

Rodrigo Xavier Silveira de Souza

**NOVO MÉTODO DE SOBREPOSIÇÃO MANDIBULAR USANDO
O PROGRAMA AUTODESK INVENTOR® PARA AVALIAÇÃO DA
ACURÁCIA DO PROTOCOLO G8 DA INVISALIGN®**

Faculdade de Odontologia
Universidade Federal De Minas Gerais
Belo Horizonte
2022

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Versão final

Dissertação apresentada ao Colegiado de Pós-Graduação em Odontologia da Faculdade de Odontologia da Universidade Federal de Minas Gerais, como requisito parcial à obtenção do grau de Mestre em Odontologia área de concentração em Clínica Odontológica.

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Novo método de sobreposição mandibular usando o programa Autodesk Inventor® para avaliação da acurácia do protocolo G8 da Invisalign®

RODRIGO XAVIER SILVEIRA DE SOUZA

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A Avó Zulmira que é a mentora deste desafio

“A teoria sem a prática vira ‘verbalismo’, assim como a prática sem a teoria, vira ativismo. No entanto, quando se une a prática com a teoria tem-se a práxis, a ação criadora e modificadora da realidade”.

Paulo Freire

Resumo

O uso de alinhadores ortodônticos transparentes tem demandado muitos esforços e recursos para que o resultado do tratamento seja o mais acurado possível. Em 2021 o protocolo G8 da Invisalign® prometeu melhor previsibilidade no tratamento. É através da sobreposição de imagens que estes resultados podem ser avaliados. Na literatura, encontram-se relatos de diversos métodos e softwares que buscam confiabilidade para sobreposição de modelos tridimensionais (3D), mas sem consenso sobre estes métodos. Assim, os objetivos deste estudo foram: (1) Desenvolver novo método de sobreposição de modelos 3D com Autodesk Inventor®, (2) avaliar a reprodutibilidade do Autodesk Inventor® utilizando o sistema de coordenadas universais (UCS) associado a único ponto para sobreposição de modelos ortodônticos 3D da mandíbula e maxila, (3) avaliar a reprodutibilidade do Autodesk Inventor® na sobreposição de modelo ortodôntico 3D da maxila e mandíbula, (4) Comparar a acurácia do protocolo G8 através do resultado previsto pelo ClinCheck® com o resultado real obtido nos movimentos de intrusão e expansão dentária posterior. Para os objetivos 1, 2 e 3, foram selecionados 11 pares de modelos em STL (estereolitografia) de ambos os arcos tratados com Invisalign® em dois tempos: início (T0) e refinamento (T1). As sobreposições foram realizadas utilizando os softwares Slicer® (versão 4.1) e Autodesk Inventor® usando como referência os planos dos 3 eixos cartesianos UCS (X, Y e Z) associado a um ponto na segunda ruga palatina na maxila e, na mandíbula, um ponto na linha muco gengival lingual. Após a sobreposição os movimentos de translação buco-lingual dos caninos, pré-molares e molares superiores e inferiores, intrusão, rotação dos caninos e incisivos mandibulares foram analisados por dois examinadores. Para o objetivo 4, a acurácia foi comparada nos movimentos alcançados e previstos pelo ClinCheck® entre três casos em que o protocolo G8 foi ativado e 8 casos em que não foi ativado para a expansão posterior maxila e mandíbula, intrusão de caninos e incisivos inferiores. Resultados do objetivo 1, 2 e 3 foram coeficientes de correlação intraclasse (ICC) maior que 0,90 em todas as medidas, não foi observado erro sistemático avaliado pela fórmula de Dahlberg. Resultados do objetivo 4 não foram observadas diferenças estatísticas significativas entre os grupos. A acurácia no grupo G8 quando comparada ao grupo não G8 para expansão posterior na mandíbula e maxila aumentou 12,7% e 7,8% respectivamente, mas sem diferenças estatísticas significante. Movimento de intrusão, a acurácia do grupo G8 foi 7,7% maior que a do grupo não G8 sem diferença estatística entre eles. Concluiu-se que o método desenvolvido se mostrou reprodutível para sobreposição de modelos tridimensionais. O protocolo G8, quando ativado, não apresenta maior acurácia para o tratamento com Invisalign®.

Palavras-chave: Invisalign®. Modelos dentários. Movimentação ortodôntica. Imagem 3D. Reprodutibilidade dos testes

ABSTRACT

New mandibular superposition method using autodesk inventor® software to evaluate the accuracy of the invisalign® G8 protocol

The use of orthodontic clear aligners has required effort and resources to ensure that the treatment outcome is as accurate as possible. In 2021 Invisalign® G8 protocol promises better treatment predictability. It is through image superimposition that these results can be evaluated. In the literature, there are reports of various methods and software that seek reliability for superimposing three-dimensional (3D) models, but no consensus on these methods. The objectives of this study were: (1) Develop a new method for superimposing 3D models with Autodesk Inventor®, (2) evaluate the reproducibility of Autodesk Inventor® using the universal coordinate system (UCS) associated with a single point for superimposing 3D orthodontic models of the mandible and maxilla (3) Evaluate the reproducibility of Autodesk Inventor® in superimposing orthodontic 3D models of the maxilla and mandible, (4) Compare the accuracy of the G8 protocol through the result predicted by ClinCheck® with the actual result obtained in intrusion movements and posterior dental expansion. To the objectives 1, 2 and 3, 11 pairs of STL (Stereo-lithography) models of both arches treated with Invisalign® were selected at two times: initial (T0) and refinement (T1). The superpositions were performed using the Slicer® (version 4.1) and Autodesk Inventor® software using as reference the planes of the three Cartesian axes (X, Y and Z) associated with a point on the second palatal crease in the maxilla and, in the mandible, a point on the lingual mucous gingival line. After superimposition, the bucco-lingual translation movements of the canines, premolars and upper and lower molars, intrusion, rotation of the canines and mandibular incisors were analyzed by two examiners. To the objective 4, the accuracy was compared in the movements achieved and predicted by ClinCheck® between three cases in which the G8 protocol was activated and 8 cases in which it was not activated for maxillary and mandibular posterior expansion, canine and mandibular incisor intrusion. Results of objectives 1, 2 and 3 were intraclass correlation coefficients (ICC) greater than 0.90 no systematic error evaluated by the Dahlberg formula was observed. Results of objective 4, no statistically significant differences were observed between the groups. The accuracy in the G8 group when compared to the non-G8 group for posterior expansion in the mandible and maxilla increased by 12.7% and 7.8% respectively but without statistically significant differences. Intrusion movement, the accuracy of the G8 group was 7.7% higher than the non G8 group with no statistical difference between groups. It was concluded that the developed method proved reproducible for three-dimensional model superimposition. The G8 protocol, when activated, does not present greater accuracy for treatment with Invisalign®

Key words: Invisalign®. Dental models. Orthodontic movement. 3D image. Reproducibility of results.

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LISTA DE ABREVIATURAS E SIGLAS

CAM	Fabricação Assistida Por Computador
CAD	Projeto Assistido Por Computador
CBCT	Tomografia Computadorizada De Feixe Cônico
DP	Desvio Padrão
IGT	Imagem Guiada Por Radiografia
ICC	Coeficiente de Correlação Intraclasse
STL	Estereolitografia
3D	Tridimensional
UCS	Sistema de Coordenadas Universais

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1 CONSIDERAÇÕES INICIAIS

Com o propósito de criar um aparelho ortodôntico que não possuísse braquetes, fios ou bandas Kesling em 1945 idealizou o *Tooth Positioning Appliance* considerado o precursor dos alinhadores. Seu sistema de planejamento foi totalmente manual realizado através de encerramento diretamente em modelos de gesso. Era feito de borracha flexível que cobria a superfície dos dentes movimentando-os na direção desejada. Apesar do uso restrito a pequenas correções ele afirmava que movimentos maiores poderiam ser conseguidos se houvesse modificações sequenciais à medida que o tratamento fosse progredindo (KESLING, 1945)

O primeiro aparelho termoplástico transparente para uso na ortodontia, baseado na ideia do Dr Kesling, foi desenvolvido por Henry Nahoum em 1964, fabricado através de uma máquina de vácuo industrial. Placas de plástico eram aquecidas e modeladas sobre o set up nos modelos de gesso. O aparelho poderia ser utilizado tanto como contenção, como para conseguir pequenos movimentos ortodônticos. Ponderou que sua utilização em movimentos maiores era restrita pois havia dificuldade em segmentar os dentes em estágios precisos utilizando modelos de gesso (NAHOUM, 1964).

Em 1971, Ponitz descreveu os primeiros experimentos com alinhadores termoplásticos, também mediante estudos do Dr. Kesling, sendo que até 1971 a ideia não apresentou progresso científico. Com o tempo e a partir de pesquisas, Ponitz *et al.*(1971) retornou com uma nova concepção nomeada de “Retentores Invisíveis”, os quais apresentam a mesma finalidade dos aparelhos do Dr. Kesling, porém com um padrão estético invisível (PONITZ; VICKI VLASKALIC,1971). A técnica de Ponitz *et al.* (1971) para fabricar aparelhos invisíveis foi posteriormente refinada por James A. McNamara em 1985. A fabricação dos aparelhos era feita através de uma máquina de pressão e não de vácuo. Poucos dentes eram movidos por estágios devido à dificuldade de adaptação dos alinhadores que poderia dificultar o uso pelo paciente (MCNAMARA; KRAMER; JUENKER, 1985).

Em 1993, John J. Sheridan apresentou a sua variação da família dos alinhadores termoplásticos, conhecida como a contenção Essix. O princípio

fundamental deste sistema baseava-se na utilização de um único aparelho em que eram realizados ajustes no curso do tratamento, criando pontos de pressão no alinhador com um instrumento aquecido provocando uma deformação pontual pressionado o dente quando o aparelho era inserido (SHERIDAN; LEDOUX; MCMINN, 1993).

O conceito da utilização de alinhadores ortodônticos já persiste há muitas décadas, os processos de planeamento e fabricação eram feitos manualmente através de procedimentos demorados e trabalhosos. Uma das maiores limitações destes processos é o fato que estavam limitados a um número pequeno de alinhadores produzindo pequenos movimentos dentários (WONG, 2002). Foi com a criação do sistema Invisalign® em 1997 através da empresa Align® Technology (Santa Clara, Califórnia EUA.), com o mesmo princípio de tratamento, que trouxe grande impulso tecnológico na área da ortodontia dos alinhadores (WOMACK *et al.*, 2002; WONG, 2002).

Os alinhadores da Invisalign® são fabricados em material plástico flexível de poliuretano. Cobrem a superfície oclusal, vestibular e lingual dos dentes O sistema utiliza tecnologia com *set-up* totalmente digital. Este método foi o primeiro que se baseou exclusivamente numa tecnologia tridimensional (3D), na qual uma sequência de estágios produz movimentos sucessivos e precisos dos dentes através de programas computadorizados que manipulam as imagens virtualmente permitindo visualizar o tratamento. Associado às placas flexíveis há necessidade, em alguns casos, da instalação de *attachments* que são dispositivos de resina colados aos dentes que permitem maior ancoragem dos alinhadores permitindo direcionar os movimentos. *Attachments* otimizados são mais específicos que os convencionais, pois alteram a posição do alinhador em toda a superfície do dente com o objetivo de melhorar a movimentação desejada. Utiliza o sistema CAD (desenho assistido por computador) e CAM (fabricação assistida por computador) para o planejamento e construção do modelo inicial onde as placas são confeccionadas para a movimentação dentária sequencial até a posição final planejada digitalmente na tentativa de aumentar acurácia e previsibilidade do resultado do tratamento (BOYD; WASKALIC, 2001; WONG, 2002)

O software ClinCheck® é a ferramenta virtual de planejamento de tratamento utilizada para comunicar um plano de tratamento para Align®.É a

forma como a Align® mostra progressão dos movimentos de cada dente até o resultado final. Todas as previsões de movimentos são resumidas na tabela do ClinCheck® que permite ao paciente visualizar o resultado previsto de modo a atingir com maior previsibilidade a simulação final do tratamento. (MORTON *et al.*, 2017).

Ao longo dos anos a Align® Technology vem aperfeiçoando o sistema Invisalign® com melhorias em seu sistema divididas em protocolos ou gerações. Surgiu em 2011 o protocolo G3 que incluem novos recursos como os *attachments* de extrusão e de rotação aperfeiçoados, *Power Ridges* e novos protocolos no software ClinCheck® de desgastes interproximais. Os *attachments* de extrusão foram desenvolvidos para aumentar o poder dos alinhadores na extrusão de dentes anteriores. Com o uso da tecnologia 3D, cada *attachment* tem um desenho customizado para o contorno do dente de cada paciente. A extremidade gengival dos *attachments* é mais fina para proporcionar contato melhor e mais consistente com o alinhador e um desenho mais estético. A área de superfície é orientada em relação ao longo eixo do dente para ajudar a controlar a força de extrusão aplicada e o desenho permite ao alinhador reter melhor com um desempenho mais previsível. Com o novo software ClinCheck®, a velocidade de movimento de cada parte do dente é mais controlada, incluindo a raiz do dente e rotações em intervalos ideais recorrendo a pontos de referência digitais no dente. Os novos *attachments* de rotação conseguem aumentar o alinhamento devido a rotação dos caninos e pré-molares mais eficaz. O *Power Ridges*, foi concebido para gerar torque lingual nas raízes dos incisivos superiores, sem necessidade de recorrer a *attachments*. Pode ser utilizado quando é necessário verticalizar incisivos retroinclinados como nos casos de Classe II divisão 2 (BELLMAN, 2011; INVISALIGN® G3, 2011)

Protocolo G4 surgiu em 2012, com novos e melhores recursos de SmartForce® projetados para movimentos dentários mais previsíveis. Os SmartForce® são recursos nos alinhadores e nos *attachments*, desenvolvidos para melhorar o sistema de forças, no controle mesio distal de angulação de raiz. Forças aplicadas na superfície ativa de dois *attachments* vestibulares criam o momento de força favorável ao movimento radicular. Estes recursos estão disponíveis para os caninos superiores, inferiores e incisivos centrais superiores,

é aplicado para fechar espaços e verticalização mesio distal de raízes. O Invisalign® G4, introduz também o novo recuso de movimento multiplano para melhor controle de incisivos laterais superiores que necessitam de extrusão junto com rotação e/ou inclinação de coroa dentária além de uma nova abordagem para tratamento de mordida aberta anterior baseada nos *attachments* de extrusão que executam movimentos extrusivos nos quatro incisivos superiores como uma unidade usando os dentes posteriores como .Neste ano, a Align adquiriu a Align Cadent Holdings, Inc., uma empresa líder de soluções de digitalização em 3D para ortodontia e odontologia, e fabricantes do iTero.18 A geração 4 também teve mudanças no ano de 2013, porém apenas foram feitas algumas melhorias e a principal mudança foi devido a implementação do seu novo material o *SmartTrack*® prometendo mais elasticidade e resistência ao alinhador durante a movimentação dentária (BRÄSCHER *et al.*, 2016; INVISALIGN® G4, 2012)

Protocolo G5 surgiu em 2014 com o objetivo de corrigir casos de mordida profunda. O Invisalign® G5 criou um novo *SmartForce*® para nivelar a curva de Spee permitindo uma correção mais previsível da mordida profunda trouxe melhorias como *pressure point* na lingual dos incisivos para controle de intrusão anterior na correção da sobremordida exagerada, *attachments* otimizados para extrusão ou ancoragem de pré-molares na correção da sobremordida exagerada, *Precision Bite Ramps*, que é uma pequena estrutura de forma piramidal ligada ao alinhador localizada na região palatina dos incisivos superiores que auxilia a correção da sobremordida exagerada desocluidando os dentes posteriores, eliminando as forças de mordida posterior que podem agir contra a correção da mordida profunda. (INVISALIGN® G5, 2014; MORTON *et al.*, 2017)

O protocolo G6 em 2015 trouxe melhorias com novo *attachments* otimizados para retração do canino no fechamento de espaço de extração do pré-molar (acompanhado ou não de elásticos), novo *attachments* otimizados para maximizar a ancoragem posterior, *attachments* otimizados modificados para acomodar *precision cuts* no canino, inserção de espaço na região dos caninos, no alinhador, para inserção do *Power Arms* que são alças utilizadas

para uso de elásticos, correntes ou molas , identificação de pôneicos e, ClinCheck® Pro (INVISALIGN® G6, 2015; JIL, 2018; ZHU; LI; LAI, 2019)

Em 2016 surgiu o protocolo G7 criando *attachments* otimizados multiplanos para controle de incisivos laterais superiores quando rotação com extrusão ou rotação com intrusão está planejada, *attachments* otimizados para controle dos laterais superiores quando intrusão de incisivos centrais ou caninos é planejada, novo *attachment* para controle radicular mesio-distal do pré-molar e o ClinCheck® Pro 5.0 (INVISALIGN® G7, 2016; MOSHIRI *et al.*, 2021)

Último protocolo criado pela Invisalign® foi o G8, em fevereiro de 2021, surgiu com o objetivo de aumentar mais a previsibilidade clínica. O sistema foi chamado de *SmartForce Aligner Activation*® que aproveita a cobertura completa do alinhador nos dentes para criar áreas de contato estratégicas para maior controle. Trabalha sinergicamente com os recursos *SmartForce*® introduzidos anteriormente para um alto controle do sistema de força que é acionado automaticamente quando há necessidade de intrusão ou expansão vestibular maior que 0,5 mm. Há também a inserção automática do dispositivo *Precision Bite Ramp*® para casos de mordida profunda moderada a grave, com sobremordida de pelo menos 4 mm, e que requer intrusão de pelo menos 1,5 mm dos incisivos inferiores Este sistema pretende melhorar a acurácia clínica dos movimentos de intrusão anterior e expansão do arco na região posterior reduzindo as inclinações dentárias prevenindo a abertura da mordida (ALIGN TECHNOLOGY®, 2021; MOSHIRI *et al.*, 2021).

A acurácia do tratamento ortodôntico com alinhadores é importante pois garante os resultados previstos, o cálculo correto do custo, do tempo e segurança na comunicação com o paciente (LAGRAVERE; FLORES-MIR, 2005). O ClinCheck® é o software que permite a movimentação virtual das coroas dos dentes. É através dele que o paciente e o ortodontista visualizarão a projeção do resultado do tratamento previsto e o progresso com cada alinhador de modo a permitir maior previsibilidade da simulação final do tratamento. (MORTON; DERAKHSHAN; KAZA; LI, 2017). Mesmo com o planejamento computadorizado, a previsibilidade do resultado do tratamento é relativa e varia de acordo com o tipo de movimento desejado (BUSCHANG *et al.*, 2015; CHARALAMPAKIS *et al.*; 2018; GRUNHEID; LOH; LARSON, 2017). Autores

relataram que até 70%-80% dos tratamentos Invisalign® exigiram correção ou refinamento (GALAN-LOPEZ; BARCIA-GONZALEZ; PLASENCIA, 2019).

Para se determinar o sucesso do tratamento com alinhadores, utilizamos da avaliação da acurácia (KRAVITZ *et al.*, 2009; CHARALAMPAKIS *et al.*; 2018; GALAN-LOPEZ; BARCIA-GONZALEZ; PLASENCIA, 2019). Dentre estes, o movimento de inclinação vestibulo-lingual é considerado de moderada a boa previsibilidade (GALAN-LOPEZ; BARCIA-GONZALEZ; PLASENCIA, 2019) Kravitz *et al.*, (2009) com o propósito exclusivo de avaliar a eficácia dos movimentos dentários com Invisalign® realizaram um estudo com modelos iniciais e finais, utilizando os dentes posteriores não movimentados como ponto de referência para sobreposição. Utilizou a ferramenta *Tooth Measure*® da própria Invisalign® para análise dos movimentos. O resultado mostrou que a média de acurácia para todos os movimentos com Invisalign® foi de 41%. Maior acurácia (47.1%) para movimentos inclinação lingual dos incisivos (KRAVITZ; *et al.*, 2009). Charalampakis *et al.* (2018) utilizando a tecnologia Smart Track®, não encontrou diferenças significantes em relação a inclinação vestibulo-lingual dos movimentos previstos e alcançados com Invisalign®. (CHARALAMPAKIS; *et al.*, 2018). Houle *et al.* (2017) encontrou previsibilidade maior na movimentação transversal de 72,8% na maxila e 87,7% na mandíbula, quando comparado com o movimento real alcançado com o previsto pelo ClinCheck® (HOULE *et al.*, 2017). Em 2020, Haouili *et al.* (2020) encontraram uma acurácia no movimento de inclinação buco lingual de 56% creditada às novas tecnologias SmartForce® e SmartTrack® incorporadas pela Invisalign® (HAOUILI *et al.*, 2020). Bilello *et al.* (2022) não encontraram diferenças estatisticamente significantes entre o movimento planejado inicialmente pelo ClinCheck® e o resultado real final alcançado com Invisalign®. A acurácia do movimento vestibulo-lingual foi de 95,9% para a mandíbula e 94,6% na maxila (BILELLO *et al.*, 2022).

Vários autores demonstraram que o movimento de expansão transversal, dos dentes posteriores, com o uso do Invisalign®, ocorre predominantemente com inclinação das coroas e não movimento de corpo do dente. Alertam para a sobrestimarão deste movimento gerado pelo ClinCheck®, que pode não ser alcançado clinicamente, sendo necessário sobrecorreção durante o planejamento virtual (BUSCHANG *et al.*, 2015; HOULE *et al.*, 2017; MORALES-BURRUEZO; *et al.*, 2020; VIDAL-BERNÁRDEZ *et al.*, 2021; ZHOU; GUO, 2020).

