UNIVERSIDAD COMPLUTENSE DE MADRID
FACULTAD DE ODONTOLOGIA

TESIS DOCTORAL

Influencia de la edad y del escáner intra-oral en la curva de aprendizaje de operadores noveles: ensayo clínico multi-céntrico

Influence of age and scanning system on the learning curve of inexperienced intraoral scanner operators: a multi-centric trial

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

Cristina Alejandra Zarauz Yáñez

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Tesis doctoral

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Memoria para optar al grado de Doctor

presentada por

Cristina Alejandra Zarauz Yañez

Directores

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En fin, a todos, muchas gracias.

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Abbreviations

3D: three (3) Dimensional

AAD: Average Absolute Deviation

AM: Additive Manufacturing

AWS: Active Wavefront Sampling

CAD: Computer Aided Design

CAM: Computer Aided Manufacturing

CE: Conformitè Europëenne

DOF: Depth Of Field

FDP: Fixed Dental Prosthesis

IOS: Intra Oral Scanner

RMS: Root Mean Square

SD: Standard Deviation

STL: Standard Tessellation Language

SM: Subtraction Manufacturing

S1: Scanner 1 (TRIOS 3)

S2: Scanner 2 (True Definition)

CL: Chair Light (10000 lux)

RL: Room Light (1003 lux)

NL: Natural Light (500 lux)

ZL: Zero Light (0 lux)

Resumen

Título:

Influencia de la edad y del escáner intra-oral en la curva de aprendizaje de operadores noveles: ensayo clínico multi-céntrico.

Introducción:

Las impresiones dentales, ya sean convencionales o digitales, deben ser lo suficientemente fiables. Por este motivo, la fiabilidad ha jugado un papel central en los estudios de investigación que evalúan la validación de los escáneres intra-orales como alternativa a las impresiones convencionales. Después de un largo desarrollo tecnológico, los escáneres intra-orales son cada vez más fiables. En consecuencia, cobran relevancia otros factores como el tiempo necesario para realizar una impresión digital intra-oral, o la curva de aprendizaje que puede ser necesaria para adquirir las habilidades necesarias para realizar dicha impresión en un tiempo razonable.

Se han investigado previamente varios factores influyentes en los tiempos de escaneado. Factores como la estrategia de escaneado, las condiciones de iluminación, la extensión de la impresión o el número de sesiones de aprendizaje. Sin embargo, el impacto de otros factores en los tiempos de escaneado y curva de aprendizaje de operadores de escáneres intra-orales, como la edad, la experiencia previa en toma de impresiones digitales, el tipo de escáner intra-oral, o la versión del software cuentan con escasa evidencia científica.. En el proceso de aprendizaje de un operador de sistemas de impresión digitales, los objetivos son tanto reducir el tiempo necesario para la toma de impresiones como, además, producir una impresión digital fiable. No está claro si el tiempo de escaneado tiene un impacto en la fiabilidad de la impresión digital resultante.

Conocer cómo diferentes aspectos, como la edad, la experiencia o el sistema de impresión digital, influyen en la curva de aprendizaje de los escáneres intra-orales es relevante debido al impacto financiero y estratégico asociado con su adquisición.

Objetivos:

El presente trabajo de investigación estableció los siguientes objetivos: *primero* evaluar si la edad, el tipo de escáner intra-oral o la versión del software tienen un impacto en el rendimiento y en la curva de aprendizaje de operadores sin experiencia previa en el uso de escáneres intra-orales, en comparación con operadores experimentados; *segundo* evaluar si la edad, el tipo de escáner intra-oral o la versión del software influyen en la fiabilidad de las impresiones digitales registradas por operadores sin experiencia en comparación con los operadores experimentados; y *tercero* establecer si el tiempo de escaneo y la fiabilidad están correlacionados.

