean difference = 0.360mm, SD = 0.144mm, p≤0.001). While statistically significant, the clinical significance may be questioned. Medial flexure occurs bilaterally, but this measurement is only on one side of the arch. When doubled (to account for both sides of the arch) the difference is still less than 1mm. This number is only an average; many subjects had less flexure and many had more flexure . Without being able to predict who will exhibit significant flexure, the findings of this study suggest that all alginate impressions be taken in the Closed Mouth position, consistent with recommendations from the prosthodontic literature. For the purpose of diagnostic models for orthodontics, >1mm of total transverse medial flexure in the posterior teeth is likely to have no clinical significance. Even for fabrication of somewhat flexible appliances like clear aligners or Essix retainers, up to 1mm of flexure is clinically insignificant. This flexure may be more problematic for rigid appliances, such as acrylic surgical splints, or Moore retainers.

The results comparing each impression modality with the mandible at rest (captured by the CBCT scan with no flexure) showed statistically significant discrepancies for all comparisons, in all regions. Data trends showed the amount of flexure to increase posteriorly in the arch for all modalities compared with the CBCT. This is in agreement with expectations of more lingually positioned teeth posteriorly due to medial mandibular flexure. Specifically, the molar region showed the greatest amount of error within the arch (Fig. 1). Comparing only the discrepancies measured at the molar region, the Open Alginate showed the most inaccuracy, while the Intraoral Scan showed the least (Fig. 2). The Intraoral Scans compared with the CBCT showed less inaccuracy than either Open or Closed Alginate impressions in all regions (Table 4). This suggests that the algorithm for scanning the teeth as it adds segments upon itself might adjust in such a way that the final model shows less mandibular flexure despite the patient's mandible flexing during parts of the scan.

Comparing mean absolute differences across groups showed clinically relevant results. Statistically there is no significant difference between alginate impressions and the intraoral scanners used in this study in the incisor region. Perhaps a larger sample size would elucidate why the only significant difference between modality groups at the premolars was between Intraoral Scanner and Closed Alginate impression. At the molar region the Intraoral Scanner captured less flexure than either Open Alginate or Closed Alginate. This suggests that these intraoral scanners are at least no worse than the alginate impressions. The amount of jaw opening (and subsequent medial mandibular flexure) may be less with intraoral scanners, making them at least statistically, if not clinically, more accurate than alginate impressions.

The current technique used to capture intraoral scans involves first scanning a 'backbone' - an initial pass that captures occlusal surfaces of posterior teeth and the lingual of the anterior teeth. Subsequent passes build additivity on this backbone. This technique may help limit the amount of medial mandibular flexure that is captured through intraoral scans.

The results comparing intraoral scan to CBCT with Alginate (open and closed) to CBCT suggest that intraoral scanners are more accurate than alginate impression and capture less mandibular flexure. These scanners can be used to capture full arch digital impressions for any procedure that previously was done with alginate impressions. In orthodontics this includes initial records, progress records, final records, retainer impressions, and impressions for clear aligner therapy, like Invisalign®.

There were several limitations of this study and sources of error. Though the CBCT was used as the "Gold standard" in this study and showed the least amount of mandibular flexure, these volumes are not without errors. Movement during CBCT scanning would create inaccuracies. However, none of the scans in this study showed motion artifacts. Additionally, metal restorations could lead to voxel scattering which could distort the size and volume of the rendered teeth. In this study there was only one tooth with metallic restoration and registration was performed using the second molar in place of the first molar. The registration process could also introduce minor errors. Though nearly fully automatic in the calculations to register the models together, it is based on specific Regions of Interest which are defined by the operator. Superimposition error was minimized by registering multiple surfaces that surround the border of the mandibular dental arch. The same operator registered all models to maintain consistency. An additional limitation of the study is that results are specific to the scanners used in this study. With the many scanners on the market and propriety software for each, it is impossible to know if all scanners capture similarly, or would have similar results for the amount of medial mandibular flexure that is captured.