Dentre os movimentos lineares, o de intrusão é considerado de mais baixa previsibilidade, alcançando diferença entre o previsto e alcançado de até 1,5mm (KRAVITZ *et al.*, 2009). Para o movimento de intrusão, a previsibilidade encontrada foi em torno de 35% por Grunheid *et al.* (2017), Charalampakis *et al.* (2018). Haouili *et al.* (2020) confirmou estes achados e afirmou que a baixa previsibilidade pode ser uma consequência da falta de *attachment* na região posterior. Al-balaa *et al.* (2021) comparou as medidas de intrusão dos dentes anteriores previstas com as medidas de intrusão reais clínicas usando a tomografia computadorizada de feixe cônico (CBCT)). A previsibilidade média alcançada com uso do Invisalign® foi de 51,19% com melhor previsibilidade entre os incisivos laterais superiores (58,1%) e a pior entre incisivos inferiores (44,7%). Bilello *et al.* (2022) alcançou previsibilidade com maior acurácia de 92,2% e 94,3% para a maxila e mandíbula, respectivamente, onde movimentos de até 2 mm foram considerados mais previsíveis (BILELLO *et al.*, 2022).

Movimentos de rotação são notoriamente considerados de baixa a média previsibilidade. A forma anatômica dos dentes influencia na previsibilidade deste movimento. Dentes planos ou retangulares como incisivos centrais e laterais têm movimentos de rotação mais previsíveis que dentes com superfícies arredondadas como os caninos e pré-molares (KRAVITZ *et al.*, 2008.). Desde Kravitz *et al.* (2009) este resultado já era confirmado com previsão de 32%, 55% e 52% para caninos superiores, incisivos centrais superiores e inferiores, respectivamente. A menor acurácia foi encontrada para os caninos inferiores com apenas 29%. Este mesmo autor afirmou que com desgastes interproximais a acurácia do movimento de rotação dos caninos aumentou para 43%. Especialmente para rotações maiores que 15° a previsibilidade do movimento tornou-se significativamente reduzida para 19% (KRAVITZ *et al.*, 2009; ROSSINI; *et al.*, 2015.). Apesar de considerar os avanços alcançados com a adoção de novos *attachments* otimizados para controle de rotação, Bilello *et al.* (2022) encontrou menor previsibilidade deste movimento entre todos os movimentos estudados sendo de 81%, 80,9% e 70,4% para os caninos, incisivos laterais superiores e pré-molares inferiores, respectivamente (BILELLO *et al.*, 2022.).

A acurácia das análises depende da acurácia da sobreposição (MILLER; KUO; CHOI, 2003). A sobreposição de imagens para avaliação de resultado do tratamento ortodôntico, assim como estudos de alterações do posicionamento

dos dentes e estruturas crânio faciais ocorridas durante a fase de crescimento, têm frequentemente levantado interesse de pesquisadores e clínicos (GARIB *et al.*, 2021; KRARUP *et al.*, 2005).

Com o avanço de novas tecnologias da era digital, modelos 3D das arcadas têm sido utilizados com mais frequência para estudos de diagnóstico e análise dos resultados do tratamento (QUIMBY *et al.*, 2004; AKYALCIN *et al.*, 2013; AKYALCIN; *et al.* 2013). A utilização de modelos digitais 3D para análise de resultado ortodôntico tem como vantagens a ausência de exposição a radiações como ocorre na telerradiografia se nas Tomografias computadorizada de Feixe cônico (CBCT), qualidade da visualização de imagens, custo menor e simplificação do estudo (STUCKI; GKANTIDIS, 2020). Tem sido usado para observação de alterações oclusal causadas pelo crescimento crânio facial (GARIB *et al.*, 2021; S. KRARUP *et al.*, 2005) análise da acurácia e previsibilidade do tratamento ortodôntico com alinhadores (CHARALAMPAKIS *et al.*, 2018; GRUNHEID *et al.* 2017; SACHDEV; TANTIDHNAZET; SAENGFAL, 2021) e avaliação da movimentação dentária (CAMARDELLA; BREUNING; VILELLA, 2017; CAMARDELLA *et al.*, 2021; JOSÉ VIÑAS; PIE DE HIERRO; 2018; KLAUS; XIROUCHAKI; RUF, 2020; STUCKI; GKANTIDIS, 2020). Os modelos 3D produzidos através de escaneamento intrabucal apresentam maior clareza nos detalhes anatômicos e mostraram ser adequados, reproduzíveis e válidos para uso na Ortodontia, além da confiabilidade superior na relação das arcadas em comparação aos modelos digitais indiretos (AKYALCIN *et al.*, 2013; AKYALCIN, *et al.*, 2013).

Na literatura diversos métodos buscam confiabilidade para sobreposição de modelos 3D através de demarcação de pontos na maxila e mandíbula que sejam estáveis e não se movimentem durante o tratamento ortodôntico (AN *et al.*, 2015; CAMARDELLA *et al.*, 2020; VASILAKOS *et al.*, 2017). Estudos que buscaram pontos de sobreposição na maxila observaram que os mais estáveis estão localizados na região posterior da papila incisiva e nas segunda e terceira rugas palatinas (CHOI *et al.*, 2010; KURALT; FIDLER, 2021; VASILAKOS *et al.*, 2017). Garib *et al.* em 2019, realizou um estudo com o objetivo de avaliar a confiabilidade da sobreposição de modelos digitais nas alterações dentárias ocorridas durante um período de acompanhamento dos pacientes dos 5 até os 40 anos de idade. Os modelos foram sobrepostos usando 9 pontos demarcados

em regiões que incluiu o limite posterior da papila incisiva, bordas mediais da segunda ruga, bordas mediais e distais da terceira ruga palatina e duas marcas projetadas 10mm distal da margem medial da terceira ruga. O programa utilizado nas sobreposições foi Slicer[®] 3D. Seu resultado mostrou que em período de até 5 anos as marcas selecionadas parecem ser confiáveis para sobreposição (GARIB *et al.*, 2019).

Para a mandíbula são mais raros os trabalhos que encontram pontos estáveis que possam ser utilizados para sobreposição de modelos em 3D (AN *et al.*, 2015; JOSÉ VIÑAS; PIE DE HIERRO; J, 2018; STUCKI; GKANTIDIS, 2020). An *et al.* (2015) realizou estudo para definir pontos estáveis na mandíbula que pudessem ser sobrepostos, por meio de sobreposição de teleradiografias laterais como modelos 3D dos mesmos pacientes os autores sobrepuseram os modelos mandibulares em quatro áreas bilaterais linguais definidas na região alveolar dos incisivos até molares e uma área, bilateral, na região vestibular próximo aos pré-molares e molares. Suas conclusões foram que nas áreas, tanto vestibular quanto lingual, em pacientes que não possuem Torus, não há estruturas estáveis que possam ser utilizadas na sobreposição de modelos de mandíbula e que os torós na região lingual, próximo aos caninos e pré-molares, são estáveis, mas esta é uma estrutura que não está presente em todos os pacientes (AN *et al.*, 2015).

Ioshida *et al.* (2019) na busca de áreas estáveis para sobreposição da mandíbula validou a linha muco gengival como área de referência. As imagens digitais foram obtidas através de escaneamento intrabucal e comparadas com resultados previamente conseguidos através de CBCT da mandíbula. Dez pontos ao longo da linha muco gengival vestibular foram usados para a sobreposição dos modelos pré e pós-tratamento ortodôntico. Foi observado que não houve diferença estatisticamente significativa entre as medidas com a CBCT e as realizadas nos modelos digitais mostrando a confiabilidade da linha muco gengival como área estável para sobreposição de modelos digitais da mandíbula (IOSHIDA *et al.*, 2019). Recentemente Garib *et al.* (2021), revalidou a linha muco gengival como área de sobreposição de modelos digitais mandibulares. Foram avaliadas as mudanças tridimensionais dentais na mandíbula em pacientes não tratados e em crescimento. Os modelos digitais obtidos em dois tempos, com um intervalo entre eles de 42 anos, foram sobrepostos utilizando 13 pontos ao longo

da linha mucogengival do primeiro molar direito ao primeiro molar do lado esquerdo. O software utilizado para aproximação dos modelos foi Slicer® versão 3.1. Com seus resultados foi possível observar pequenas mudanças na posição de alguns dentes entre os 17 e 60 anos de idade em relação à linha mucogengival, considerada estável ao longo dos anos, mesmo durante movimentação dentária (GARIB *et al.*, 2021).

Pesquisas realizadas utilizaram diversos softwares, mas não chegaram a um senso comum sobre a previsibilidade dos movimentos. Todos esses programas necessitam de demarcação de diversos pontos nos modelos 3D o que pode gerar erros sistemáticos. Softwares específicos para a Odontologia têm demonstrado limitações e dificuldades para uso em pesquisa (FELTER *et al.*, 2018; TALAAT *et al.*, 2017; WESTERLUND *et al.*, 2015). Autodesk Inventor® é um software proveniente da engenharia que utiliza o sistema CAD/CAM na construção de um produto/peça e no auxílio ao entendimento de como um produto ou um corpo se comporta em determinadas condições. Utiliza o sistema de coordenadas Sistema de Coordenadas Universais (UCS) que permite marcar apenas um ponto, que será a origem de um sistema de coordenadas para cada modelo (<https://knowledge.autodesk.com/support/inventor-products>). Através da demarcação deste único ponto, em cada modelo em estereolitografia (STL), é gerado um sistema de coordenadas tridimensionais definido por três vetores, representando os eixos cartesianos (X, Y E Z), onde o software, de forma automática, alinha estes eixos criando uma sobreposição de todos os pontos do espaço (BOLDRINI *et al.*, 1980). Isso torna o estudo dos movimentos tridimensionais dos modelos mais próximo da realidade, gerando modelos sobrepostos mais acurados, sem utilização de inúmeros pontos para sobreposição garantindo a equivalência do espaço cartesiano de ambos os modelos mantendo a alta precisão (<https://knowledge.autodesk.com/support/inventor-products>).

Diversos trabalhos têm buscado medir a previsibilidade com o sistema Invisalign® através do ClinCheck®. Nenhum deles até o momento avaliou a acurácia do protocolo G8 comparado a protocolos antigos para verificar se houve melhora na previsibilidade principalmente nos movimentos de intrusão e expansão posterior. Neste sentido, nosso estudo visou desenvolver um protocolo de sobreposição usando um software da área de engenharia de alta precisão

utilizando planos cartesianos associados a um único ponto na maxila e mandíbula para sobreposição. Posteriormente analisar através destes modelos a acurácia do protocolo G8 do tratamento ortodôntico com Invisalign® nos movimentos de intrusão e expansão dentária.

2 OBJETIVOS

2.1 Objetivo geral

Desenvolver um novo método de sobreposição de modelos digitais e, a partir disso, avaliar a previsibilidade dos movimentos de intrusão e expansão de casos tratados com o novo protocolo G8 da Invisalign®.

2.2 Objetivos específicos

- 1- Estabelecer novo método de sobreposição utilizando o sistema Cartesiano associado a ponto de único em modelo 3D de maxila e mandíbula;
- 2- Desenvolver um método de sobreposição de modelos 3D para maxila e mandíbula no software Autodesk Inventor®;
- 3- Avaliar a confiabilidade e reprodutibilidade do método proposto para realizar sobreposição de maxila e mandíbula utilizando modelos 3D;
- 4- Avaliar a previsibilidade do movimento de intrusão e expansão dentária com ativação do protocolo G8 da Invisalign® utilizando a nova metodologia de sobreposição proposta no presente estudo.

3 METODOLOGIA

3.1. Desenho do estudo

Foi realizado um estudo observacional retrospectivo.

3.2. Considerações éticas

Este estudo foi aprovado pelo Comitê de Ética e Pesquisa da Universidade Federal de Minas Gerais (CAAE: 48546321.4.0000.5149), foi registrado na base do Registro Brasileiro de Ensaio Clínicos (ReBEC) com o número RBR-7df547he. Este trabalho seguiu a Declaração de Helsinque

3.3. Seleção da amostra

A amostra, de conveniência, deste estudo foi composta por 56 modelos, STL, 28 da maxila e 28 da mandíbula de 14 pacientes das fases iniciais (T0) e refinamento (T1), exportados da plataforma My iTero® (<https://bff.cloud.myitero.com/doctors/home> Align Technology, Santa Clara, CA, USA). Os casos foram tratados por um único ortodontista pertencente a uma clínica privada na cidade de Belo Horizonte, MG, Brasil, através do sistema Invisalign® (Align Technology, Santa Clara, CA, USA). Todos os pacientes foram escaneados através do escaner iTero® (modelo Element RTC2018 W06A228) por um único operador. Onze casos foram tratados exclusivamente com o protocolo anterior ao G8 e três casos o protocolo G8 foi ativado.

3.3.1 Critérios de inclusão:

Foram selecionados participantes com más oclusões de Classe I, II ou III com apinhamento moderado inferior de até 4mm, alteração na sobremordida (3 mm até 5 mm), dentição permanente, presença de todos os dentes até os segundos molares, com idades entre 18 a 45 anos. Todos tratados entre os anos de 2020 e 2022 através do sistema Invisalign®.

3.3.2 Critérios de exclusão

Foram excluídos participantes que apresentaram restaurações nos dentes movimentados durante o tratamento, pacientes não colaboradores, portadores de síndromes ou anomalias crânio faciais e/ou com sinais ou sintomas de inflamação nos tecidos periodontais. Três casos foram descartados: um por apresentar restaurações com resina composta em dentes movimentados,

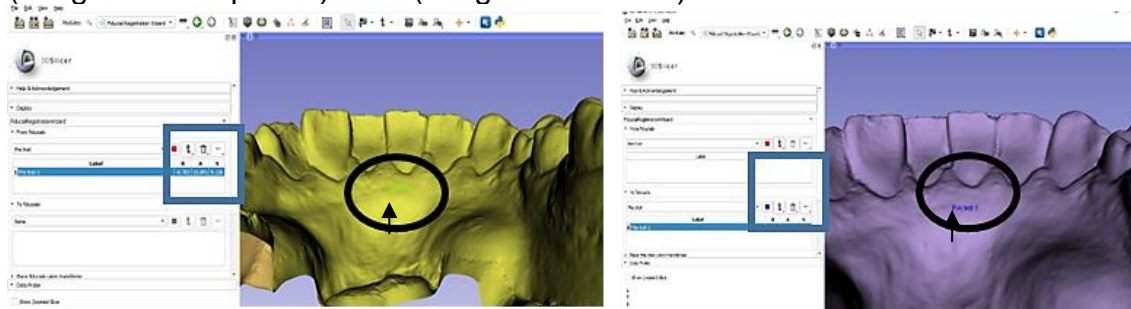
na qual alterou a proporção dentária e dois casos por apresentarem distorção na malha STL no momento de exportação para o software, em nenhum destes o protocolo G8 foi ativado. Restando desta forma 44 modelos STL 22 maxilares e 22 mandibulares. Em 12 modelos STL (6 pares de modelos sobrepostos 3 maxilares e 3 mandibulares) o protocolo G8 foi ativado.

3.4. Sobreposição dos modelos

Material detalhado com guia contendo passo a passo sobre a sobreposição utilizando os softwares e medições dos movimentos estão inseridos no material suplementar do artigo 1. A abordagem abaixo são considerações gerais

Para marcação dos pontos de sobreposição os modelos STL foram exportados para o programa Slicer® CMF (Versão 4.11; <http://slicer.org>). A demarcação de um ponto foi realizada utilizando a ferramenta “*Fiducial Image Guided Therapy*”(IGT) no modelo T0 e o mesmo ponto no modelo T1. Este ponto foi localizado na região central e mais superior na linha muco gengival entre os incisivos centrais inferiores na porção lingual na mandíbula (FIGURA 1) e, na região medial da segunda ruga palatina na maxila. A marcação de cada ponto gerou coordenadas espaciais UCS que foram transferidas para os modelos no Autodesk Inventor® (FIGURA 2).

Figura 1: Identificação pontos na mandíbula, linha muco gengival, modelos T0 (imagem da esquerda) e T1 (imagem da direita)

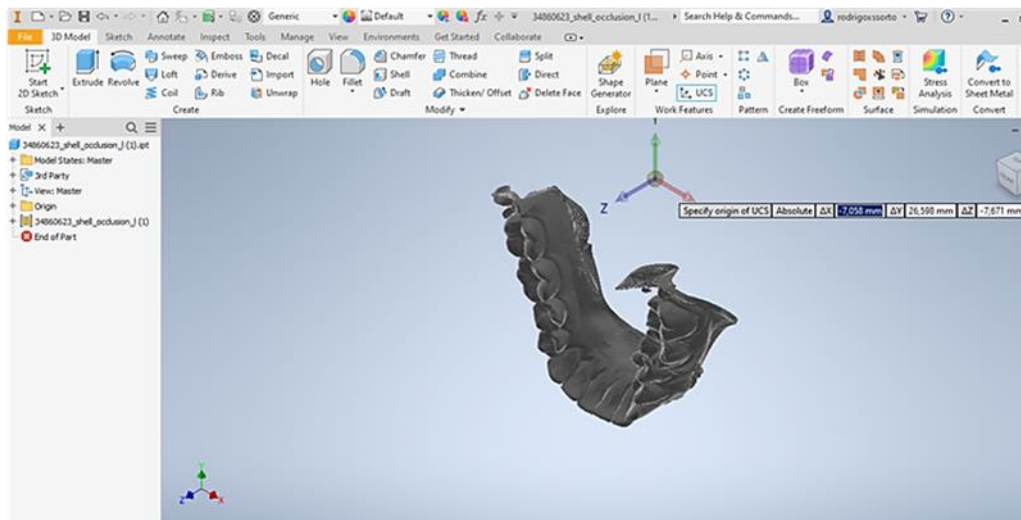


Fonte: Próprio autor, 2022

Os valores das coordenadas, representando os 3 eixos espaciais, X, Y e Z foram transferidos para o Autodesk® Inventor® 2022 e demarcados em cada

modelo (T0 e T1) usando a ferramenta UCS (Sistema de Coordenadas Universais) (FIGURA 2).

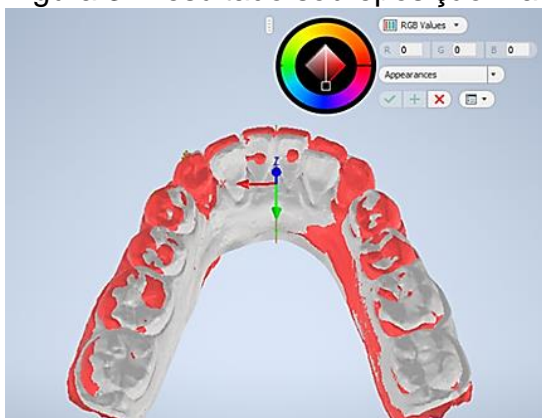
Figura 2: Inserção das coordenadas através da ferramenta UCS



Fonte: Próprio autor, 2022

A sobreposição dos modelos T0 e T1 foram realizadas através da ferramenta “Cosntrain” utilizando como referência os pontos demarcados em cada modelo na etapa anterior. Desta forma a sobreposição ocorre através dos eixos (X, Y e Z) com infinitos pontos ao longo destes. O resultado da sobreposição da mandíbula é mostrado na Figura 3 onde a cor cinza representa o modelo T0 e o vermelho o modelo T1.

Figura 3: Resultado sobreposição mandibular



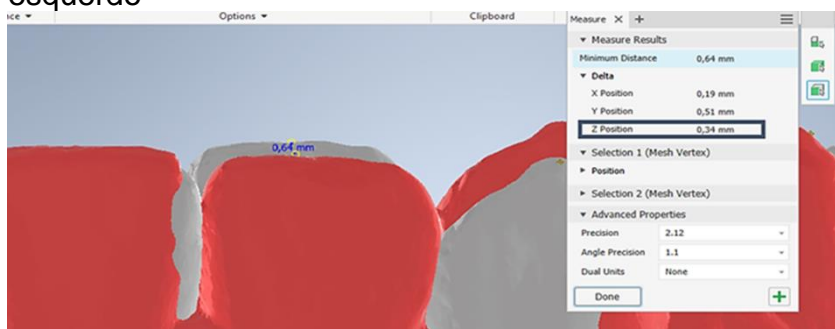
Fonte: Próprio autor, 2022

3.5 Medidas dos movimentos dentários

Foram realizadas as medições das distâncias entre as cúspides vestibulares dos caninos molares e pré-molares nos modelos T0 e T1 da maxila e mandíbula representando a translação buco-lingual (GRUNHEID, *et al.*,2017; VIDAL-BERNÁRDEZ,*et al.*,2021; MORALES-BURRUEZO *et al.*,2020). Estes movimentos foram representados pelo eixo X.

O movimento vertical dos caninos e incisivos mandibulares foram medidos através da distância na ponta das cúspides dos caninos de T0 e T1 e no meio das bordas incisais dos incisivos de T0 e T1 (CHARALAMPAKIS *et al.*, 2018) (FIGURA 4). Deslocamentos no sentido gengival, ou seja, movimento de intrusão, foram considerados com sinal positivo (+). Deslocamentos no sentido oclusal/incisal, ou seja, movimento de extrusão, foram considerados com sinal negativo (-) (De Oliveira *et al.*, 2019), e assim observado a quantidade de movimento no eixo Z em milímetros (mm).

Figura 4: Exemplo de medição de movimento de intrusão do incisivo lateral esquerdo



Fonte: Próprio autor, 2022

A rotação mesio-distal dos caninos e incisivos mandibulares foi calculada através do ângulo formado pelas linhas traçadas nas bordas incisais ligando ponto na mesial e distal dos incisivos ou ponta das cúspides dos caninos. A rotação é expressa em graus referente a inclinação formada pela linha traçada em T0 com T1.