Material y métodos:

Treinta y cuatro participantes, divididos en 3 grupos, fueron incluidos en este estudio clínico multi-céntrico. Dos grupos sin experiencia en el uso de escáneres intra-orales: grupo test i) estudiantes de odontología (menores o iguales a 25 años); grupo test ii) dentistas (mayores o iguales a 40 años); y un grupo control) operadores experimentados (sin límite de edad). Todos los participantes realizaron impresiones digitales intra-orales parciales, del cuadrante 1 y del cuadrante 4. Cada grupo de estudio realizó impresiones iniciales y finales en pacientes voluntarios antes y después de un programa de entrenamiento de 3 sesiones, con dos escáneres digitales diferentes: TRIOS 3 (S1) y True Definition (S2). Los tiempos de escaneado inicial y final se registraron en segundos y se exportaron en formato STL (Standard Tessellation Language) para el análisis de la fiabilidad (exactitud y precisión) con el software Geomagic Control X.

Resultados:

Los resultados del presente ensayo clínico mostraron que la edad tiene un impacto en el rendimiento del tiempo de escaneado ($r = 0.29$, $p < 0.05$), y en la curva de aprendizaje de operadores de sistemas de impresión digital noveles ($p < 0.05$)..

El tipo de escáner demostró tener un impacto en el rendimiento del tiempo de escaneado ($p < 0.001$), y en la curva de aprendizaje de operadores noveles y experimentados ($p < 0.001$).

La versión del software demostró tener un impacto en el rendimiento del tiempo de escaneado inicial ($p = 0.032$), pero no en el tiempo de escaneado final ($p = 0.051$).

En cuanto a la fiabilidad, la edad tuvo un impacto en la fiabilidad ($p < 0.05$), mientras que el tipo de escáner o la versión del software no afectaron a la fiabilidad de los STL resultantes ($p > 0.05$).

Se estableció una correlación entre el tiempo de escaneado y la exactitud ($r = 0.25$, $p < 0.003$), y entre el tiempo de escaneado y la precision ($r = 0.44$, $p < 0.000$).

Conclusiones:

La edad y el tipo de escáner intra-oral influyeron en el rendimiento y la curva de aprendizaje de los operadores noveles de escáneres intra-orales. El entrenamiento redujo el impacto de la versión del software en el tiempo de escaneado.

La edad influyó en la fiabilidad de las impresiones digitales registradas por operadores sin experiencia, mientras que el tipo de escáner intra-oral o a versión del software no afectaron a la fiabilidad. El tiempo de escaneado y la precisión revelaron una correlación.

Abstract

Title:

Influence of age and scanning system on the learning curve of inexperienced intraoral scanner operators: a multi-centric clinical trial.

Introduction:

Dental impressions, whether conventional or digital, need to be sufficiently accurate. For this reason, accuracy has played a central role in the validation of intraoral scanners (IOSs), as an alternative to conventional impressions. After a long technological development, IOSs are becoming increasingly accurate. With this prospect in mind, other factors gain relevance, such as the time required to complete a digital intraoral impression, or the learning curve it may be needed to acquire the skills to perform said impression in a reasonable amount of time.

Several factors affecting scanning times, learning curves and accuracy have been previously investigated, such as scanning path, lighting conditions, scanning extension, or number of training sessions. Evaluating whether factors such as operator's age, previous intraoral scanning experience, the scanning system itself or its software version influence the performance and learning curve of IOS operators in a clinical setting needs further clarification. In the learning process of an IOS operator, the goals are both to reduce the time required for impression taking, and additionally to produce an accurate digital impression. It remains unclear whether scanning time has an impact on the accuracy of the resulting digital scan.

Gaining knowledge on how the different aspects, such as operator's age, experience or IOS system, influence the learning curve to IOSs is relevant due to the financial and strategical impact associated with the acquisition of an IOS.

Objectives:

The objectives of the present investigation aimed to evaluate: *first* whether the operator's age, type of IOS or software version has an impact on the performance and the learning curve of inexperienced IOS operators compared with experienced operators; *second* whether the operator's age, type of IOS or software version influences the accuracy of digital scans registered by inexperienced IOS operators compared with experienced operators; and *third* whether scanning time and accuracy are correlated.

Material and methods:

Thirty-four operators pertaining divided in 3 group were included in this multi-centric clinical study. Two test groups with no experience in the use of IOSs: test group i) dental students (younger or equal to 25 years old); test group ii) dentists (older or equal to 40 years old); and control group) experienced IOS operators (no age limitation). All participants performed baseline and final quadrant scans on a volunteer subject, before and after a training program of 3 sessions, with two different IOS: TRIOS 3 and True Definition. Baseline and final scanning times were registered in seconds and were exported in Standard Tessellation Language (STL) format for accuracy analysis.