Future studies could validate the registration and measurement techniques using the maxillary arch which undergoes no flexure on opening. With more time and resources, it would be fascinating to compare alginate impressions and intraoral scans with full mouth PVS impressions to see how much medial mandibular flexure was captured a material with much higher accuracy and dimensional stability. Future studies could compare multiple scanners on the same individual to see where discrepancies lie. To gain further understanding of medial mandibular flexure, a similar study to this could be done on patients with implants, thus negating any flexure introduced or negated by the PDL.

Conclusions

The results from this study answered the primary aims. Mandibular arch alginate impressions should be taken with the mouth as nearly closed as possible to limit capturing tooth positioning errors caused by medial flexure of the mandible.

Current intraoral scanners capture less medial mandibular flexure than alginate impressions. These scanners appear to be fully acceptable for use in orthodontics when replacing any impression that previously was taken with alginate, and are statistically more accurate at the molar region than their alginate counterparts, though that statistical accuracy is likely not clinically significant except for full arch, fully rigid appliances or prostheses.

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APPENDIX 1: TABLES AND FIGURES

Table 1: Open Alginate Impression vs. Closed Alginate Impression[1]

	Mean Difference (mm)	Standard Deviation	95% C.I.	P value
Incisors:	0.128	0.057	0.105-0.147	<0.001
Canine/Premolars:	0.177	0.067	0.152-0.202	<0.001
Molars:	0.360	0.144	0.306-0.413	<0.001

Table 2: Open Alginate Impression vs. CBCT[2]

	Mean Difference (mm)	Standard Deviation	95% C.I.	P value
Incisors:	0.243	0.119	0.198-0.287	<0.001
Canine/Premolars:	0.318	0.089	0.285-0.351	<0.001
Molars:	0.440	0.146	0.385-0.494	<0.001

Table 3: Closed Alginate Impression vs. CBCT[3]

	Mean Difference (mm)	Standard Deviation	95% C.I.	P value
Incisors:	0.337	0.221	0.254-0.420	<0.001
Canine/Premolars:	0.351	0.110	0.310-0.392	<0.001
Molars:	0.428	0.124	0.382-0.475	<0.001

Table 4: Intraoral Scanner vs. CBCT[4]

	Mean Difference (mm)	Standard Deviation	95% C.I.	P value
Incisors:	0.240	0.106	0.197-0.284	<0.001
Canine/Premolars:	0.263	0.105	0.220-0.306	<0.001
Molars:	0.337	0.154	0.274-0.401	<0.001

[1] One sample t-test, level of significance set to ≤0.004

[2] One sample t-test, level of significance set to ≤0.004

[3] One sample t-test, level of significance set to ≤0.004

[4] One sample t-test, level of significance set to ≤0.004

Figure 1: Mean Difference at each Region grouped by Modality Comparison[5]