3.6 Calibração inter e intraexaminador

A calibração inter e intra examinadores foi realizada através da análise das medidas, após a sobreposição, dos movimentos dentários descritos acima,

totalizando 22 medições (5 medidas de translação buco lingual dos caninos e molares mandibulares e 5 de caninos e molares maxilares, 6 de intrusão/extrusão de caninos e incisivos inferiores e 6 rotação mesio distal de caninos e incisivos inferiores) , dos 26 dentes de cada modelo totalizando 242 medidas em 286 dentes. O examinador 1 (RS) repetiu as medidas 2 vezes com um intervalo entre elas de 15 dias (intra examinador) e o examinador 2 (GS) realizou estas medições uma vez (inter examinador).

3.7 Análise estatística

O Coeficiente de Correlação Intraclasse (ICC) foi utilizado para verificar a concordância intra- e inter- examinadores. O erro sistemático foi avaliado através da fórmula de Dahlberg. Os resultados foram expressos como média \pm desvio padrão (DP). A análise da distribuição normal dos dados foi verificada pelo teste de normalidade Omnibus de D'Agostino & Pearson. Para acurácia dos movimentos foi utilizada a equação: porcentagem de acurácia= $100\% - ((\text{previsto} - \text{alcançado}) / \text{previsto}) \times 100\%$. O movimento previsto foi considerado o resultado expresso na tabela de movimentos do ClinCheck®. O movimento alcançado foi o movimento real conseguido analisado pelo método das superposições dentárias. Teste *T-student* foi utilizado para comparação entre dois grupos experimentais.

4 RESULTADOS

Os resultados e discussão serão apresentados na forma de dois artigos científicos

4.1 Artigos

4.1.1 Artigo 1- Resposta ao objetivo geral e específicos 1, 2 e 3.

Artigo submetido ao: periódico "The Angle Orthodontist" Qualis A1. Elaborado nas normas da revista

.. Dear Dr. Macari:

On September 12, 2022, I received your manuscript entitled "Step-by-step guidelines for mandibular and maxillary arches superimposition by Autodesk Inventor® using a single point in 3D models" by authors:

Your manuscript has been assigned the Paper #: 090822-632.

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.

I will contact you as soon as this process is complete. In the interim, you may check on the status of this manuscript by selecting the "Check Manuscript Status" link under the following URL:

<https://angle.msubmit.net/cgi-bin/main.plex?el=A6PO6JjB4A7LUw5F7A9ftd889d8IKro7z9zf1Q8E3kQZ>

(Press/Click on the above link to be automatically sent to the web page.)

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

Sincerely,

Steven J Lindauer

Editor, The Angle Orthodontist.

Step-by-step guidelines for mandibular and maxillary arches superimposition using the Cartesian coordinate system and a single point in 3D models

Objective: To develop a method for superimposing 3D models of the maxilla and mandibular arches using Autodesk Inventor® engineering software using the Cartesian coordinate system (CCS).

Methods: A total of 44 STL models of the maxilla and mandibular arches exported from ClinCheck® were retrospectively selected, where T0 was initial and T1 refinement periods (n = 11 per group). The X, Y and Z coordinates associated to a single point in each arch were inserted into the models with Autodesk Inventor® software for model orientation. The arch models with CCS registration were transferred to SlicerCMF® for superimposition and to measure the movements performed during the Invisalign® treatment. The 3D movements of bucco-lingual translation of maxillary and mandibular canines, pre-molars and molars were analyzed and, the intrusion and rotation movements of the mandibular incisors and canines were measured by two examiners. The Intra- and interrater agreements were evaluated using intraclass correlation coefficients (ICC). The error of the method was performed by the Dahlberg's formula, and t-test was used to compare the differences between the movements achieved and predicted by ClinCheck® (p < 0.05).

Results: ICC showed excellent intra- and interrater correlation (ICC > 0.90). Systematic error was not found in relation to linear and angular measurements (< 1mm and < 1.5°, respectively), and the achieved movements did not exhibited statistical differences in comparison to ClinCheck®.

Conclusion: The developed method was proven reliable and reproducible for superimposing of 3D models of the maxillary and mandibular arches by using CCS registration and demarcating a unique point using Autodesk Inventor® software.

Key words: Dental models, Superimposition, reproducibility of results

INTRODUCTION

The digital models superimposition are mainly used for observation of occlusal changes caused by craniofacial growth,^{1, 2} analysis of the accuracy and predictability of orthodontic treatment with aligners³⁻⁵ and, evaluation of orthodontic tooth movement.⁶⁻¹¹ The use of three-dimensional (3D) digital models for orthodontic outcome analysis has advantages over other methods, such as less exposure to radiation, quality of image visualization and, lower cost.⁸

Several methods seek reliability for overlapping 3D models by demarcating points in the maxilla and mandible, that are stable and do not move during orthodontic treatment.^{7, 12-14} Studies that looked for superimposition points in the maxilla observed that the most stable are located in the posterior part of the incisor papilla and the palatal rugae^{13, 15, 16}. Regarding the mandible, solid points that can be used for superimposition in 3D models are scarce^{8, 11, 14} Thus, more studies are needed to establish stable points for better accuracy of mandibular superimposition.¹⁷

Dental software programs have been developed to assist orthodontists in treatment planning, but all have shown limitations and difficulties to be used in research.¹⁸⁻²⁰ Autodesk Inventor® is an engineering software program that uses the Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) system to build products and items, and to help understand how a product or body behaves under certain conditions. It uses the Universal Coordinate System (UCS) that defines orientation of the Cartesian axes X, Y and Z in three-dimensional space, associated with a single point mark on the part/model with high accuracy. Due to its advantages, the use of Autodesk Inventor® in the superimposition of 3D models in Dentistry might bring reliability to the studies of three-dimensional movements in the maxilla and mandible arches.²¹

Understanding of 3D models superimposition steps is of paramount importance for its conduction. It is not simple to be done as there are difficulties that could face the researcher. To decipher those obstacles, this methodology study aimed to provide a step-by-step approach mainly for beginners and junior researchers, in the field of orthodontics and other specialties in the use of 3D models, on how to properly conduct a superimposition, in which all the steps here

depicts our experience and expertise combined with free software with no additional cost for the researcher.

The objective of this study was to create a step-by-step guide to superimpose 3D models of the maxillary and mandibular arches, using the UCS coordinates and a single point mark on the model with Autodesk Inventor® Professional 2022 software ^{21, 22} to make the analysis easier and accurate.

MATERIAL AND METHODS

This retrospective observational study was approved by the Ethics and Research Committee of the Federal University of Minas Gerais (CAAE: 48546321.4.0000.5149) and in the Brazilian Clinical Trials Registry (ReBEC, # RBR-7df547h). The inclusion and exclusion criteria were determined. The sample was composed of 44 stl models STL (Stereo-lithographic or Standard Triangle Language) models, treated with the Invisalign® system (Align Technology, Santa Clara, CA, USA) and exported from the ClinCheck® software (<https://ClinCheck®.invisalign.com> Align Technology, Santa Clara, CA, USA). The maxillary and mandibular arches (n = 22 per group) were scanned using an iTero® scanner (model Element, S/N: RTC2018 W06A228) by a single operator, under the same conditions (same room, same chair), at two points in time: T0 (start of treatment) and T1 (refinement phase). The 3D movements of bucco-lingual translation of maxillary and mandibular canines, pre-molars and molars were analyzed and, the intrusion and rotation movements of the mandibular incisors and canines were measured by two examiners. The inter- and intra-examiner calibration was performed through the analysis of measurements of tooth movements. Thirty-two measurements were made on 26 teeth of each model, totaling 242 measurements on 286 teeth. Examiner 1 (RS) repeated the measurements twice with a 15-day interval (intra-examiner) and examiner 2 (GS) performed these measurements once (inter-examiner).

Briefly, the superimposition steps were:

1. Marking of points for superimposition (Fig. 1): The program SlicerCMF® (Version 4.11; <http://slicer.org>) was used to define a point on each model (T0 and T1)

2. On Autodesk Inventor® software: using the UCS tool, the X, Y and Z coordinates were inserted into the models (Fig. 2)
3. The model points were superimposed using the "Constrain" tool (Fig. 3) and then linear (Fig. 4) and angular (Fig. 5) movements were measured
4. Inter- and intra-examiner calibration was performed.

A full step-by-step guide was developed to superimpose 3D models of the maxillary and mandibular arches to help researchers.

STATISTICAL ANALYSIS

The inter- and intra-examiner calibration was checked by the Intraclass Correlation Coefficient (ICC) (2-way random, single measurement, absolute agreement), using the SPSS program (IBM SPSS Statistics version 19.0, Inc., New Armonk, NJ, EUA). For assessment of systematic error, the Dahlberg formula was used. For systematic error evaluation, linear measurements should not exceed 1 mm and angular measurements should not exceed 1.5°. The steps for model analysis were performed by two examiners (RS and GS, inter-examiner). The first examiner performed the steps twice, with a 15-day interval between examinations (intra-examiner). ICC values of 0.9 to 1 were considered excellent, 0.6 to 0.7 were good, 0.4 to 0.5 were considered reasonable, and less than 0.4 were categorized as poor²³. Student's t-test was used to analyze the differences between the groups, where $P < 0.05$ was considered statistically significant. Statistical analysis was performed using the program GraphPad Prism (Version 8.0 for Mac, La Jolla, California, USA).

RESULTS

The step-by-step guide to superimposing 3D digital models in STL using Slicer® CMF® and the Autodesk Inventor® software was prepared (Supplementary Material).

For the inter-examiner analysis, the mean ICC for maxillary and mandibular buccal-lingual translation movements was 0.98 and 0.97 (Table 1), respectively. The mean ICC for rotation and intrusion movements was 0.99 and 0.99, respectively. Values above 0.9 were considered excellent (Table 2). Similar values were found for the intra-examiner evaluation with a mean ICC for maxillary and mandibular buccal-lingual translation movements of 0.99 and 0.989 (Table

3). The mean ICC for rotation and intrusion movements were 0.995 and 0.991, respectively, being considered excellent (Table 4).

Dahlberg values were always smaller than 1, demonstrating that no systematic error was found for inter- (Tables 1 and 2) and intra-examiners (Tables 3 and 4). Statistical significance between measurements for inter- (Tables 1 and 2) and intra-examiners (Tables 3 and 4) was considered $P < 0.05$.

DISCUSSION

Our work was the first to use the association between the SlicerCMF[®] software and the Autodesk Inventor[®] engineering program, using the basic principle of the Universal Coordinate System (UCS). This technique allowed to determinate a single point in the region of the palatine rugae, in the maxilla, and a point in the lingual region of the mandible, at the mucous-gingival junction. The results proved to be reliable and reproducible for superimposing 3D orthodontic models of the maxilla and mandible in STL format.

In the literature several methods of superimposition have been proposed.^{10, 15, 24-26} The search for stable structures that are not influenced by orthodontic movement has been the main prerogative of current studies.⁸ Even in cases of orthodontic aligners, where no movement of posterior teeth is planned, making them assumedly immobile, the tooth movement is observed.³

Studies have pointed out that both the palatal rugae region and the mucous gingival region are stable for model superimposition, using a wide area of the maxilla and mandible, respectively^{1, 8, 10, 12-15, 25, 26, 27, 28}. The greatest difficulties in superimposing STL models have been in the mandible.^{8, 16, 26} One of the points used that proved stable for mandibular superimposition is the Torus located on the lingual alveolar surface, however, this is a structure that is not present in all patients,¹⁴ thus its use was discarded in our research. The region of the mucous-gingival junction has been chosen for 3D overlays in the mandible because it is easy to locate and because it is stable and does not change²⁶, even during intrusion and extrusion movements of the teeth and with mandibular growth.^{1, 25, 26, 27} Usually, in the literature, these points are demarcated along the mucous-gingival junction from the first molar on the right side to the first molar on the left side, totaling 13 marks on average^{1, 25, 26}. The enhanced number of marks

might increase the chance of errors and possibly decreasing the reliability of the method. The solution to this impasse in our study was the use of the Cartesian axes associated with a single point at the mucogingival junction in the mandibular region. Through the demarcation of a single point, in each model, the three Cartesian axes (X, Y and Z) were generated and the program, through the software, aligns these axes in models T0 and T1, creating infinite points of spatial superposition, as it is a stable structure present in all cases, with ease location, stability and reproducibility^{1, 8, 25, 26}.

In the maxillae, studies have shown that the rugae regions, especially the second and third rugae, are stable regions for superimposition.^{1, 14, 25, 27} In the current study the Cartesian axes with a single point in the medial region of the second rugae was used for superimposition of the maxillary models. This area is considered safe because it is not affected by tooth movement,^{10, 13, 26} thus decreasing the chance of errors during the marking of similar points.

Several studies seek to increase the reliability of the overlay by searching for the spatial reference planes using manual tools for the elaboration of the coordinates.^{7, 14, 15, 19, 26, 30} The use of only one point in each 3D model was possible due to the use of the UCS coordinate system. Through UCS in Autodesk Inventor® it was possible to automatically match the Cartesian axes by reading the coordinates of the points in the two models, T0 and T1, and thereby evaluate the displacements of the X (bucco-lingual displacement), Y (mesio-distal displacement) and Z (vertical displacement) coordinates. Thus, it was possible to observe each variation individually, without an approximation mechanisms or manual interference. This method is an essential tool for many precision operations in engineering and can be used in Dentistry, reducing the amount of work required for the superimposition of 3D models.²⁹

Autodesk Inventor® is commonly used in bioengineering for stress and strain assessment that requires accurate positioning of the models prior to mechanical analyses.^{31, 32} In our research, this software was fundamental to ensure the correct positioning of the models, which is essential in studies for 3D models overlap. Autodesk Inventor®, as well as other CAD/CAM software, is compatible with several 2D and 3D file extensions, especially the so-called "neutral formats", such as Standard Triangle Language (.STL), parasolid (.x_t)²⁵. The use of this software proved to be very useful in this study, since the maxilla

and mandible scans performed in Invisalign® orthodontic treatments use the STL format. Thus, it was possible to easily manipulate the models using Autodesk Inventor® 2D and 3D design tools.

The software used in our research was the freely available SlicerCMF® that is commonly used in Dentistry and has demonstrated its accuracy and reliability²⁶. It has been used for superimposing 3D models of the maxilla, despite using several points on the palatal rugae,^{26, 33} and for superimposing points on the mucous gingival region of the mandible, using 13 points as a reference for superimposition.^{1, 26} We used the SlicerCMF® for single point demarcation on both T0 and T1 models. The superimposition was not performed by this software as it requires more than one point for this purpose.²⁶ In this study, the marks in the lingual mucosa gingival region were easily visualized and demarcated, and registered through the association with the X, Y and Z coordinates generated by the software itself, having as an advantage their easy use.

In the present research, the treatment was focused in mild to moderate malocclusions with duration of eight-month period. After the treatment with the aligners there were few changes in the adjacent gingival tissues, however none of them could hinder the identification of similar points or structures in the T0 and T1, allowing the 3D models proper superimposition. The same anatomical structures used in this research can be visualized in more severe malocclusions, showing that there are no limitations to the use of the new superimposition method proposed in this study.^{16, 25}

Considering the ICC of each movement, high values in the linear movements expressed in millimeters were obtained. The lowest value for ICC was for the rotation, expressed in degrees. The reason was the high sensitivity of Autodesk Inventor® for angular measurements, especially for values smaller than 5°. During insertion of the points on the incisal edges, minimal displacements in the bucco-lingual direction within the incisal edge could alter the reading of the angle formed by the two lines (T0 and T1), especially when the models were approached to enlarge the STL mesh. A different situation was found in the linear measurements, as small horizontal displacements did not affect the result so significantly, due to the size of the measurements. Regarding the systematic error, some authors state that less than 1 mm and 1.5° for linear and angular,

respectively, are acceptable³⁴ but in our study the magnitude of these values may mean clinically relevant movements.

The STL models were obtained retrospectively by scanning exclusively with iTero®, as carried out in other studies.³⁵⁻³⁷ The spatial position of the models was established by this program automatically. In future studies another scanner brand may be used in order to evaluate if this is a factor that influences the spatial positioning of the models, so as to increase accuracy. Another suggestion for future studies would be an analysis of accuracy and predictability with the use of aligners using the movements predicted by ClinCheck® as the gold standard, which would be very useful to compare the actual movement with the planned virtual one. Additionally, more complex movements need to be tested since our study only included samples with mild to moderate malocclusions

Inexperience with engineering software can become a real challenge and limitation for dental researchers. However, in this study, a very detailed step-by-step procedure was developed allowing complex and, unfamiliar commands, that may become easy and intuitive after professional training. After the high agreement and reproducibility results achieved with this program, it may become a new and useful diagnostic tool for outcome assessment and orthodontic treatment predictability within all clinicians' reach.

CONCLUSION

The model superimposition method for measuring tooth movement by means of Autodesk Inventor® software using the Cartesian axes and a single point for superimposing 3D models of the maxilla and mandible proved to be reliable and reproducible.

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FIGURES

Figure1. Demarcation points on the maxilla and mandible in Slicer 3D® software

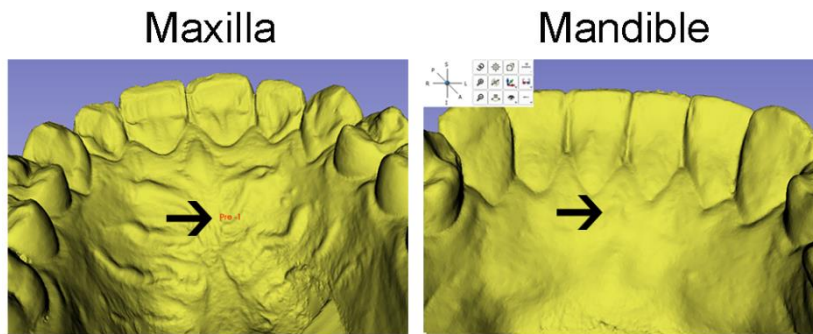


Figure 2. By entering the coordinates in the mandible using the UCS tool in Autodesk Inventor® software.

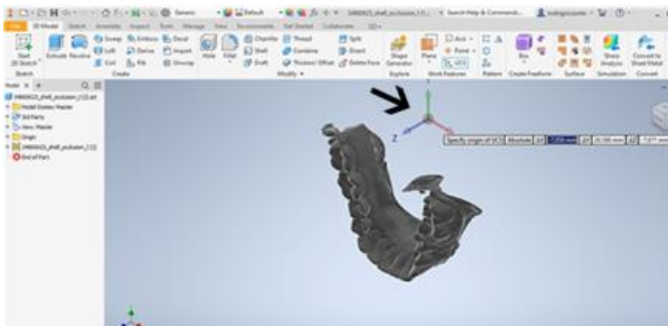


Figure 3. Superposition result

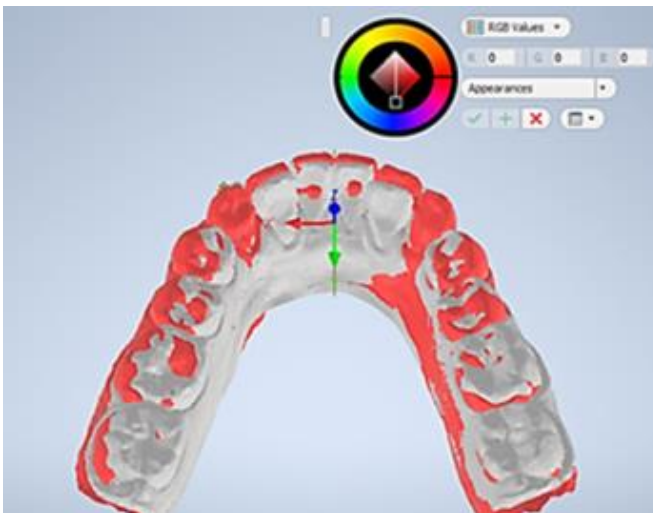


Figure 4. Using tools to measure the vertical movement of incisor and canines

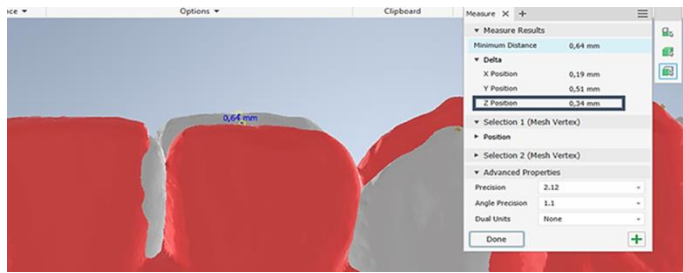
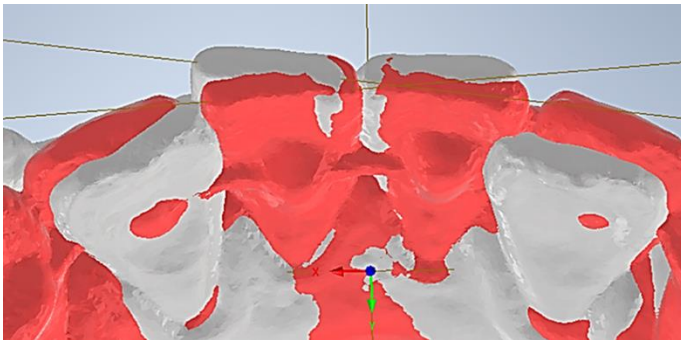


Figure 5. Using tools to measure mesio-distal rotation of the mandibular incisor



TABLES

Table 1: Results of the buccal-lingual translation interrater agreement of the mandibular and maxillary canines, premolars and molars