Results:

The findings of the present clinical study showed that the operator's age had an impact on the scanning time performance ($r = 0.29$, $p < 0.05$) and learning curve of novel IOS operators ($p < 0.05$).

The IOS system demonstrated to have an impact on the scanning time performance ($p < 0.001$) and learning curve of novel and experienced IOS operators ($p < 0.001$). The software version had an impact on scanning time at baseline ($p = 0.032$), but not after training ($p = 0.051$).

Concerning accuracy, age had an impact on trueness and precision ($p < 0.05$), while the IOS system or their respective software versions did not impact the trueness and precision of STLs performed by IOS novel operators ($p > 0.05$).

A correlation was stablished between scanning time and trueness ($r = 0.25$, $p < 0.003$), and between scanning time and precision ($r = 0.44$, $p < 0.000$).

Conclusions:

Age and type of intraoral scanner had an influence on the performance and the learning curve of inexperienced IOS operators. Training reduced the impact of software version on scanning time.

Age had an influence on the accuracy of the digital impressions registered by inexperienced IOS operators, while the type of intraoral scanner or its software version did not impact the accuracy. Scanning time and accuracy revealed a correlation.

1 Introduction

1.1 Background

Impression and registration of intra-oral structures from natural dentition to dental implants and adjacent tissues is a critical step in different areas of dentistry. In restorative dentistry, prosthodontics, or orthodontics, dental impressions allow the transfer of information to the dental laboratory in order to produce restorations or appliances to be used intra-orally. The accuracy of this step is critical for the final success of the treatment (Abduo 2018, Ender 2016). Other factors, such as the time it requires to be performed, or the learning curve required to learn to use it properly, the patient or the clinician perception, the costs needed for purchase or maintenance, also play a role in the convenience of use, and finally, the choice which each clinician will make to decide which impression method will be used in their practice.

In this thesis, a brief introduction of conventional impressions will be made and a more thorough introduction of digital impressions. Henceforth the study material and methods will be described, which were applied to evaluate the influence of age and scanning system on the learning curve of novel intraoral scanner operators. The thesis will be concluded after reporting the results, with the discussion and conclusions.

1.2 Conventional impressions

Traditionally, intra-oral impressions were performed using trays and impression materials.

The conventional impression workflow (before design) is composed of multiple steps:

Table 1: Conventional impression workflow:

Steps			
1	Impression material selection	elastic or non-elastic (Table 2)	
2	Tray selection	standard	metallic or plastic
			perforated or solid
			full arch or partial
			single or double arch
		customized	requiring a previous impression for its fabrication
3	Tray adaptation / conditioning	perforation	for implant open tray impressions
		border molding	
		adhesive application	
4	Impression technique	one step impression technique	
		two step impression techniques	
5	Impression disinfection		
6	Impression packaging		
7	Impression storage		
8	Impression transportation		
9	Casting procedure	material selection	
		setting time	
		humidity conditions	
		trimming	
		die fabrication	

Once a physical model is produced, it can be digitized in a laboratory scanner, initiating a digital workflow.

Table 2: Classification of impression materials:

Non-elastic	Reversible	impression compound	
	Irreversible	impression plaster	
		zinc oxide eugenol	
		impression paste	
Elastic	Hydrocolloid	Reversible	agar
		Irreversible	alginate
	Elastomeric impression materials	Irreversible	polysulfides
			polyethers
			addition silicones
			condensation silicones

Impression materials are commonly classified by considering their elastic properties once set (Wassel 2002).

The ideal impression material must-have qualities that make it biocompatible, accurate, dimensionally stable, with elastic recovery, fluid, flexible, hydrophilic, adequate working time, pleasant taste, and economical (Martínez-Rus 2005). Today, it is not disputed that elastomeric impression materials are the most appropriate choice for taking impressions in fixed prosthodontics, specifically addition silicones and polyethers (Hunter 1990, Martínez-Rus 2005).

Like other procedures, however, conventional impressions have advantages and disadvantages.