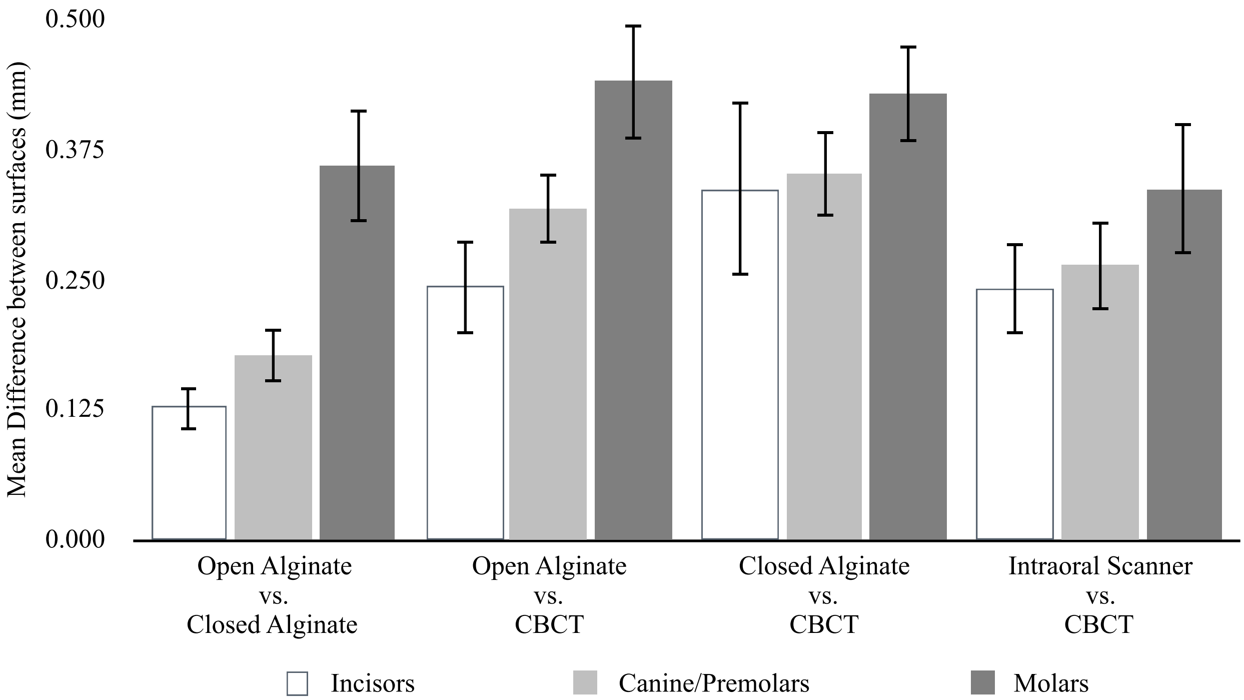
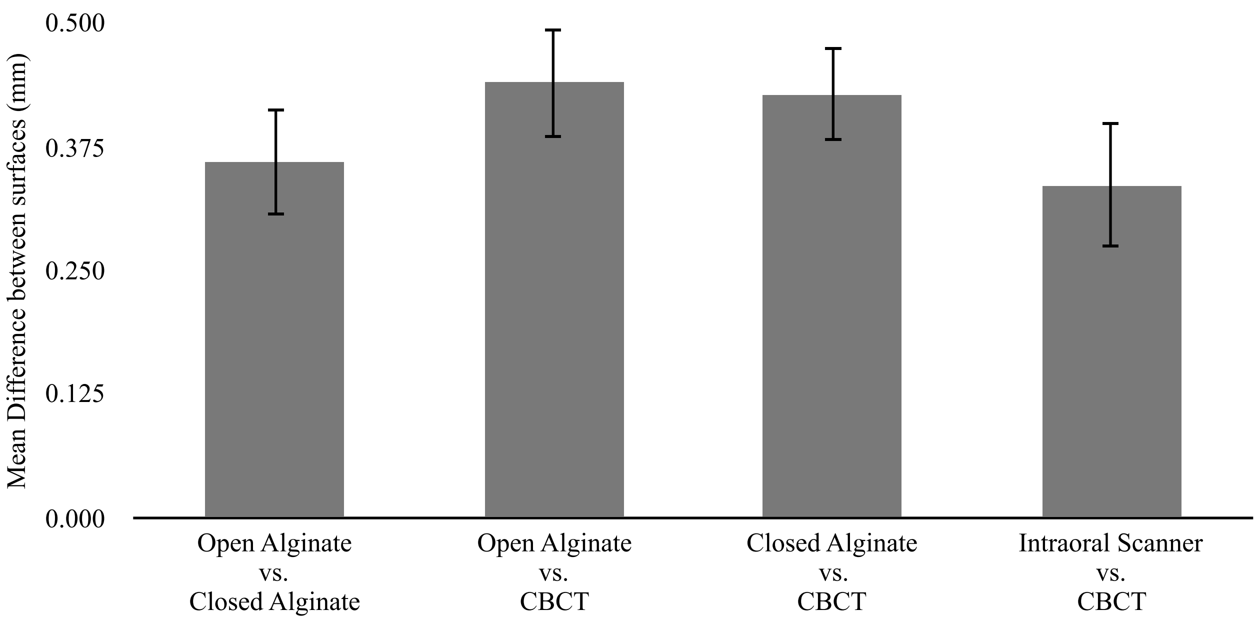


Figure 2: Mean Difference at the Molar Region for each Modality Comparison[6]



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[5] Error bars indicate 95% confidence interval

[6] Error bars indicate 95% confidence interval