Tooth	Buccal-lingual translation				
	ICC	CI 95%	D	p	n
13	0,991	0,915-0,998	0,046	0,745	11
14	0,986	0,612-0,997	0,069	0,636	11
15	0,989	0,773-0,998	0,072	0,689	11
16	0,985	0,510-0,997	0,041	0,606	11
17	0,987	0,957-0,996	0,044	0,935	11
23	0,976	0,917-0,993	0,047	0,969	11
24	0,988	0,958-0,996	0,101	0,938	11
25	0,986	0,952-0,996	0,124	0,989	11
26	0,985	0,948-0,996	0,063	0,986	11
27	0,985	0,948-0,996	0,037	1,000	11
33	0,992	0,992-0,998	0,031	0,781	11
34	0,971	0,969-0,893	0,097	0,987	11
35	0,994	0,992-0,999	0,076	0,792	11
36	0,984	0,798-0,997	0,067	0,670	11
37	0,915	0,688-0,997	0,098	0,827	11
43	0,95	0,818-0,987	0,102	0,874	11
44	0,98	0,928-0,995	0,101	0,798	11
45	0,986	0,95-0,996	0,103	0,987	11
46	0,937	0,773-0,983	0,151	0,634	11
47	0,993	0,973-0,998	0,023	0,952	11

ICC: Intraclass Correlation Coefficient; CI: Confidence Interval; D: Dahlberg; $p \leq 0,05$

Table 2: Results of the rotation and intrusion/extrusion movements interrater agreement mandibular

Tooth	Rotation					Intrusion- extrusion				
	ICC	CI 95%	D	p	n	ICC	CI 95%	D	p	n
43	0,992	0,972-0,998	0,762	0,872	11	0,993	0,976-0,998	0,056	0,976	11
42	0,992	0,972-0,999	0,635	0,903	11	0,993	0,976-0,998	0,031	0,860	11
41	0,989	0,945-0,997	0,635	0,776	11	0,995	0,988-0,999	0,030	0,983	11
31	0,988	0,957-0,996	0,638	0,963	11	0,994	0,962-0,999	0,039	0,811	11
32	0,993	0,997-0,998	0,507	0,953	11	0,992	0,607-0,999	0,041	0,723	11
33	0,993	0,997-0,998	0,664	0,854	11	0,985	0,948-0,996	0,103	0,819	11

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ICC: Intraclass Correlation Coefficient; CI: Confidence Interval; D: Dahlberg; $p < \leq 0,05$

Table 3: Results of the bucco-lingual translation intraerrater a agreement movement of the mandibular and maxillary canines, premolars and molars

Tooth	Buccal-lingual translation				
	ICC	CI 95%	D	p	n
13	0,994	0,981 - 0,998	0,299	0,906	11
14	0,99	0,968 - 0,997	0,425	0,900	11
15	0,99	0,966 - 0,997	0,475	0,898	11
16	0,991	0,968 - 0,997	0,323	0,889	11
17	0,989	0,965 - 0,997	0,259	0,718	11
23	0,982	0,922 - 0,995	0,247	0,819	11
24	0,993	0,967 - 0,998	0,542	0,833	11
25	0,991	0,954 - 0,998	0,567	0,841	11
26	0,991	0,958 - 0,998	0,350	0,844	11
27	0,989	0,961 - 0,997	0,195	0,844	11
33	0,989	0,914 - 0,997	0,036	0,715	11
34	0,991	0,955 - 0,998	0,036	0,799	11
35	0,990	0,964 - 0,997	0,065	0,915	11
36	0,986	0,949 - 0,996	0,037	0,931	11
37	0,988	0,958 - 0,997	0,015	0,875	11
43	0,986	0,935 - 0,996	0,278	0,770	11
44	0,990	0,966 - 0,997	0,318	0,952	11
45	0,990	0,965 - 0,997	0,461	0,780	11
46	0,992	0,941 - 0,998	0,364	0,768	11
47	0,991	0,958 - 0,997	0,027	0,806	11

220

ICC: Intraclass Correlation Coefficient; CI: Confidence Interval; D:Dahlberg; p<0,05

Table 4: Results of the rotation and intrusion/ extrusion intrarrater agreement mandibular.

Tooth	Rotation					Intrusion- extrusion				
	ICC	CI 95%	D	p	n	ICC	CI 95%	D	p	n
43	0,930	0,582 - 0,983	0,399	0,827	11	0,993	0,972 - 0,998	0,037	0,875	n
42	0,948	0,785 - 0,986	0,440	0,681	11	0,996	0,984 - 0,999	0,029	0,961	11
41	0,985	0,838 - 0,997	0,749	0,823	11	0,993	0,972 - 0,998	0,036	0,975	11
31	0,984	0,829 - 0,997	0,833	0,795	11	0,995	0,978 - 0,999	0,038	0,824	11
32	0,896	0,353 - 0,976	0,517	0,663	11	0,975	0,78 - 0,994	0,036	0,839	11
33	0,970	0,876 - 0,993	0,920	0,979	11	0,994	0,973 - 0,999	0,053	0,923	11

66

66

ICC: Intraclass Correlation Coefficient; CI: Confidence Interval; D:Dahlberg; p<0,05

Supplemental Table 1. Supplemental Material and Methods: Inclusion and exclusion criteria and inter- e intra- examiner's calibration

Inclusion criteria: patients who had Class I, II and III malocclusion with moderate inferior crowding of up to 4 mm, change in overbite (from 3 to -5 mm), permanent dentition, presence of all teeth up to the second molars, aged 18 to 45 years.

Exclusion criteria: patients who had restorations in the teeth moved during treatment, non-cooperating patients-with craniofacial syndromes or anomalies, and those with signs or symptoms of inflammation in the periodontal tissues. Three cases were discarded, two because the mesh was distorted for unknown reasons and one because a composite resin restoration was inserted in a tooth after movement altering the dental proportion, resulting 11 pairs of STL models. All participants were treated by the same professional in a private clinic in Belo Horizonte, Minas Gerais, Brazil and the cases were selected retrospectively.

Inter e intra examiner's calibration: To evaluate the calibration of the main examiner (RS) with the software, a total of 22 measurements were taken, after superimposition 10 on posterior teeth in the bucco-lingual direction of canines, first and second premolars, first and second molars mandibular and maxillary represented by the X axis, in millimeters; 6 measurements in the vertical direction on anterior teeth of canines and mandibular incisors, movement represented by the Z axis in millimeters; and, 6 measurements on anterior teeth for the mesio-distal rotation, carried out by mandibular and maxillary incisors and canines, analyzed in degrees. The superimposition of 11 STL models were performed, totaling 242 measurements in 286 teeth, in both phases T0 (initial) and T1 (refinement), and repeated 2 times with a 15-day interval between them. To evaluate the accuracy and reliability, the same measurements were repeated by two examiners (RS- and GS) of the 11 cases. The two examiners did not participate in the orthodontic treatment.

Supplementary Material and Methods

Briefly step-by-step guide:

A step-by-step guide has been developed for researchers to easily replicate (Suppl. Material 2). Briefly, the method for superimposing maxillary and mandibular STL models using Autodesk Inventor® software followed these steps:

1. Marking the points for overlay (Fig 1): STL models were exported to the Slicer® CMF program (Version 4.11; <http://slicer.org>). The demarcation of a point was performed using the IGT tool (Image Guided Therapy) in Fiducial Registration Wizard on the T0 model and the same point on the T1 model. This point was located in the lingual mucosa gingival region, in the region of the mandibular central incisors, and in the medial region of the second or third rugae palatine in the maxilla. The marking of each point generated spatial coordinates that were transferred to the models in Autodesk Inventor®.

2. The values of the X, Y and Z coordinates were noted or saved in the T0 and T1 models.

3. The demarcated points were transferred to the Autodesk Inventor® 2022 program (free student license; <https://www.autodesk.com.br/education/edu-software/overview>. Inventor Professional product). (Fig 2)

2). The STL models were imported into Autodesk Inventor® 2022 Using the UCS (User Coordinate System) tool, the X, Y, and Z coordinates were entered one at a time into the T0 model and saved. The same operation was repeated for the T1 model.

4. Superposition the models: Using the "Assembly" (place) tool, the T0 and T1 models were imported with the points demarcated. The UCS axes X, Y and Z were opened in the navigation tree and with the "Constrain" tool each axis was selected individually to be superimposed.

5. Visualize the superimposed models: Using the tool "View"- "Visual Style"- 'Realistic". The models were colored individually to identify T0 and T1 in "Adjusted" (Fig 3)

6. Tooth movement analysis between T0 and T1: The bucco-lingual translation movement was measured using the "Tools" tool by measuring the distances between the buccal cusps of the canines, premolars and mesio buccal molars on the X axis in mm ^(9, 24, 28). The vertical movement of the mandibular canines and incisors were measured from the tip of the canine cusps and the middle of the incisal edges ⁽⁹⁾ (Fig 4). Displacements in the gingiva (intrusion) direction were considered with a positive sign (+). Displacement in the incisal occlusal (extrusion) direction was considered with a negative sign (-)(1) . Thus, they observed the amount of movement in the Z-axis in millimeters (mm).

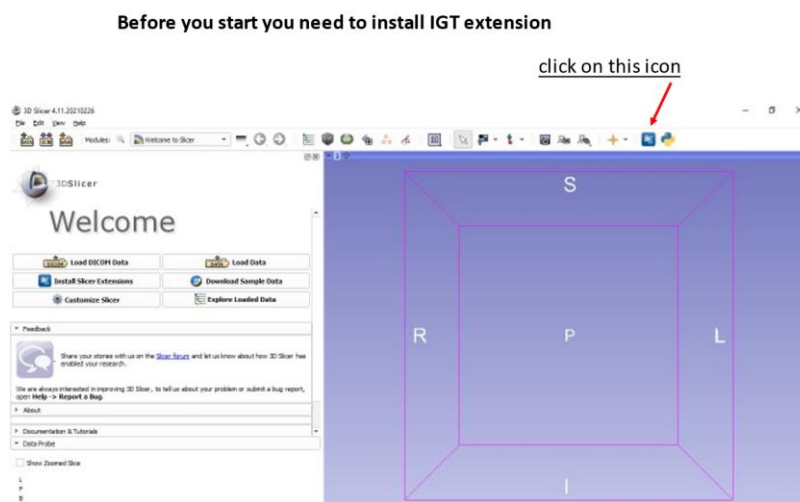
7. The mesio-distal rotation was calculated through the angle formed by the lines drawn on the incisal edges, connecting the mesial and distal points of the incisors or the tip of the cusps of the canine.(Fig 5) The rotation is expressed in degrees referring to the inclination formed by the line drawn at T0 with line T1(2)

1. De Oliveira NS, Rossouw E, Lages EMB, Macari S, Pretti H. Influence of clinical experience on accuracy of virtual orthodontic attachment bonding in comparison with the direct procedure. Angle Orthod 2019;89(5):734-41.10.2319/100618-724.1

2. Charalampakis O, Iliadi A, Ueno H, Oliver DR, Kim KB. Accuracy of clear aligners: A retrospective study of patients who needed refinement. Am J Orthod Dentofacial Orthop 2018;154(1):47-54.10.1016/j.ajodo.2017.

Supplementary material 2:Step-by-step guide:

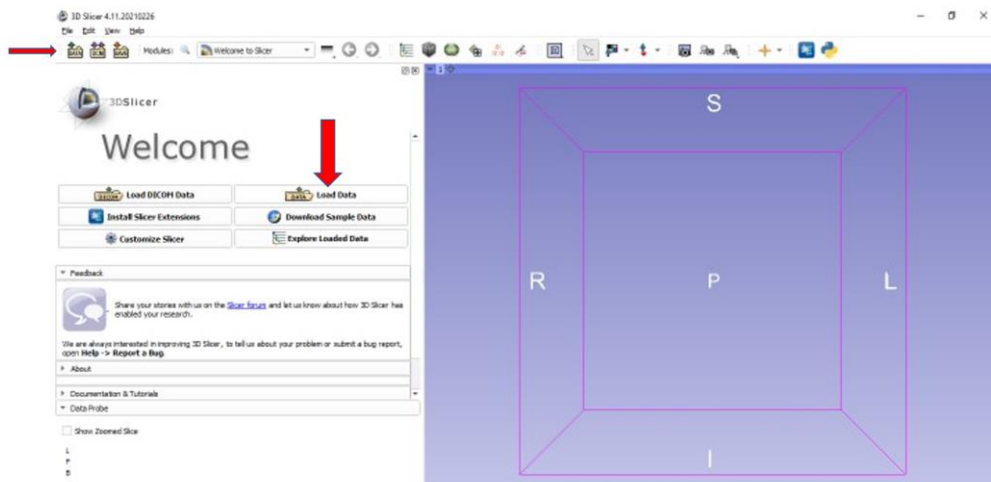
Slicer's version 4.11 <http://slicer.org>.



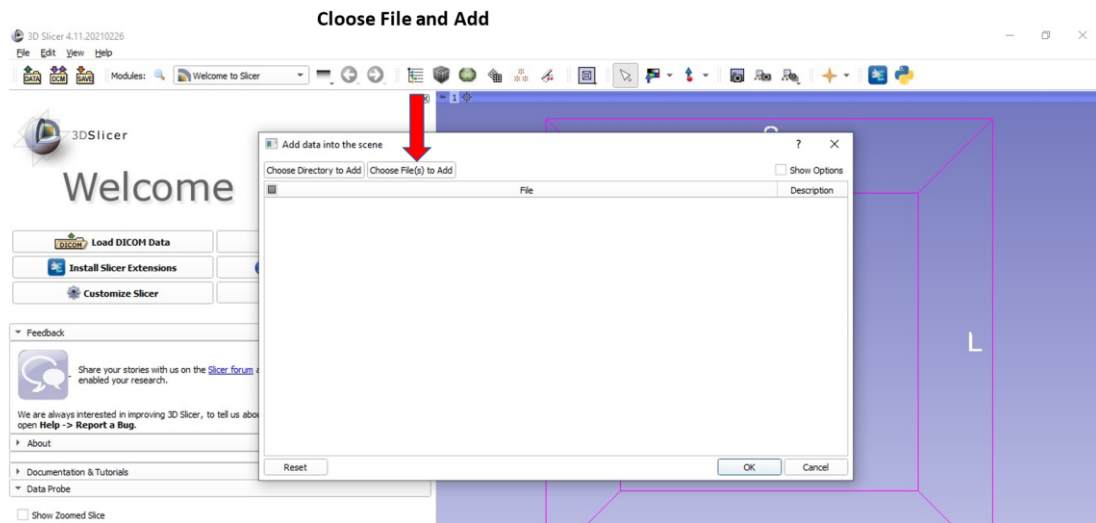
Get "Slicer IGT"(black arrow) and install (red arrow)



On the home page select date or load data (rede arrows)

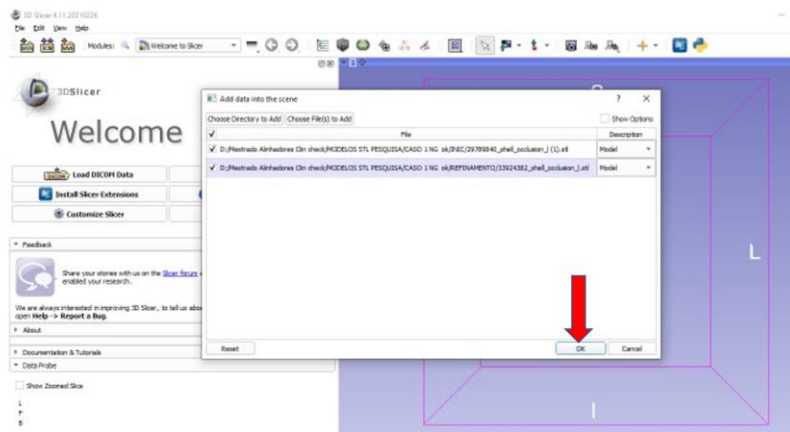


Choose the STL models



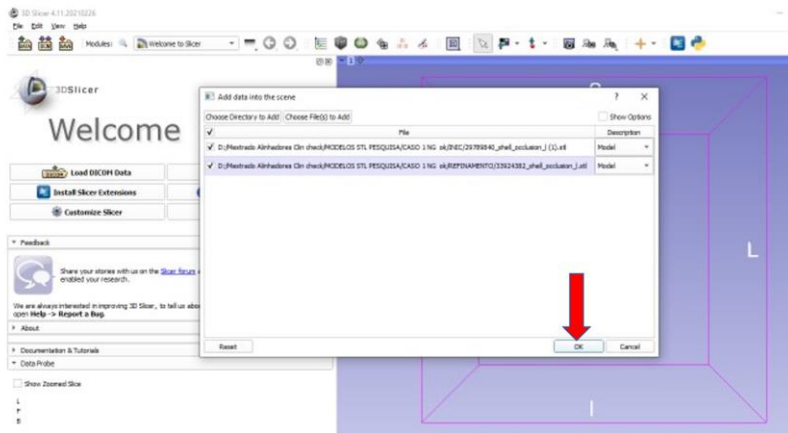
Choose the STL models

After selection click "OK" (red arrows)

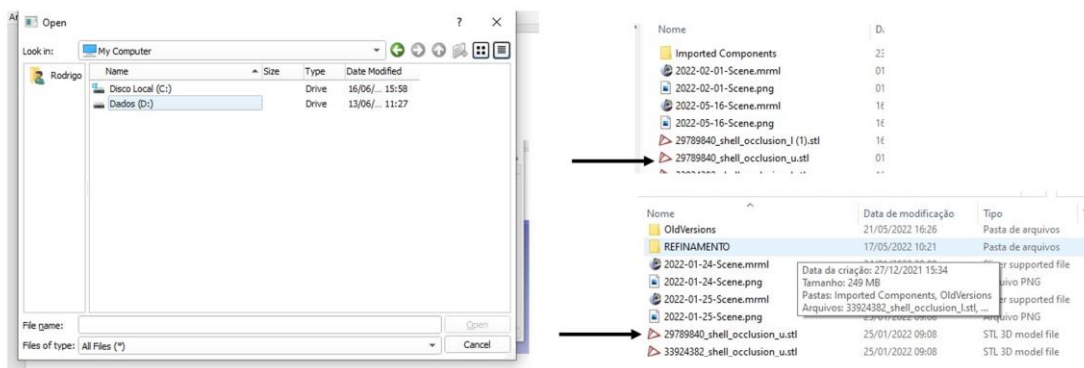


Choose the STL models

After selection click "OK" (red arrows)

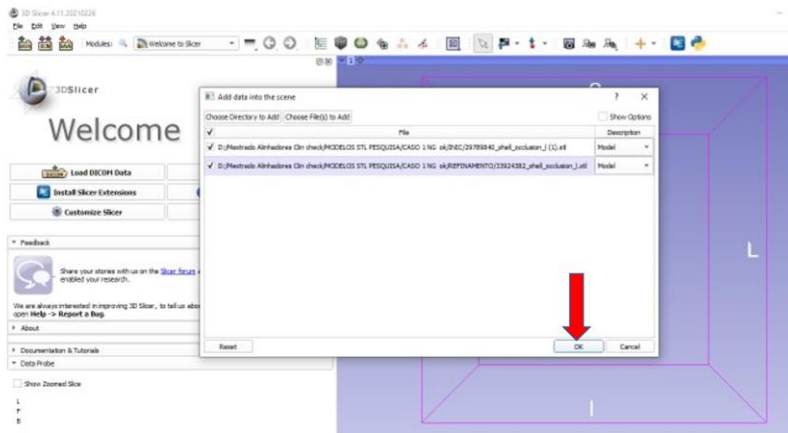


Select the initial and final STL models (black arrows)

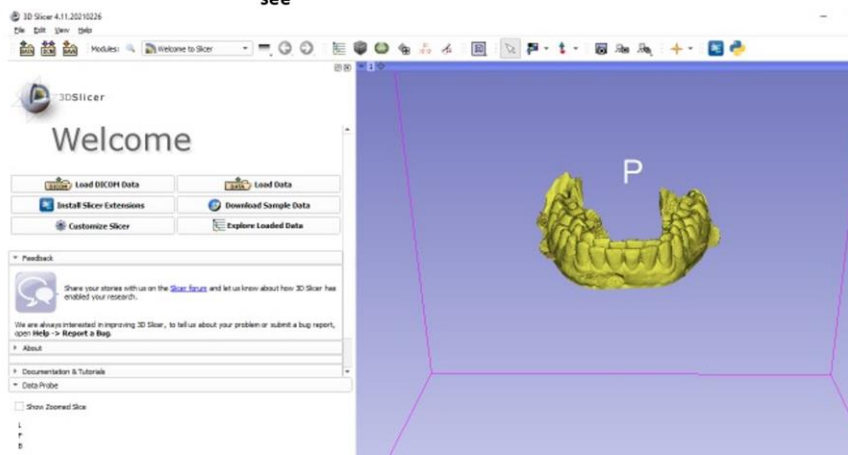


Choose the STL models

After selection click "OK" (red arrows)



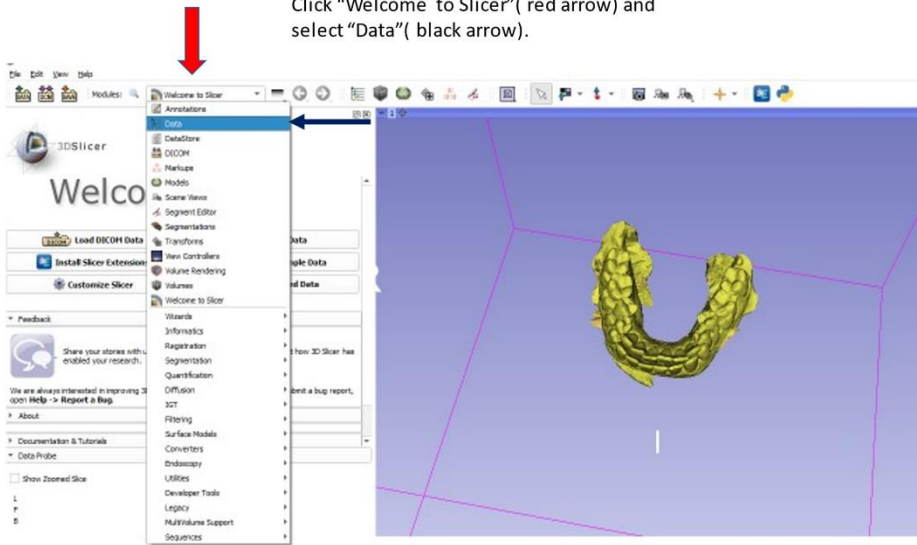
Both models appear on the screen, change the color of one of them to make it easier to see



Next stage color change for easy viewing

Color change for easy viewing

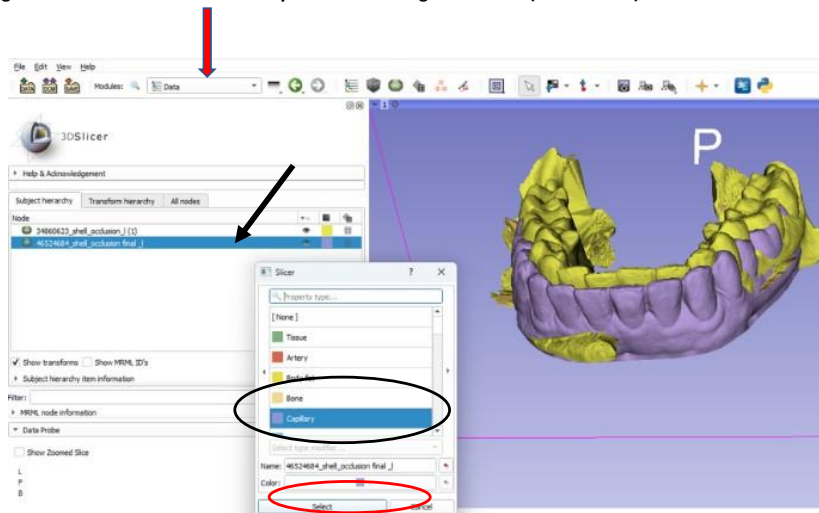
Click "Welcome to Slicer"(red arrow) and select "Data"(black arrow).