1.2.1 Advantages of conventional impressions

Conventional impressions are an approach that has been widely used and has shown to be reliable and to allow the fabrication of clinically acceptable prostheses and appliances, both on dentate, implant, partially or completely edentulous patients (Levartovsky 2013).
Setting times for different materials are known and consistently reported by the manufacturer in the provided user instructions.
The ability to plan the agenda with sufficient precision is of high value for clinicians in private practice. Unexpected delays in clinical procedures are unwelcome, as if regularly repeated, may be of high cost. As mentioned previously, there are several steps (Table 1) that are required to complete a successful conventional impression, and these steps may be planned into everyday clinical practice with high predictability.

Additionally, conventional impressions still have specific indications for which they remain the gold standard. For full arch cases, conventional impressions remain more accurate than intraoral digital impressions (Mangano 2017), or for deep preparation margins (Mangano 2017), which are difficult to register for optical scanners, which remains the primary acquisition method for intraoral scanners (IOSs).

1.2.2 Disadvantages of conventional impressions

In conventional impressions, each step (Table 1) may add inaccuracies incrementally, which may compromise the outcome (Nagy 2020, Richert 2017). Conventional impressions are usually associated with specific disadvantages:

- Discomfort, created by trays and impression materials in the oral cavity, by applying pressure, or triggering the gagging reflex.
- Logistical issues such as storage and transportation.
- Technique sensitive procedure, with precise handling of impression and casting materials, limiting humidity and setting time specifications (Nagy 2020, Richert 2017).

1.3 Digital workflow

Computer aided design / computer aided manufacturing (CAD/CAM) in dentistry, comprises all the phases required to produce a prosthesis or dental appliance within the digital workflow.

1.3.1 Digital workflow phases

- The digitization phase.
- The design phase (CAD).
- The manufacturing phase (CAM).

1.3.1.a The digitization phase

The digitization phase, necessary to obtain a digital model from which the digital workflow can begin, can be accomplished with either an intra-oral scanner, directly in the oral cavity from the patient, or with a laboratory scanner by registering a model or a conventional impression.

1.3.1.b The design phase (CAD)

The second phase is the design phase, accomplished with computer design software, which allows us to create conceptions from surgical guides, orthodontic appliances/guides, fixed and removable prostheses.

1.3.1.c The manufacturing phase (CAM)

The 3rd phase is the production phase. The designed model is transferred to a computer-controlled production fabrication system, which either mills (subtraction manufacturing) or three dimensional (3D) prints (additive manufacturing) the previously designed appliance (Hollender 2014).

Subtraction manufacturing

The subtraction manufacturing (SM) usually involves milling the designed volumetric shape from a pre-sintered or sintered material using a milling machine that performs either in a wet or dry condition, that moves in defined paths, referred to as 3-, 4-, or 5-axes milling systems (Abduo 2014).

Additive manufacturing

Additive manufacturing (AM) is a process by which the designed reconstruction or appliance is constructed, adding layer by layer, with a computer-controlled manufacturing system.
There are seven categories of AM technologies: stereolithography, material jetting, material extrusion or fused deposition modeling, binder jetting, powder bed fusion, sheet lamination, and direct energy deposition (ASTM Committee 2009). The stereolithography and material jetting technologies are the most used in dentistry.
AM is an emerging technology that is gaining increasing interest thanks to its advantages, such as reducing material waste, reducing energy consumption, and cost efficiency; many models may be printed simultaneously. However, its accuracy remains below that of SM, limiting its application to dental

appliances, which are less demanding regarding accuracy, such as surgical guides, temporary restorations, occlusal splints, bite-guards, scaffolds, and orthodontic appliances (Sulaiman 2020).

1.4 History of digital impressions

Digital impressions were introduced in the early '70s, with the objective to counteract the disadvantages of conventional impressions (Duret 1985). The initial idea was to improve efficiency by avoiding the inconveniences of the analog processes (Richert 2017). The first theoretical conception was published by Dr. François Duret in his doctoral thesis in 1973, L'Empreinte Optique (Duret 1973). During the 'Entretiens de Garancière, a French conference in 1983, Dr. Duret presented the 1st ever IOS prototype (Duret 1988), which he developed with the support of the company Hensonn International, and patented in 1984 (Duret 1988). During the Chicago Winter Conference in 1985, he produced, live in 4 hours, a posterior crown for his wife, using an IOS, CAD software, and a milling unit (Duret 1996).