Color change for easier viewing

After clicking on "data" select the model that you want to change the color (black arrow)

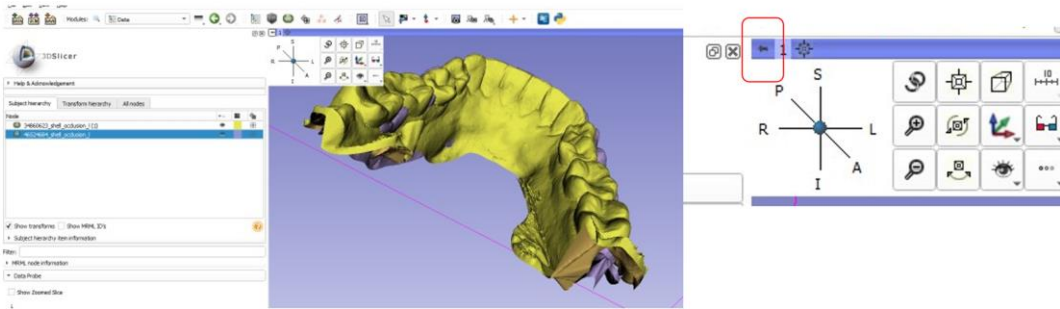
Select the desired color (black circle) and



to finish click on "Select" (red circle) and the color will change

Position the models

Positioning the models: icon (red rectangle) or left button and drag on the mouse. Place the models in the position that makes it easy to see the point

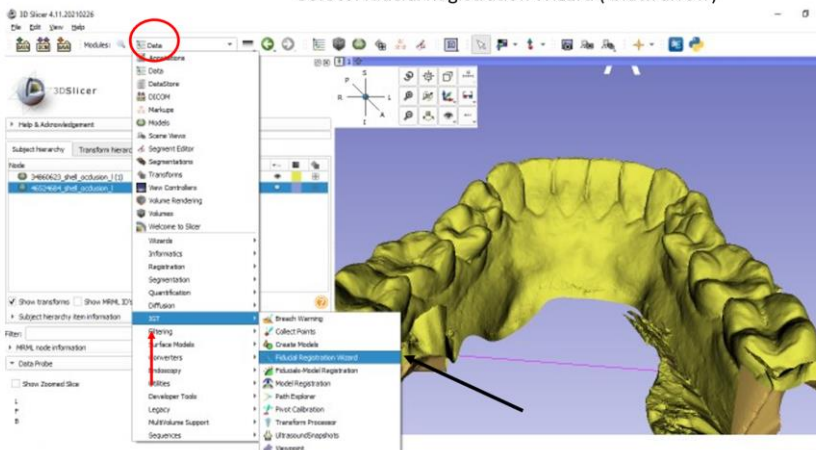


The model moves when you press and hold the center or left mouse button

Identify initial and final models:

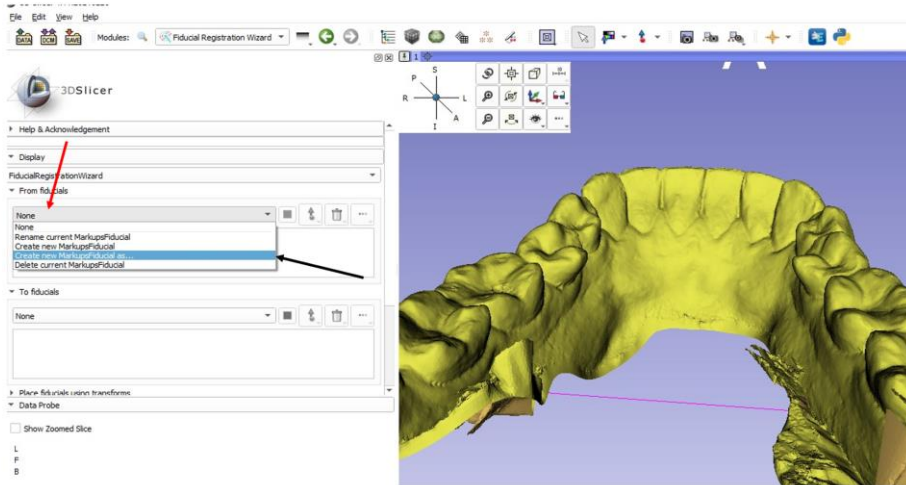
Click on "data," (red circle) search IGT (Image Guided Therapy) (red arrows)

Select Fiducial Registration Wizard (black arrow)



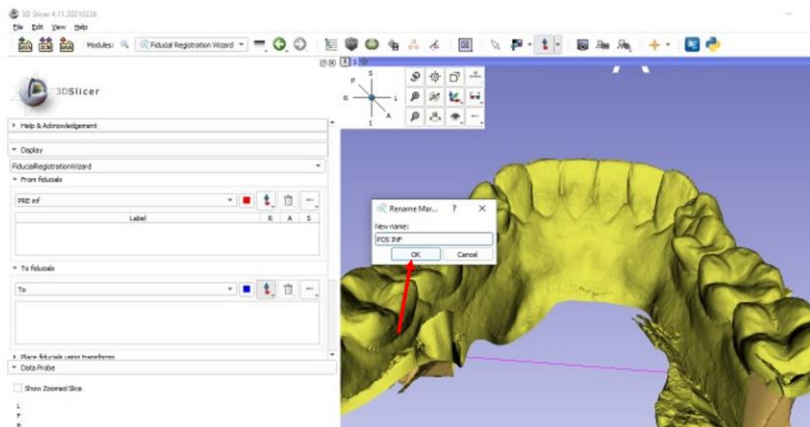
Naming the models:

Click “none”(red arrow)and “Create new markups fiducial as”(black arrow).



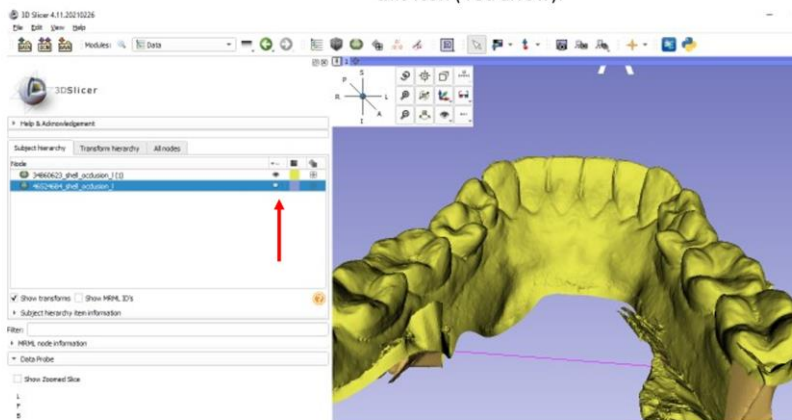
Identify the models click ok (red arrow)

Repeat for the other model



Marking the point is done on each model separately

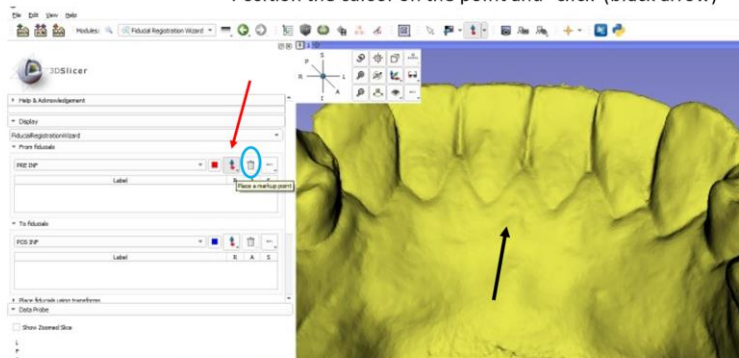
To make it easier, you can remove the visibility of one of the models by clicking on this icon (red arrow).



Landmarks

To mark the point select "Place markup point"(red arrow)

Position the cursor on the point and "click"(black arrow)

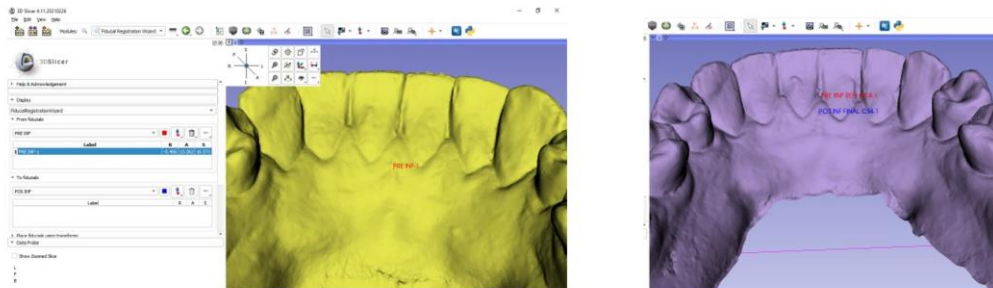


If you want to remake it, click on the "trash can" symbol on the right side and repeat the operation (blue circle)

Landmarks

Retry the operation in the pos model

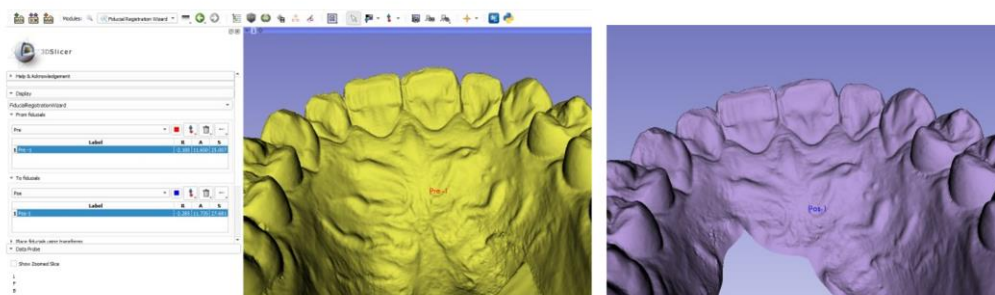
View of the two models with the point for superimposition labeled:



Landmarks

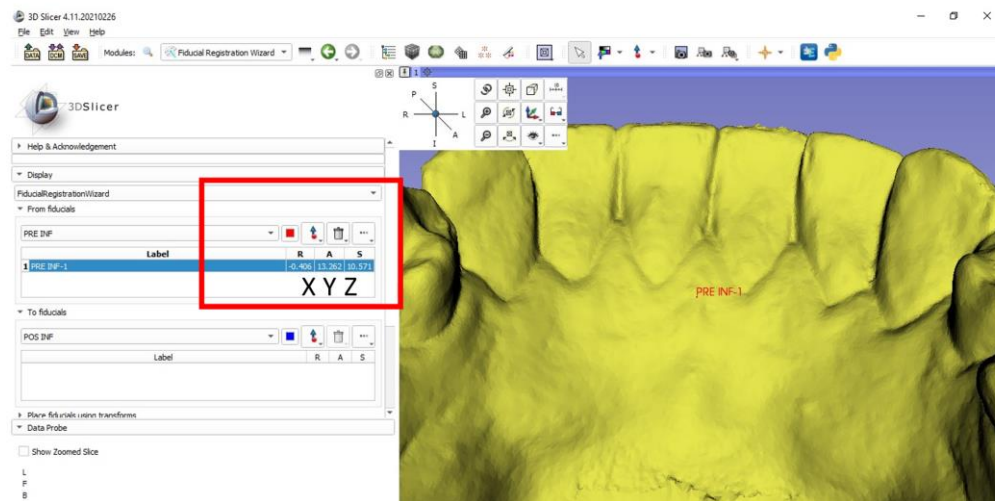
Illustration of the points demarcated on the maxillary models:

Medial to the second rugae

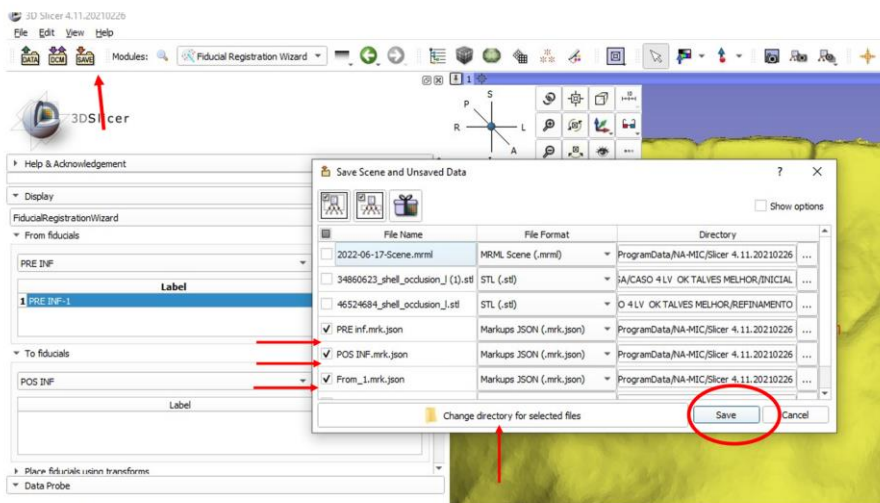


Universal Coordinate System

These are the coordinates(x,y,z) that will be used to demarcate the point in the autodesk program



Save this operation in the folder where the models are



Use the "position". These are the X,Y,Z coordinates of the points marked on the "POS" and "PRE" model Slicer.

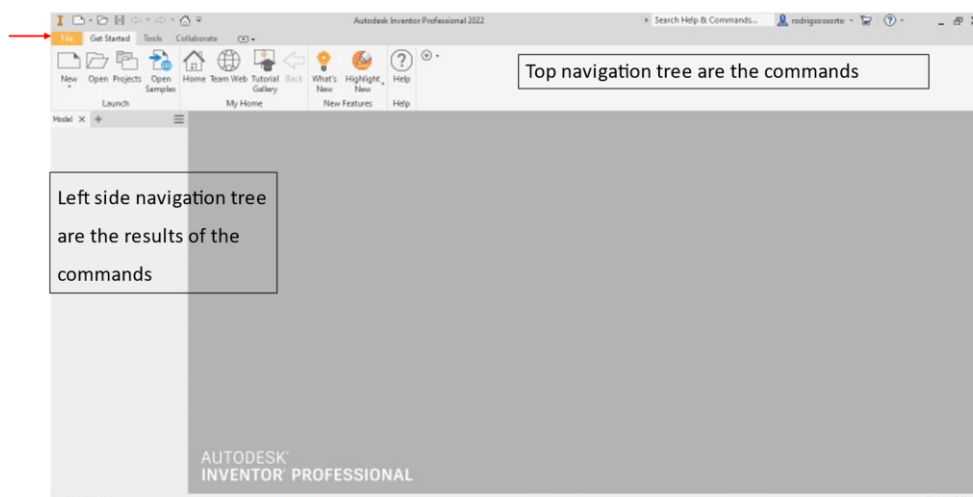
```

R [{"@schema": "https://raw.githubusercontent.com/slicer/slicer/master/Modules/Load",
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          "locked": false,
          "visibility": true,
          "positionStatus": "defined"
        }
      ]
    },
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      "color": [0.0, 0.0, 1.0],
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      "activeColor": [0.4, 1.0, 0.0],
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      "textScale": 3.0,
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      "glyphSize": 5.0,
      "useGlyphScale": true
    }
  ]
}],
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      "coordinateSystem": "LPS",
      "locked": false,
      "labelFormat": "%N-%d",
      "controlPoints": [
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          "label": "PRE INF 3-1",
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          "orientation": [-1.0, -0.0, -0.0, -0.0, -1.0, -0.0, 0.0, 0.0],
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          "locked": false,
          "visibility": true,
          "positionStatus": "defined"
        }
      ]
    },
    "measurements": [],
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      "opacity": 1.0,
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      "activeColor": [0.4, 1.0, 0.0],
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      "glyphSize": 5.0,
      "useGlyphScale": true
    }
  ]
}],

```

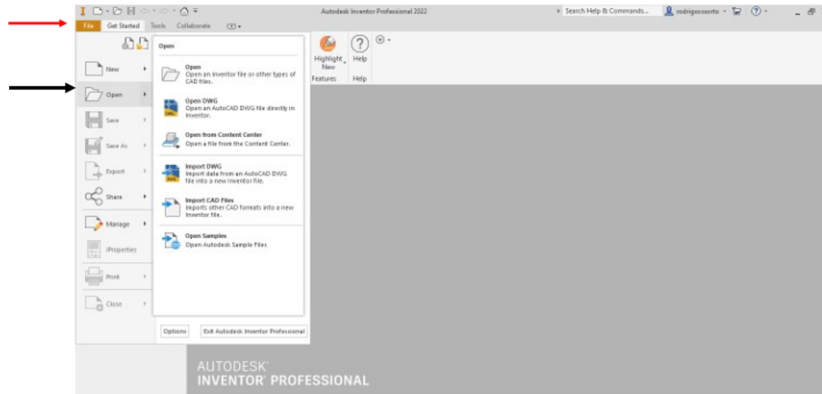
Autodesk Inventor®

All commands start with "File" (red arrow)



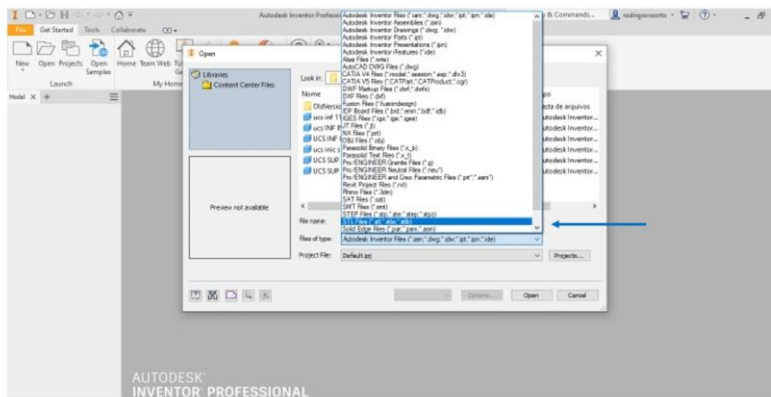
Search STL file

Click on "File" (red arrow) "Open" (black arrow) to select the "Pre" model that the point should be marked...

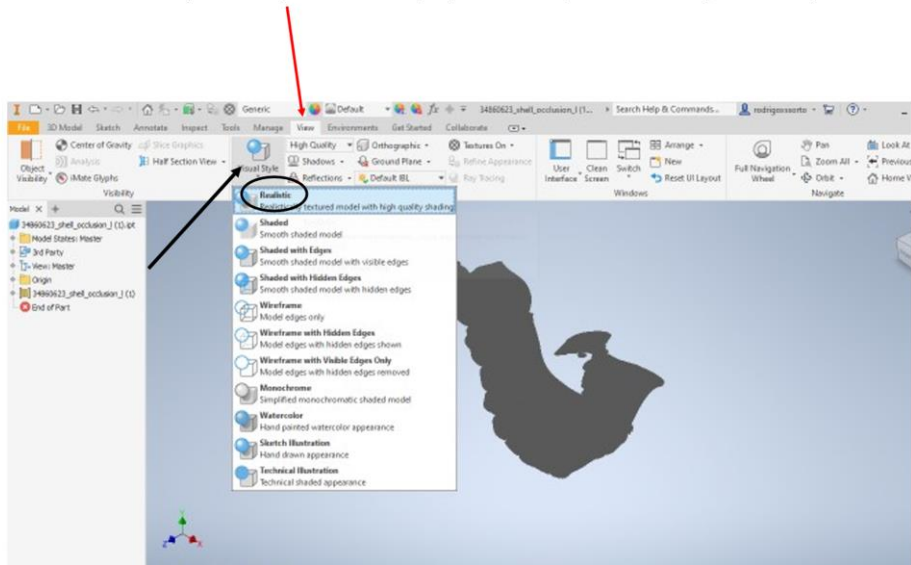


Search STL file

and select the first model (stl files) that will be used to mark point (Blue arrow)

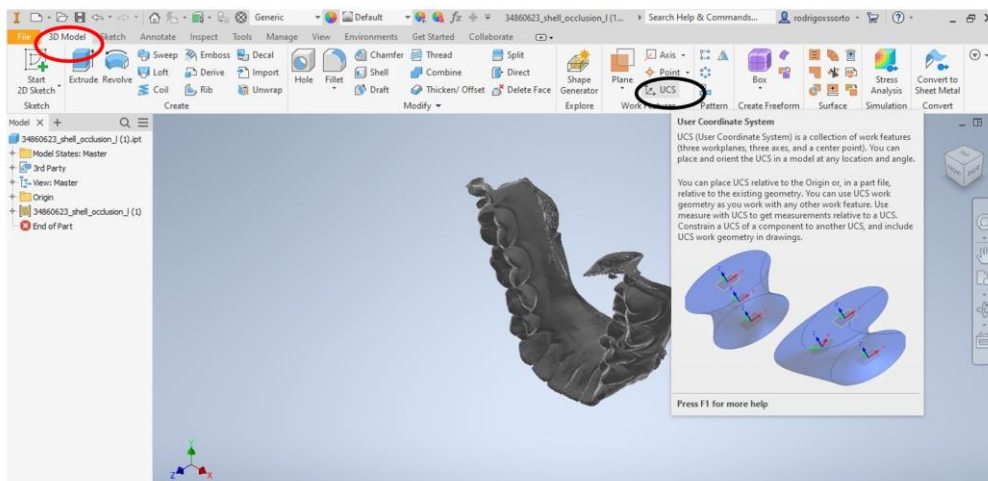


The model image can be transformed into a more realistic image, making it easier to see
Click on view(red arrow) and "visual style"(black arrow) and "Realistic"(black circle)



Use these commands to start inserting the points for the model superimposition:

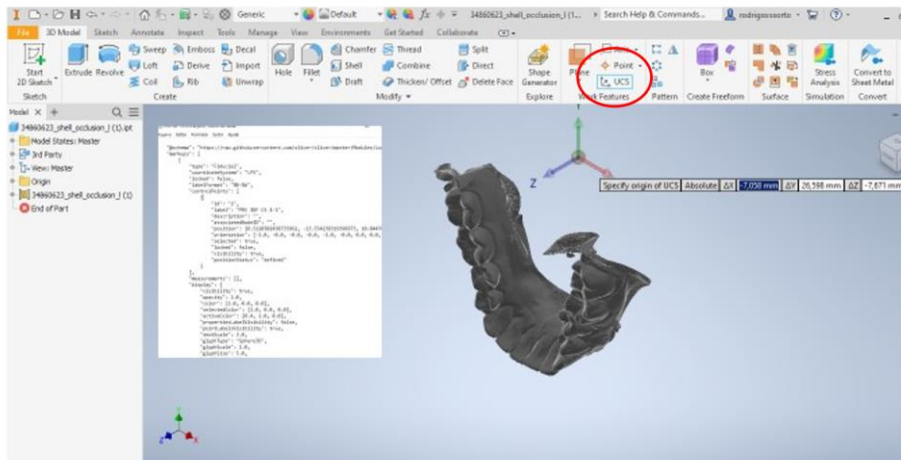
Click "3D Model" (red circle) and "UCS"(black circle).



Fill in the UCS

Copy the coordinates (one by one)into the UCS. in the order X,Y,Z. To change from X to Y and from Y to Z do not press enter but "Tab". At the end click "Enter" twice and save the model.

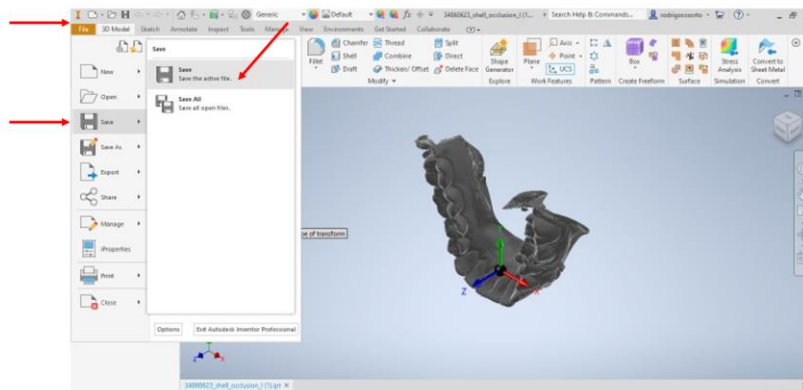
Insert the signs (negative if any) for each coordinate



Tab key
and
Enter key

Save

Repeat operation "post" model and save again

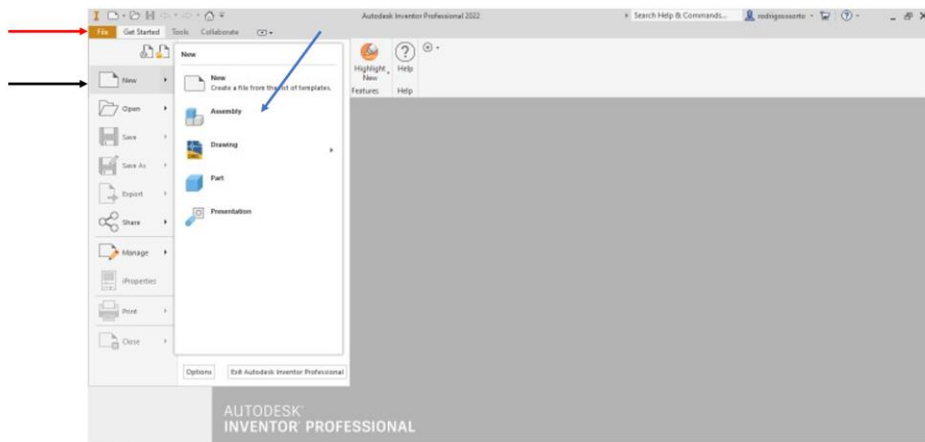


Name the file:

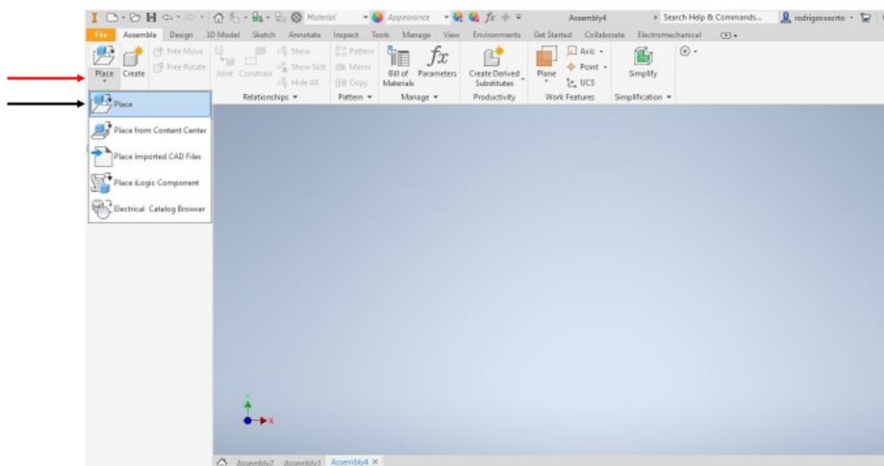
- ucs inf refin 11.ipt 20
- uCS INF REFIN 12.ipt 11
- UCS INF REFIN PARA FINAL.ipt 31
- UCS POS INF.ipt 21
- UCS SUP POS REFIN.ipt 21
- UCS SUP REFIN 2.ipt 21
- ucs sup refin 3.ipt 31
- ucs sup refin 4.ipt 01

Seeking the models to be superimposed

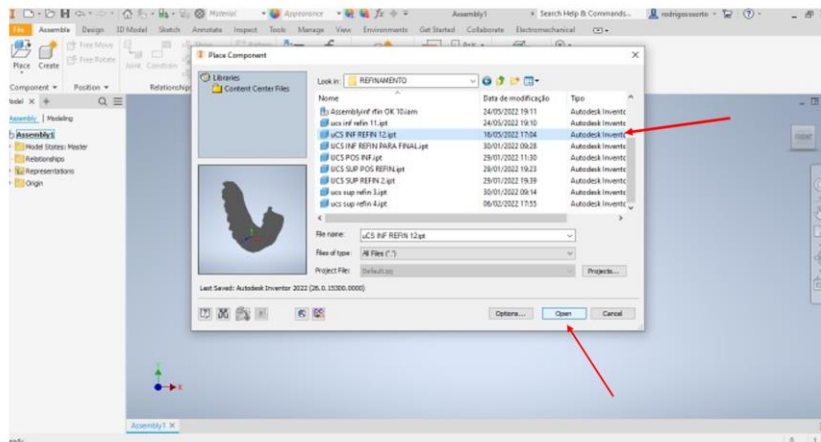
To superimpose the coordinates select "File"(red arrow), "New"(black arrow) and "Assembly"(blue arrow).



Click on "Place"(red arrow) and "Place (black arrow)

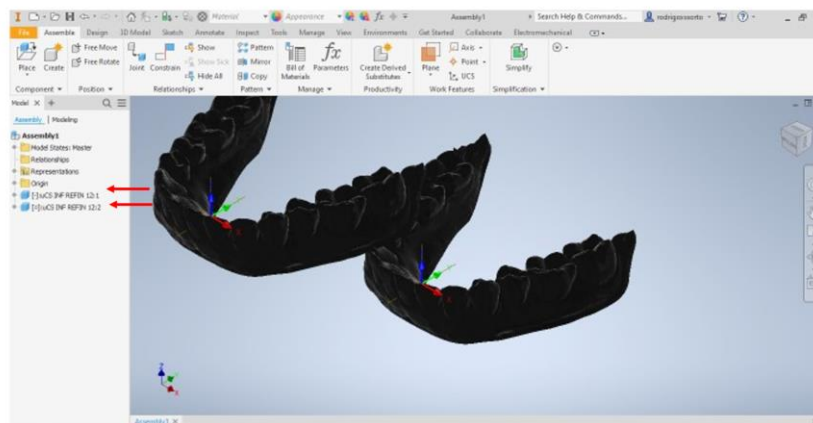


Select the two (Pre o Post) models using the CTRL key



The result of this command will be appear in the navigation tree on the left(red arrows)

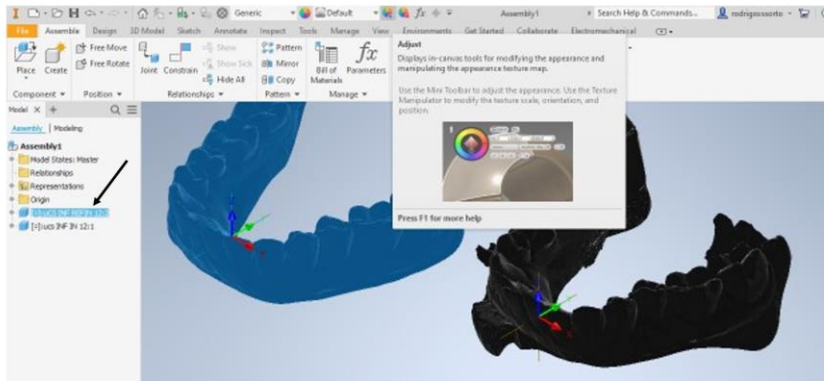
Use enter key and to delete quadruplicate esc key



Differentiate models by changing color to create contrast

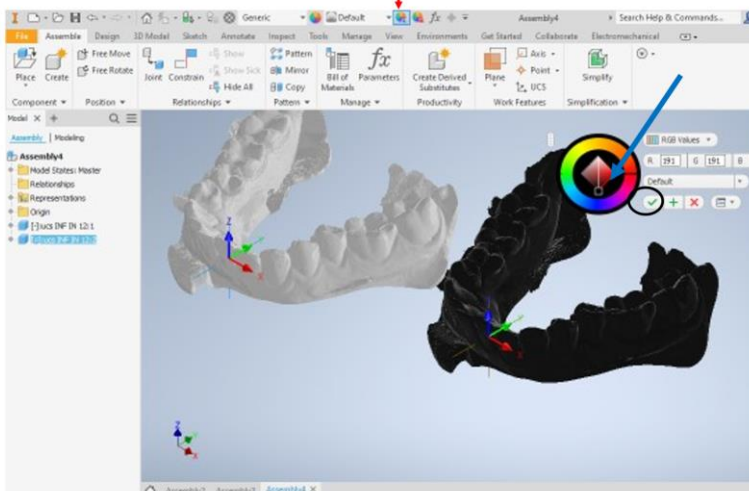
First select the model that you want to select the color by clicking on it(black arrow)

Second Click em "Ajust" (red arrow)



Click again on the model with the "adjust" tool activated and it will change the color

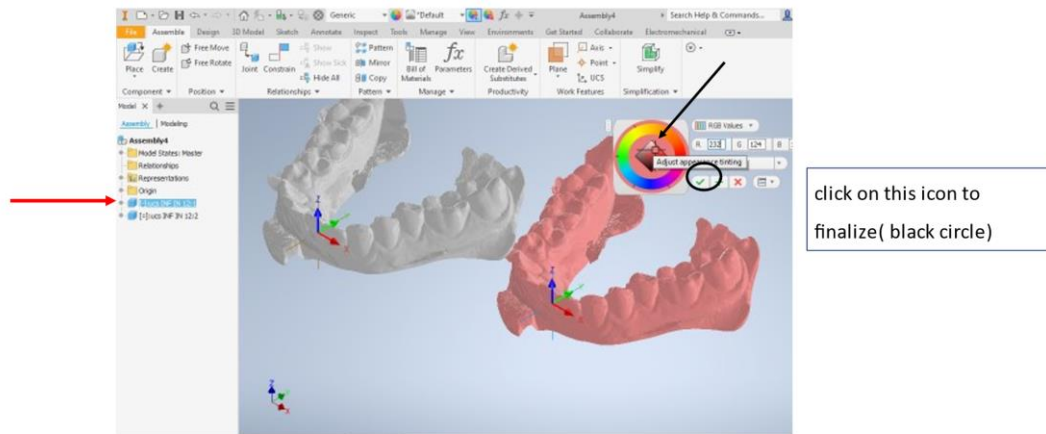
The color can be chosen by changing the position of the cursor within the color scale(blue arrow)



Click on this icon to finalize(black circle)

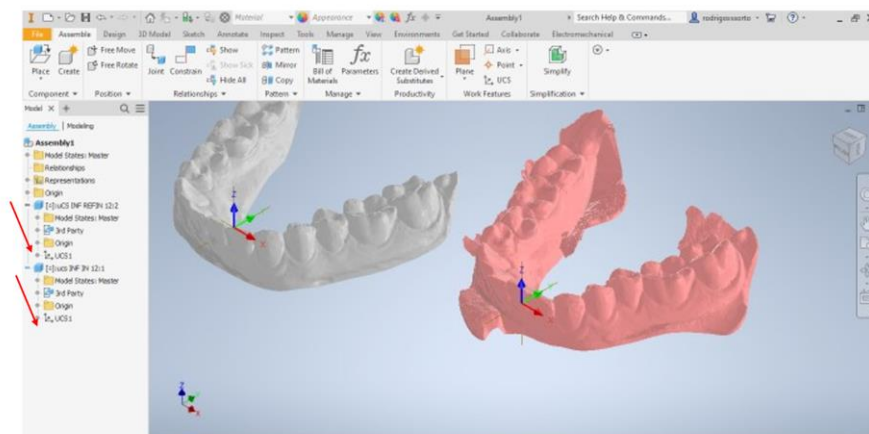
Repeat the operation with the other model

The color can be chosen by changing the position of the cursor within the color scale (black arrow).



Sobreposition through the constrain tool

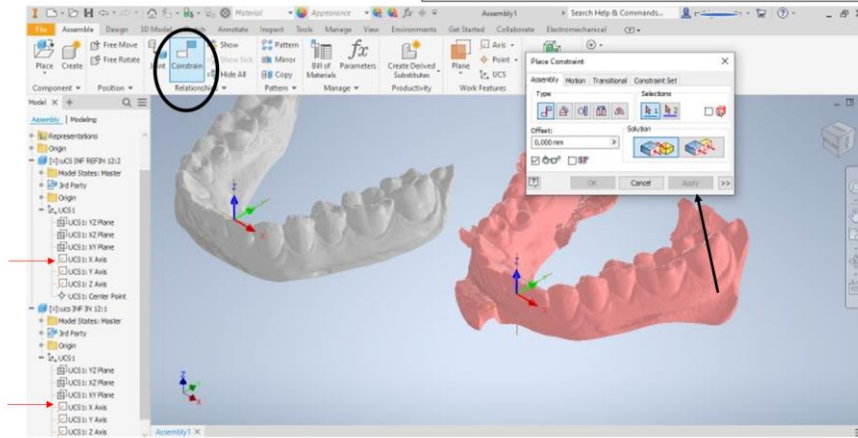
Open the navigation tree to display the UCS (red arrow)



Click on the "constrain" (black circle)

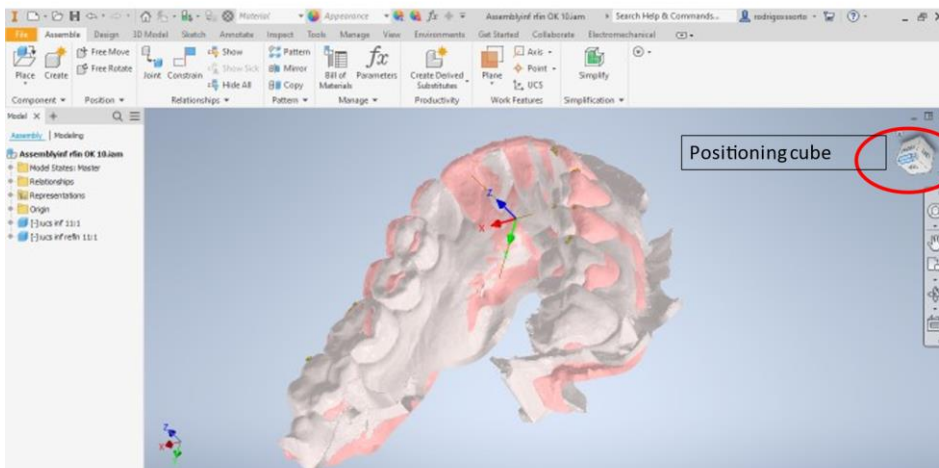
Select the axes in pairs to be superimposed (red arrow)

Between one selection and another click "Apply"(black arrow) to continue until the 3 axes (X, Y Z) are overlapped



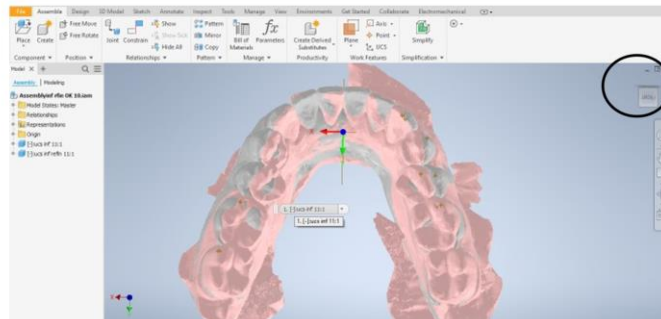
Apply

To move the model click on middle mouse button and drag positioning cube (red circle)



Buccal-lingual translation

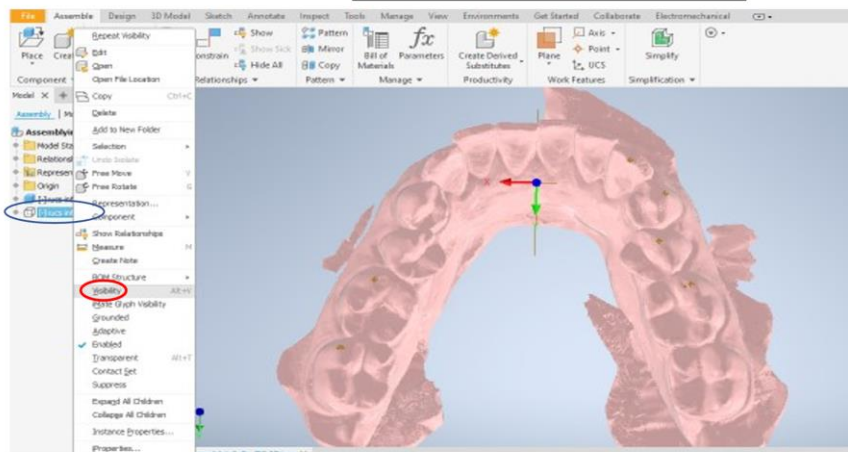
To analyze the buccal-lingual translation movement (x-axis), position the model in the 'front' position in the positioning cube(Black circle)



To facilitate point markup on each model, make one of the models invisible.