In parallel, Dr. Werner H. Mörmann and Marco Brandestini (an electronic engineer), with the support of Siemens AG (Germany), were developing the CEREC system, now commercialized by Dentsply Sirona Inc (York, PA, USA), which became the first commercialized IOS (Mörmann 1989).

For several decades, the CEREC system was the only IOS available (Reich 2013). This could be due to accuracy remaining inferior to conventional impression methods, limiting the interest of potential industry competitors to develop other systems. This changed in the late 2000' when general technological advancements caught up, and several IOSs were launched in the market (Birnbaum 2008), such as the LAVA COS (3M ESPE, St. Paul, MN, USA), the iTero (Cadent, Tel Aviv, Israel), or the E4D (D4D Technologies, Texas, USA).

During the decades when only the CEREC system was available as IOS, the digital workflow and materials were being developed in the laboratory setting, with the assistance of laboratory scanners (Birnbaum 2008). The Procera system was developed by Andersson and Oden, and launched in 1993 by the company Nobel Biocare (Zurich, Switzerland) as an extra-oral tactile laboratory scanner, beginning mass production of individualized restorations made of different materials (Birnbaum 2008, Strub 2006).

1.5 Laboratory scanners

Laboratory or extra-oral scanners are indirect digitization systems, which generate a digital file by registering a cast model or a conventional impression. They use either palpation or optical technology.

Laboratory scanners show high accuracy regardless of the range of the impression (short-span or full-arch), due to the fact that they capture the entire range of the model in a single scan (Miyoshi 2020). IOSs, on the other hand, present the challenge of having to stitch the separate images together in order to create the digital scaffold of the model, on a moving patient, with a moving hand-held optical wand. For this reason, they are more prone to stitching and overlapping errors than laboratory scanners, especially the more challenging the scanning scenario gets, like for edentulous cases (Miyoshi 2020).

Laboratory scanners have reported similar accuracy to industrial scanners, with an estimated error of 4 - 10 microns (Kim 2021, Nedelcu 2018, Pan 2020, Revilla 2020.a, Yilmaz 2021, You 2021).

While laboratory scanners have proven high accuracy, facilitating the development of the digital workflow and CAD-CAM materials, the current tendency is to evolve into a full digital workflow (Chiu 2020). This starts with a digital impression intra-orally, and eliminates the requirement of scanning either the cast model or the conventional impression (Chiu 2020).

1.6 Intraoral scanners (IOSs)

Intraoral scanners (IOSs) are mainly optical scanners (Joda 2014). They are composed of a hand-held intraoral camera (or wand), shaped like a narrow stick of varying sizes, connected to hardware (usually a computer on a trolley provided by the manufacturer or a laptop), and software for acquisition and digital data post-processing (Richert 2017). The goal of an IOS is to create a digital impression of the oral structures directly inside the oral cavity.

IOSs exhibit specific advantages and disadvantages.

1.6.1 Advantages and disadvantages of IOSs

Table 3: Advantages and limitations of IOSs, as reported by the current literature:

Advantages	Disadvantages
Di Fiore 2018, Joda 2014, Lim 2018, Mangano 2017, Mangano 2019, Robles-Medina 2021, Wismeijer 2014, Yuzbasioglu 2014, Zimmermann 2015.	Agnini 2015, Kim 2016, Lawson 2015, Lee 2013, Lim 2018, Mandeli 2017, Mangano 2017, Mangano 2019, Marti 2017, Zimmermann 2015.
Reduced patient discomfort (pain to tray pressure, vomiting or gagging reflex, breathing difficulties).	Difficulty detecting deep preparation margins, or undercut regions.
Optional selective scanning of a partial section allows corrections of deficient registered areas.	Learning curve
Reduced use of consumable materials (impression material, dispensation points, trays, and adhesive materials).	Purchasing and managing costs
Storage and data recovery from the cloud.	Reduced accuracy in full arch impressions
Real time visualisation and evaluation of virtual models and dental preparations prior to sending to the laboratory.	Edentulous cases remain a limitation
Improved and more fluent communication between dentist, dental lab and patient.	Difficulties related to computerised devises, such as software or hardware bugging, stitching or overlapping errors.
No need of impression processing avoiding handling errors and reducing the impact of materials limitations.	
Greater time efficiency in impression taking, specially true for short span impressions.	
Marketing tool.	
Possibility of linking with a CAD software and a milling machine for chair-side production.	