Make a model invisibly

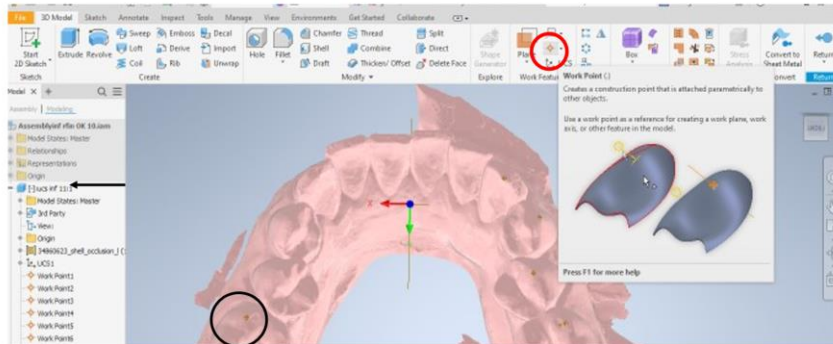
- Right click on the model (Blue circle)
- disable visibility(red circle)



Enlarges the view by scrolling the middle mouse button

Select the model - 2 clicks (black arrow)

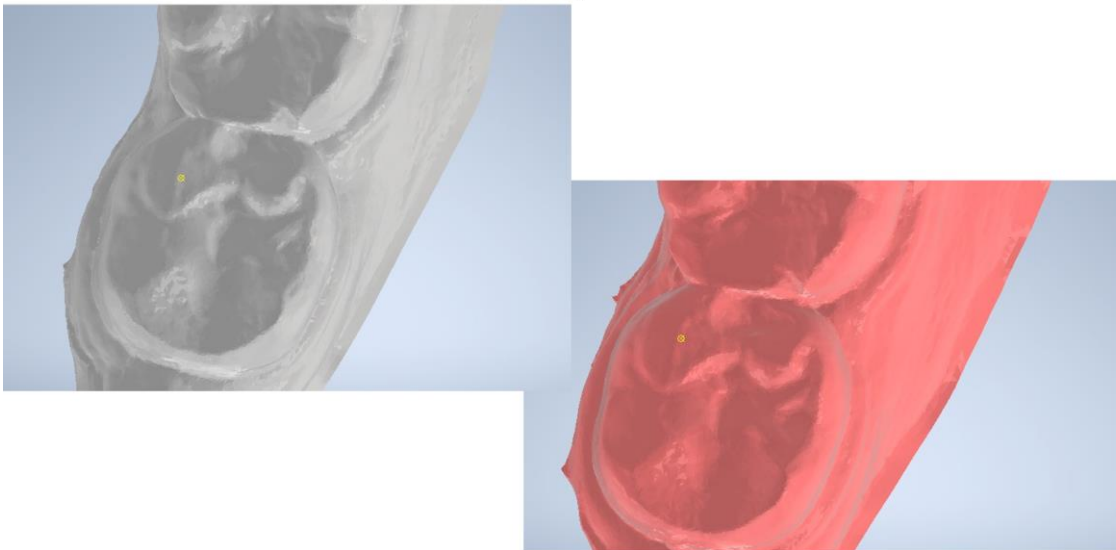
On the upper navigation tree click "Work Points"(red circle)



Position the point on the vestibular cuspid tip and
"Click (Black circle)

Repeats the operation on the "post" model

The marked point on the "Pre" model (gray color) and on the
"post" model (red color)

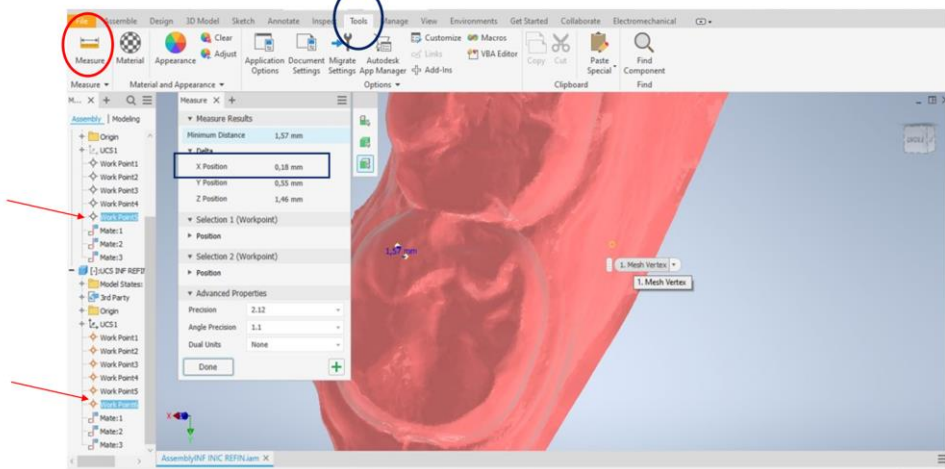


To measure the distance between the two points(buccal-lingual translation):

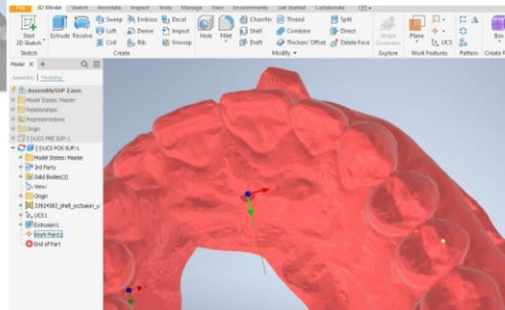
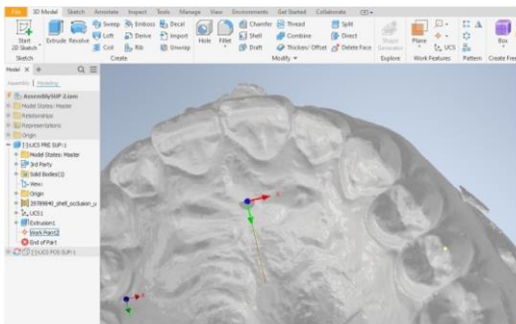
- Click
- “Tools”(Black ring)
 - “Measure”(Red ring)

Selects from both points
(red arrows)

Read delta result
(Black rectangle)

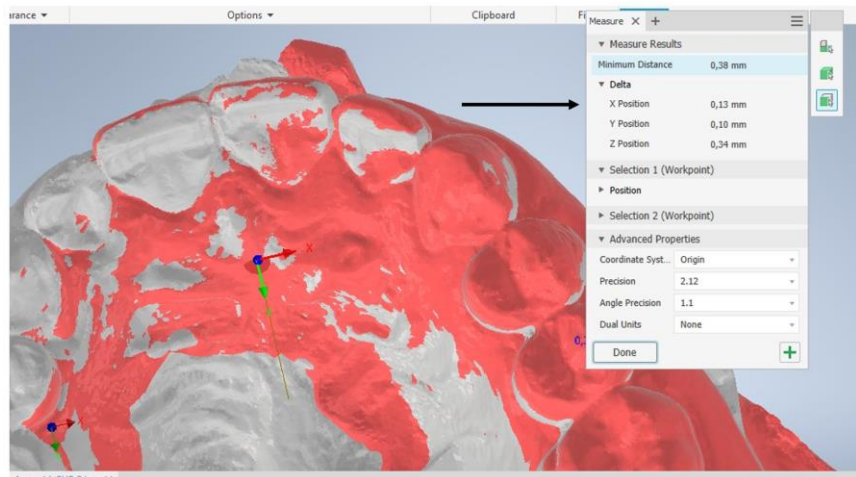


Bucco-lingual translation of the left maxillary second pre molar (initial model gray and final model red)



Buccal-lingual translation

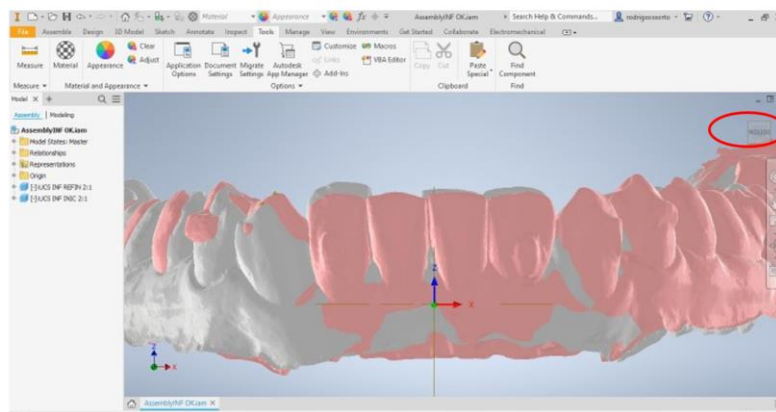
Delta result(black arrow)

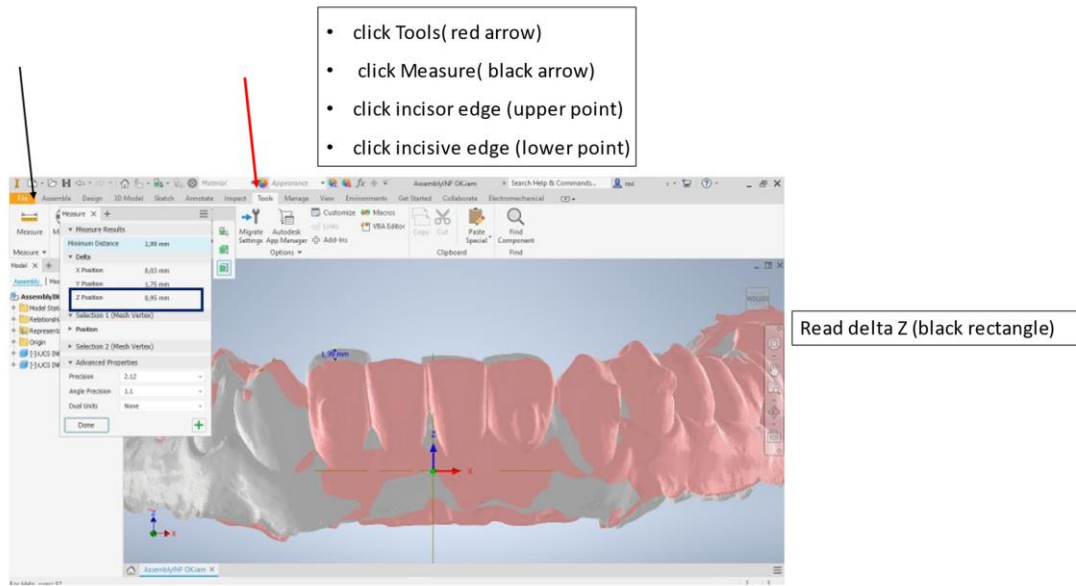


To measure the amount of intrusion or extrusion (axis Z):

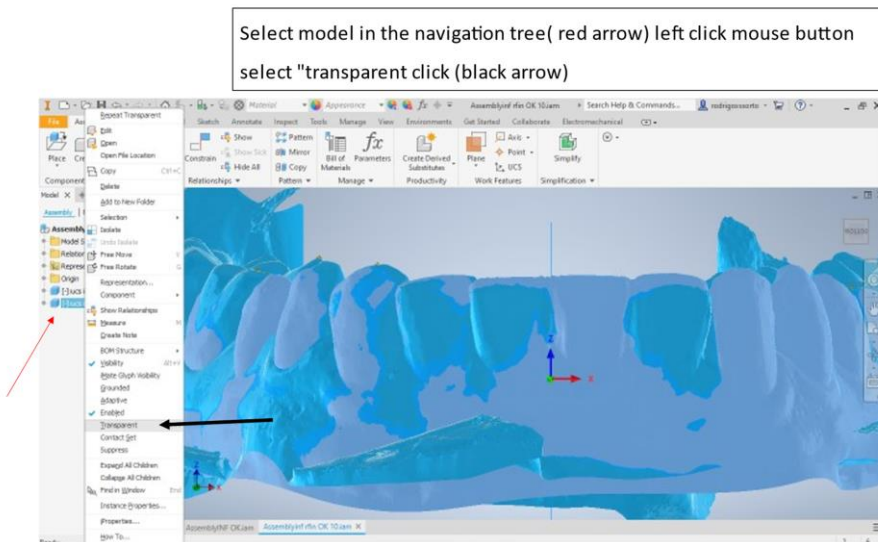
'Bottom' position model (red circle)

References: canine tip and middle of the incisal edge of the incisors

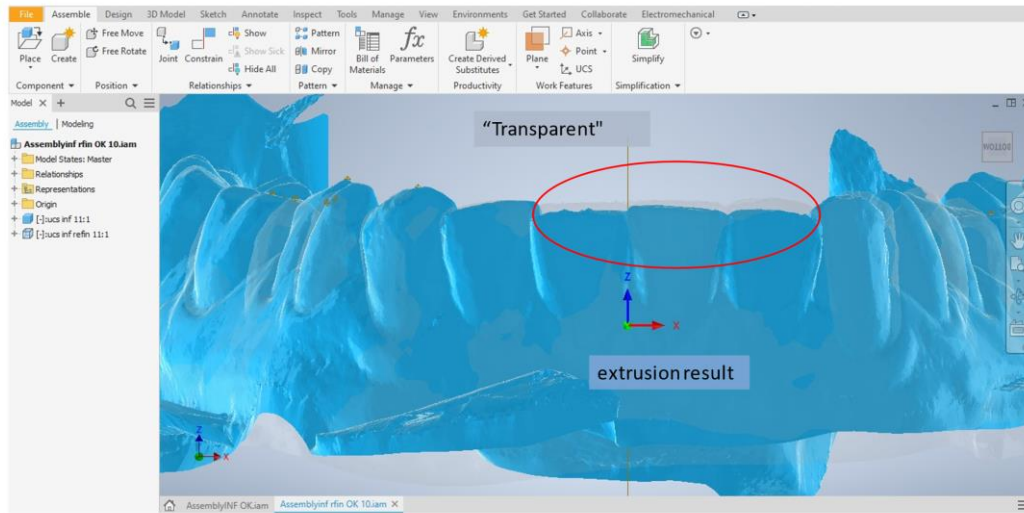




Difficulty in visualizing some movement use “transparent” tool:

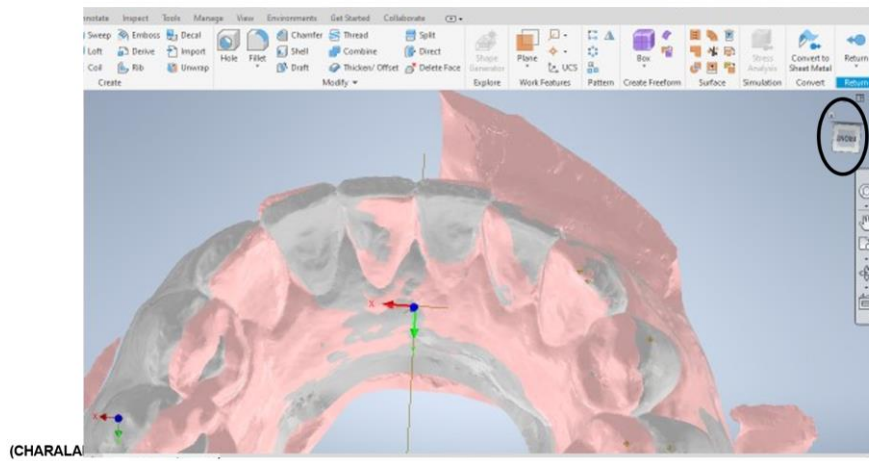


Measure in the same way



Mesial-distal rotation

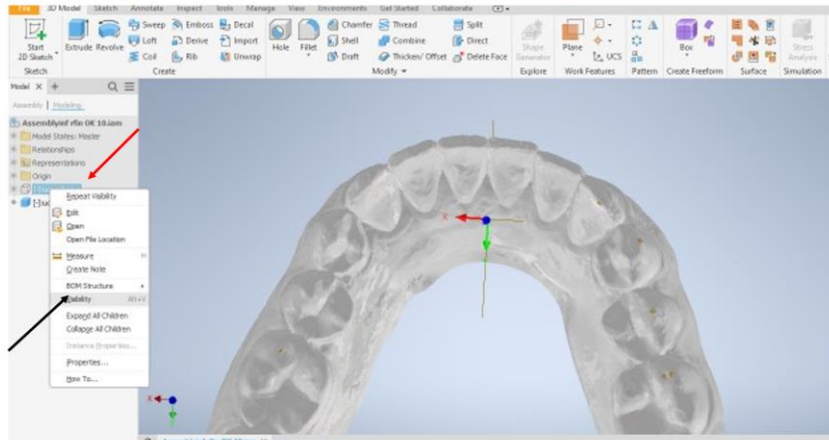
Position the model in the "front" position (navigation cube black circle)



(CHARALA

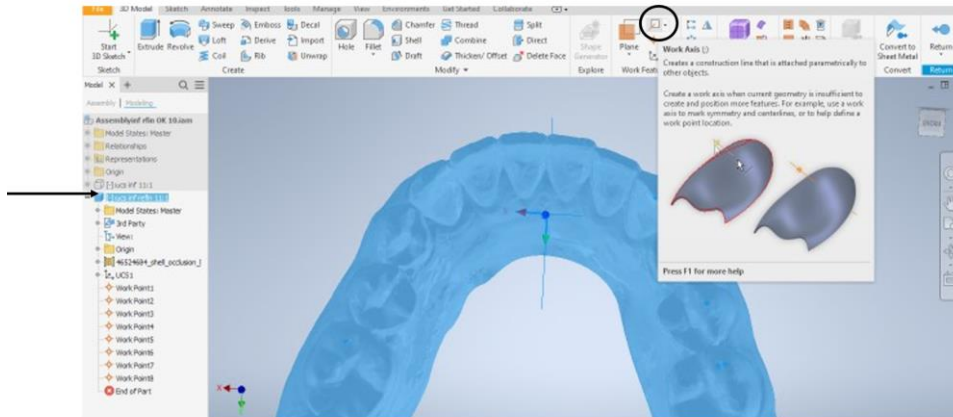
Mesial-distal rotation

Choose one of the models(red arrows) to invisible click visibility (black arrows)

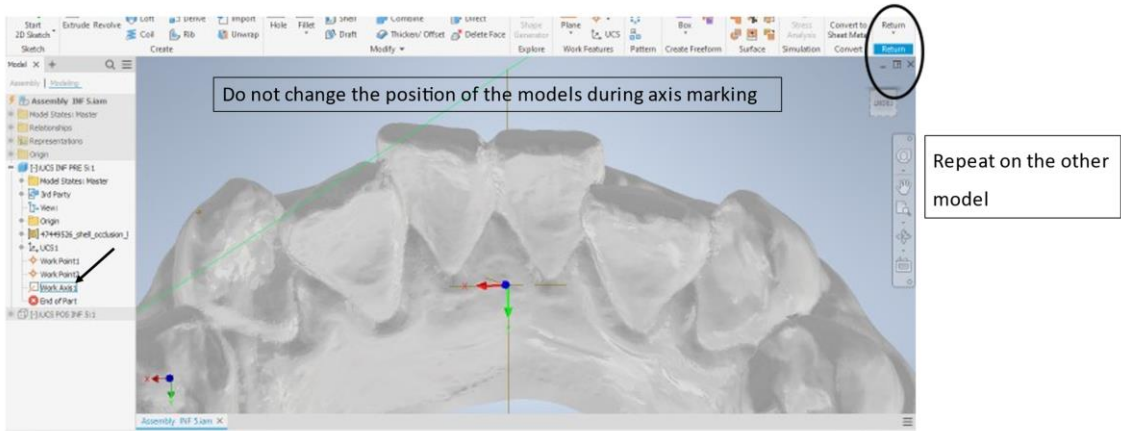


Mesial-distal rotation

Double-click on the model(black arrow) A upper navigation tree appears, click on the "Work axis"(black circle).

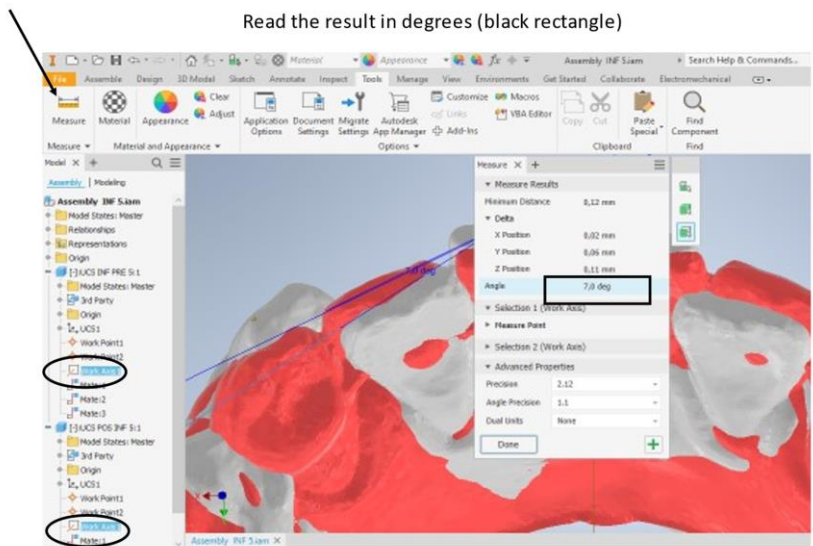


- Click on selected point distal to the incisal edge and another click on the distal portion of the incisal edge
 - Click "Return" to register the command (black circle)
 - The result of this command will be appear in the navigation tree (black arrow)



Measuring the angle formed

- Click on "mesure"(black arrow) and Click on "Work axis" 1 and 2(black circle)
- Read the result in degrees (black rectangle)



4.1.2 Artigo 2 Resposta ao objetivo específico 4

Artigo a ser submetido ao periódico "The Angle Orthodontist" Qualis A1, após correções e sugestões da banca.

Accuracy of the Invisalign® G8 protocol: a pilot study

ABSTRACT

Introduction; The objective of this study was to evaluate the accuracy of the Invisalign® G8 protocol compared to previous protocols in the posterior expansion and intrusion movements of anterior mandibular teeth.

Materials and Methods: 11 pairs of STL models of the maxilla and mandible were obtained from My Itero® (3 cases with the G8 protocol activated and 7 cases were no G8 protocol). The patients showed malocclusion of Class I, II or III, moderate crowding requiring intrusion of the canines, mandibular incisors and posterior expansion of both arches. The initial (T0) and refinement (T1) models were superimposed using Slicer® software version 4.1 and Autodesk Inventor®. The 3D movements of bucco-lingual translation of the canines, pre-molars and molars, and intrusion of the canines and mandibular incisors were analyzed. The movements achieved and predicted by ClinCheck® were analyzed and, the G8 and no-G8 protocols were compared. D'Agostino & Pearson's omnibus normality test were used and student *t*-test ($P < 0.05$).

Results. No statistical difference were exhibited between the achieved and movements predicted by ClinCheck®. The comparison of the 3D movements performed by G8 and no-G8 were statistically similar. Although not significant, a small improvement of the accuracy was observed when the G8 protocol was activated. The mean accuracy for the expansion movement of the maxillary teeth in the G8 and no-G8 protocols was 75.3% and 66.5%, respectively. In the mandible it was found 68% for G8 and 67% for no-G8, and the intrusion movement accuracy for G8 was 62.3% and no-G8 54.6%. **Conclusion:** The movements performed with the activation of the Invisalign® G8 protocol did not show improvement in the treatment accuracy. This was a pilot study and more sets of aligners in a refinement phase still have to be considered in future studies.

Key words: Invisalign, Tooth movement, Clinical efficacy.

INTRODUCTION

Since the creation by Kesling in 1945 of the "Tooth-positioning appliance", the bracket less aligner system has achieved great developments and changes⁽³⁾. It was with the creation of the Invisalign® system in 1999 by the company Align Technology (Santa Clara, California, USA), with the same treatment principle, that there was a major boost in the field of orthodontic aligners^(4, 5) and, is currently estimated that more than 18 million people have been treated with Invisalign®⁽⁶⁾.

Invisalign® aligners are made of flexible polyurethane plastic material. The system uses totally digital set up technology, in which a sequence of stages produces successive and precise movements of the teeth through computerized programs that manipulate the images virtually allowing the visualization of the treatment. Even with computerized planning, the predictability of the treatment result is relative and varies according to the type of movement desired^(5, 7-12).

Some authors have reported that up to 70%-80% of Invisalign® treatments required correction or refinement⁽¹³⁾ and, the average accuracy found for all tooth movements using Invisalign® is approximately 50%.⁽⁹⁾ The movements with the lowest accuracy are the mesial rotation of the mandibular first molar followed by upper and lower incisor intrusion. Greater accuracy is found in buccal-lingual tipping movements.^(9, 14)

When a transverse dento-alveolar expansion movement is planned, the average accuracy achieved is up to 72.8%. The accuracy reduces from the anterior to the posterior region. In ClinCheck® prediction (Align Technology, Santa Clara, Calif) of posterior expansion tooth tipping is more common⁽¹⁵⁻¹⁷⁾ than tooth body movement. The accuracy of the intrusion movement of the mandibular canines and incisors is considered low, around 40% and 47% respectively^(9, 14). Even with the adoption of a new protocol, G5, to improve intrusion control, the results remained the same⁽⁸⁾.

Invisalign® has made constant modifications to its software system to achieve better accuracy of the Clinchek®. The latest modification was the release of G8 protocol in February 2021 to achieve greater predictability. This system aims to improve the clinical accuracy of anterior intrusion movements and arch expansion in the posterior region by reducing tooth tipping and preventing bite opening. The system is called SmartForce Aligner Activation® and is activated

automatically when the need for intrusion or buccal expansion is greater than 0.5 mm. There is also automatic insertion of a device called the Precision bite ramp for cases of moderate and severe deep bite with an overbite of at least 4 mm and requiring intrusion of at least 1.5 mm of the lower incisors⁽¹⁸⁾. Since the G8 protocol is the great novelty in Invisalign[®], there are no studies that evaluated the accuracy of the treatment when G8 is automatically activated by the ClinCheck[®].

Previous awareness of the accuracy and predictability of the treatment result in the initial ClinCheck[®] can help orthodontists modify their planning by overcorrecting to achieve a more predictable result, improving the final quality and gaining more confidence in the communication with the patient (8, 13, 14)

The objective of this pilot study was to evaluate whether the new Invisalign[®] G8 protocol, when activated, provides more accuracy for expansion and intrusion movements than the previous protocols.

MATERIAL AND METHODS

This study was approved by the Ethics and Research Committee of the Federal University of Minas Gerais (CAAE: 48546321.4.0000.5149) and in the Brazilian Registry of Clinical Trials (ReBEC) under the number RBR-7df547h.

The sample, of this study was composed of 44 pairs of STL (Stereolithographic) models exported from the My iTero[®] (<https://bff.cloud.myitero.com/doctors/home> Align Technology, Santa Clara, CA, USA). Maxilla and mandible 3D models of patients were retrospectively selected from a private practice in the city of Belo Horizonte MG, Brazil, and treated with the Invisalign[®] system (Align Technology, Santa Clara, CA, USA) by a single Invisalign[®] Doctor in the period of 2020-2022,. The experimental phases were: initial and refinement. All patients were scanned using the iTero[®] scanner (Element model (S/N: RTC2018 W06A228) by a single operator, at two moments: T0 (initial), and T1 (refinement phase). Eight cases were treated exclusively with no-G8 protocols and in three cases the G8 protocol was activated for bucco-lingual translation movements of the first molars, pre-molars and canines of both arches and intrusion of the mandibular incisors and canines.

The patients included in this study had Class I, II and III malocclusion with moderate crowding of up to 4 mm, overbite change (from 3 to -5 mm), permanent dentition, presence of all teeth up to the second molars, without the use of any

auxiliary appliance or orthodontic elastics during treatment, and aged 18 to 45 year-old. The exclusion criteria were: patients who had restorations in the teeth moved during treatment, non-cooperating patients, and patients with craniofacial syndromes or anomalies, patients with signs or symptoms of inflammation in the periodontal tissues.

The STL 3D models were superimposed using Autodesk Inventor® software with following the steps:

1. Marking the points for overlay STL models were exported to the SlicerCMF® program (Version 4.11; <http://slicer.org>). The demarcation of a point was registration on the T0 model and the same point on the T1 model. This point was located in the lingual mucosa of the gingival region between the mandibular central incisors, and in the medial region of the second or third rugae patina in the maxilla. The marking of each point generated spatial Cartesian coordinates that were transferred to the models in Autodesk Inventor®.
2. The values of the X, Y and Z coordinates were transferred to the Autodesk Inventor® 2022 program (free student license; <https://www.autodesk.com.br/education/edu-software/overview>. Inventor Professional product) using the UCS (Universal Coordinate System) entered one at a time into the T0 model and T1 model
3. The STL 3D models were superimposed using the "Assembly (place) tool, the T0 and T1 models were imported with the points demarcated.
4. The tooth movement analysis was the difference between T0 and T1 after superimposition. The bucco-lingual translation movement was measured using the "Tools" tool by measuring the distances between the buccal tip cusps of the canines, pre-molars and mesi- buccal molars on the X axis in millimeters (mm) ^(14, 19, 20). The vertical movement of the mandibular canines and incisors were measured from the tip of the canine cusps and the middle of the incisal edges ⁽⁹⁾. Displacements in the gingiva direction (intrusion movement) were considered with a positive sign (+). Displacements in the incisal occlusal direction (extrusion movement) were considered with a negative sign (-)⁽²⁰⁾. The amount of the vertical movement was observed in the Z-axis in millimeters.

The accuracy was evaluated by comparing the results obtained with the superimposition of the models at T0 and T1 (actual achieved movement) with the findings verified in Clincheck® (predicted movement). The effectiveness of the G8 protocol was analyzed by comparing the G8 and no-G8 groups. The percent accuracy was determined by the following equation: percentage of accuracy = $100\% - \left(\frac{\text{predicted} - \text{achieved}}{\text{predicted}} \right) \times 100\%$.

STATISTICAL ANALYSIS

The results are shown as mean \pm standard deviation (SD). The program GraphPad Prism 8.0 GraphPad Prism Version 8.0 for Mac, La Jolla, California, USA) was used for statistical analysis. Student *t*-test was used to analyze the differences among G8 and no-G8 groups in bucco-lingual translation movements of molars and pre-molars and intrusion movements of mandibular canines and incisors. $P < 0.05$ was considered statistically significant. D'Agostino & Pearson's omnibus normality test was performed.

RESULTS

Table 1 shows the results of the teeth where the G8 protocol was activated in the bucco-lingual translation movement. There was no statistical difference between the predicted and achieved bucco-lingual translation movements of the teeth using G8 protocol. The maximum desired expansion movement was 1.5 mm for the left mandibular second premolar with an achieved buccal displacement of 1 mm, however with no statistical difference. The G8 protocol was not activated in the canines 13, 23 and 43.

The mean and \pm SD of the ClinCheck® and actual intrusion movements of the G8 protocol are presented in Table 2. No statistical difference was observed between the movements.

The amount of movement and the percentage of the accuracy of the bucco-lingual translation shift of the group G8 in comparison to no-G8 are shown in Tables 3 and 4, respectively. Greater accuracy was observed when protocol G8 was activated; however, no statistical difference was observed between the groups.

The amount of intrusion tooth displacements obtained by the use of protocol G8 in comparison to no-G8 group and its accuracy are shown in Tables 5

and 6, respectively. Although not statistically significant, the accuracy percentage of the intrusion movement of the inferior incisors and canines were highest in G8 protocol in comparison to no-G8.

DISCUSSION

To know which tooth movement will be the easiest and the more difficult using Invisalign® technique is essential from the initial planning stage to achieve the desired result, since the expectations generated by the virtual set-up and the result achieved in clinical practice can be quite different. The goal of this study was to verify the accuracy and predictability of the translation movements of the posterior teeth and intrusion of the canines and mandibular incisors when the Invisalign® G8 treatment protocol was activated.

In 2009, Kravitz *et al.*⁽⁹⁾ claimed that in cases where there is severe crowding in the mandible, treatment should be directed to Interproximal reduction (IPR) instead of archwire expansion. This prerogative has changed over the years with the adoption of new technologies, especially SmartTrack® material adopted by Invisalign® in 2013, which would allow better control of movement, enabling the expansion of arches to assist in the correction of crowding.^(16, 21, 22) In our study, when the new G8 protocol was activated using the SmartForce Aligner Activation® technology for arch expansion, the accuracy of the movements achieved was 77.3% in the G8 protocol compared to 65.5% in the non-G8 protocol, on average 11.5% greater in the mandible, and the maxilla showed 8.8% greater accuracy in the G8 protocol compared to the non-G8, with values of 75.3% and 66.5%, respectively, both being considered reasonable accuracy. This result corroborates other studies that demonstrate that the predictability and accuracy of dentoalveolar expansion in the mandible is better than in the maxilla due to the lower need for expansion of the lower arch.^(15, 22)

Results with lower accuracy than in the present study were found by Houli *et al.*⁽⁸⁾ where the accuracy for the expansion movement in the mandible was 29.9% and in the maxilla 36%. Other studies showed a result more similar to our study where the accuracy obtained for maxillary expansion was 72.8% and for mandibular expansion 87.7%.^(10, 15) Accuracy close to 100% was found in G. Bilello's study⁽²³⁾ pointed to the translation movement of the mandibular premolars. An important observation to be made is that in this work a set of

additional aligners, from the refinement phase, was offered to the patients who needed some correction. In our study all cases were evaluated before the start of the second or refinement phase. Among all the teeth that obtained the highest accuracy of buccal expansion movement were the mandibular premolars with 93% followed by the maxillary premolars with 86% when the G8 protocol was activated and an accuracy of 70% and 60% for these same teeth when the previous protocol was used (table 3), which corroborates other studies⁽¹⁵⁻¹⁷⁾. The tooth that presented the lowest accuracy in our study was the left mandibular canine with 67%. This result should be interpreted with moderation because a single tooth obtained a difference between the movement predicted and achieved of 0.78 mm which negatively impacted the accuracy of this movement. In our study, the accuracy of buccal-lingual translation of the second molars was not evaluated because these teeth do not cause activation of the G8 protocol⁽¹⁸⁾.

Intrusion is considered a low accuracy movement and remains a challenge for Invisalign® treatment⁽⁹⁾. Our result for the accuracy of this movement in the six mandibular anterior teeth was 62.3% when the G8 protocol was activated and 54.6% when this protocol was not used. This result presents values with better accuracy than those presented by other authors, such as Kravitz *et al.*⁽¹⁾ the intrusion accuracy was 41.3 %, closely followed by that found by Haouili *et al.*⁽⁸⁾ and Grunheid *et al.*⁽¹⁰⁾ 2017de 35 % of accuracy.

In our study the mean value of the highest intrusion projected on set up by ClinCheck® was 1.18 mm (table 2) with a maximum of 1.6 mm, with a mean attempted intrusion of 0.96 mm in the group of patients where the G8 protocol was activated, and 0.6 mm was achieved. No teeth were intruded more than 2 mm. The mean accuracy for the incisors and canines was 52.3% and 58.5% respectively. Results are closer to the ones of Al-Balaa *et al.*⁽²⁴⁾, who found an average intrusion of 0.9 mm with 51.9 % accuracy, where canines and mandibular incisors obtained 52.3 % and 44.7 % respectively. In only one study the intrusion accuracy was higher than what we found, achieving 86.7% and 98.0% for canines and mandibular central incisors. these results are probably leveraged by the use of additional aligners, which did not occur in our study⁽²³⁾.

Since Kravitz in .2009⁽⁷⁾ conducted one of the first studies to evaluate the efficacy of Invisalign® aligners, several other^(8, 9, 14, 21-23) has been trying to test the new protocols claimed by Align in search of improved predictability, and this

is what has been happening. Tables 2 and 3 show that the p-values < 0.05 show no statistical differences between the groups examined. This shows that the accuracy of the predicted and achieved movements is getting closer. It was observed that when the G8 protocol was activated, all the movements evaluated showed a slight improvement in accuracy compared to the previous protocol.

Even with improved predictability the ClinCheck®, which is the main tool for comparison between predicted and achieved movements, overestimates the result. It should be interpreted with moderation. Overcorrection and a phase with new aligners are still necessary to achieve the desired final result ^(8, 14, 23) One limitation of this study is the small sample of cases in which the G8 protocol was activated. Movements of greater amplitude, which are desired when using this new protocol, could not be widely evaluated.

CONCLUSIONS

No improvement in accuracy was observed for the posterior expansion and intrusion movements of the mandibular canines and incisors when the G8 Invisalign® protocol was activated. The predicted and achieved movements using G8 protocol were similar.

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Table 1: Descriptive statistics of the buccal-lingual translation movements mandibular and maxillary teeth

Tooth	n	Predicted (clincheck)G8		Actual,G8		p
		Mean	SD	Mean	SD	
33 (G8)	3	0,63	0,23	0,21	0,19	0,07
34 (G8)	3	0,98	0,33	0,76	0,27	0,35
35 (G8)	3	1,50	0,30	1,10	0,31	0,17
36 (G8)	3	0,96	0,48	0,77	0,47	0,53
46 (G8)	3	1,03	0,38	0,70	0,36	0,33
45(G8)	3	1,20	0,29	0,94	0,38	0,22
44(G8)	3	0,89	0,31	0,66	0,31	0,30
14 (G8)	3	0,97	0,31	0,74	0,30	0,53
15 (G8)	3	0,74	0,18	0,85	0,07	0,51
16 (G8)	3	0,90	0,10	0,74	0,09	0,11
24 (G8)	3	0,70	0,26	0,57	0,22	0,54
25 (G8)	3	1,13	0,08	0,84	0,08	0,09
26 G8	3	0,95	0,07	0,56	0,28	0,19

*SD - Standard deviation. P ≤0,05.

Table 2: Descriptive statistics of the intrusion mandible

Tooth	n	Predicted (clincheck)G8		Actual G8		p
		Mean	SD	Mean	SD	
31 (G8)	3	1,03	0,42	0,70	0,50	0,42
32 (G8)	3	1,13	0,35	0,63	0,45	0,20
33 (G8)	3	0,60	0,20	0,33	0,06	0,56
41 (G8)	3	1,15	0,44	0,64	0,43	0,14
42 (G8)	3	1,18	0,40	0,73	0,36	0,83
43 (G8)	3	0,68	0,21	0,53	0,16	0,31

*SD - Standard deviation. P ≤0,05.

Table 3. Amount of movement of the bucco-lingual translation movement of the no-G8 and G8 groups.

Tooth	n	No G8		G8			p
		Mean	SD	n	Mean	SD	
33	8	0,39	0,24	3	0,21	0,19	0,24
34	8	0,43	0,36	3	0,76	0,27	0,11
35	8	0,39	0,24	3	1,10	0,31	0,35
36	8	0,38	0,22	3	0,77	0,47	0,51
44	8	0,37	0,21	3	0,66	0,31	0,20
45	8	0,33	0,22	3	0,94	0,80	0,46
46	8	0,39	0,24	3	0,70	0,80	0,23
14	8	0,76	0,41	3	0,74	0,31	0,99
15	8	0,37	0,30	3	0,85	0,85	0,52
16	8	0,52	0,40	3	0,74	0,73	0,08
24	8	0,72	0,35	3	0,54	0,52	0,88
25	8	0,68	0,40	3	0,84	0,89	0,79
26	8	0,49	0,40	3	0,56	0,56	0,44

P<0,05. SD : standard deviation

Table 4: Descriptive statistics accuracy of the buccal-lingual translation movements mandibular and maxillary teeth

Tooth	n	G8			n	No G8			p
		Mean	Median	SD		Mean	Median	SD	
33	3	63,38	67,00	23,86	8	66,67	63,00	17,79	0,83
34	3	78,50	79,50	12,29	8	67,00	63,00	21,10	0,35
35	3	77,33	71,00	23,16	8	63,75	72,50	26,85	0,46
36	3	74,00	78,00	17,66	8	64,29	66,00	11,25	0,27
46	3	75,00	72,50	11,52	8	70,22	82,00	34,02	0,79
45	3	92,00	93,00	8,54	8	70,57	75,00	26,78	0,22
44	3	93,33	93,00	1,53	8	69,82	78,00	25,21	0,14
14	3	64,67	56,00	15,01	8	68,50	72,00	10,33	0,62
15	3	86,33	83,00	9,45	8	60,36	80,00	32,86	0,21
16	3	77,33	77,00	2,52	8	75,00	80,00	18,12	0,83
24	3	81,33	81,00	5,51	8	68,09	91,00	38,75	0,58
25	3	80,67	79,00	4,73	8	71,43	77,00	14,55	0,33
26	3	58,33	60,00	17,56	8	63,00	76,00	25,50	0,78

*SD - Standard deviation. $p \leq 0,05$

Table 5. Amount of intrusion movement, the no-G8 and G8 groups

<i>Tooth</i>	<i>n</i>	<i>No G8</i>		<i>G8</i>		<i>p</i>
		<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
31	8	0,70	0,50	1,30	0,42	0,42
32	8	0,63	0,45	1,13	0,75	0,20
33	8	0,53	0,94	0,68	0,21	0,09
41	8	0,64	0,16	1,15	0,44	0,15
42	8	0,73	0,36	1,18	0,40	0,10
43	8	0,53	0,16	0,68	0,21	0,31

*DP - Desvio Padrão, *p<0,05

Table 6. Percentage of the accuracy of the intrusion movement of no-G8 and G8 groups

<i>Tooth</i>	<i>n</i>	<i>G8</i>			<i>n</i>	<i>No G8</i>			<i>p</i>
		<i>Mean</i>	<i>Median</i>	<i>SD</i>		<i>Mean</i>	<i>Median</i>	<i>SD</i>	
43	3	79,25	78,50	5,38	8	60,43	68,00	34,96	0,32
42	3	64,50	62,00	12,48	8	44,43	45,00	36,66	0,33
41	3	57,33	62,00	11,72	8	49,25	57,50	22,52	0,58
31	3	65,00	77,00	23,43	8	62,50	74,50	31,39	0,90
32	3	57,00	73,00	30,35	8	57,30	60,00	30,00	0,99
33	3	57,67	50,00	15,04	8	54,11	64,00	22,77	0,81

*SD - Standard deviation. p≤0,05

5. CONSIDERAÇÕES FINAIS

A sobreposição de modelos 3D é um método de avaliação do tratamento ortodôntico bastante interessante, pois não expõe o paciente a radiação e fornece informações com acurácia. O método de sobreposição utilizando o software Autodesk Inventor® utilizando o sistema Cartesiano associado a um ponto se mostrou reproduzível e confiável na maxila e mandíbula. Este método, além de inédito na Odontologia, permite avaliar o resultado do tratamento ortodôntico especialmente com os alinhadores e está ao alcance do clínico e se mostrou confiável e reproduzível.

Último investimento feito pela empresa Align®, o protocolo G8, com o objetivo de melhorar a previsibilidade dos tratamentos com Invisalign® parece ter surtido pouco efeito. Para o ortodontista continua sendo necessário planejamento com sobrecorreções e uma nova fase de alinhadores chamada de refinamento para se obter resultado mais acurado.

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