1.6.2 Technology

The digital file is created by a three-dimensional reconstruction of the oral structures (teeth, mucosa, and implants) based on the generation of a point cloud in which every single point has a specific spatial location in the Cartesian Coordinate System (Medina-Sotomayor 2018). The combination of those points, through a triangulation process, creates a polygonal mesh composed of a variable number and size of triangles, also known as Standard Tessellation Language file (STL format file) (Nagy 2020).

There are two phases to obtain a digital model, an acquisition phase of data which creates a point cloud, and a second phase of reverse engineering, which reproduces the information of the point cloud to create a digital model (Tapie 2015).

The acquisition phase for digital scanners (extra or intra-oral), as mentioned previously, may be by palpation or optical technology. For IOSs, however, it is limited to optional scanners, as a palpation mechanism cannot be introduced into the oral cavity. A light is projected onto the target surface (to be digitized). This light may be a structured light or a laser beam, projected by one or several cameras, which create a reflected image when the light contacts the target structure and is captured by a sensor. Additionally, the data acquisition mode may be based on the 'stitching’ of several consecutive images with either a photo, or a video-based technology. IOSs with a continuous scanning flow (video) have shown better accuracy than some photo-based IOSs (Robles-Medina 2021).

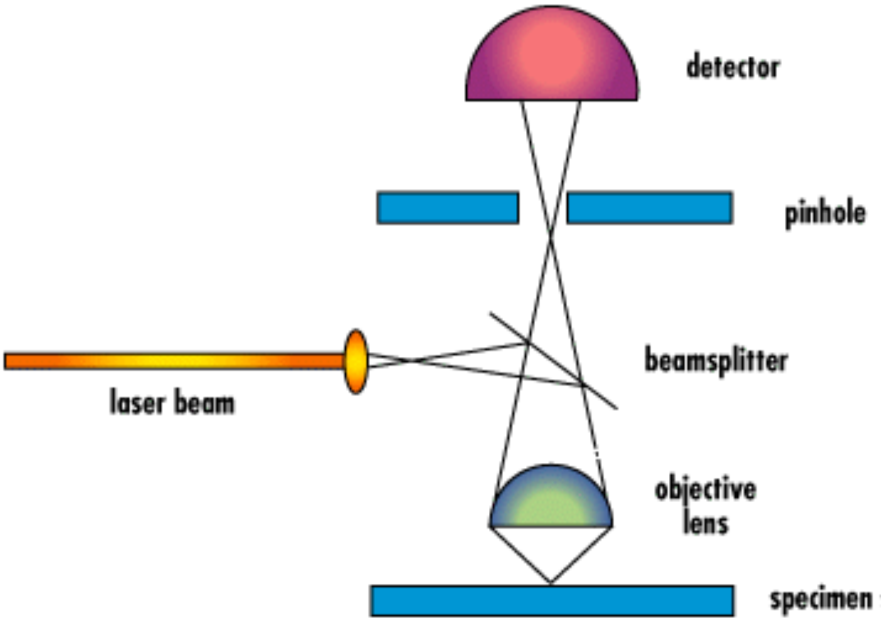
There are three main types of scanning technologies used in intraoral impression devices; *Confocal Microscopy*, *Triangulation and Active Wavefront Sampling*.

1.6.2.a Confocal Microscopy

Confocal microscopy, or confocal laser scanning microscopy, is an optical technology that uses a laser light source for acquiring images with high-resolution and in-depth selectivity. Laser beam images are projected point-by-point, line-by-line, onto a beam-splitter, pass through a lens, and are projected on the specimen. The image reflects through a pinhole onto the detector or sensor and is three-dimensionally reconstructed with a computer (Carlsson 1985). The key feature of confocal microscopy is its ability to produce optical slices of the objects at various depths with high resolution and contrast in the x, y, and z coordinates. The depth of field is known for every optical slice, and the in-focus images are recorded. Spatial filtering is employed to eliminate out-of-focus glare or light of background information (Paddock 2014).

The basic principle of confocal microscopy was pioneered by Marvin Minsky in 1957 (Paddock 2014).

Figure 1: Confocal microscopy principle (Stancovski 2014):



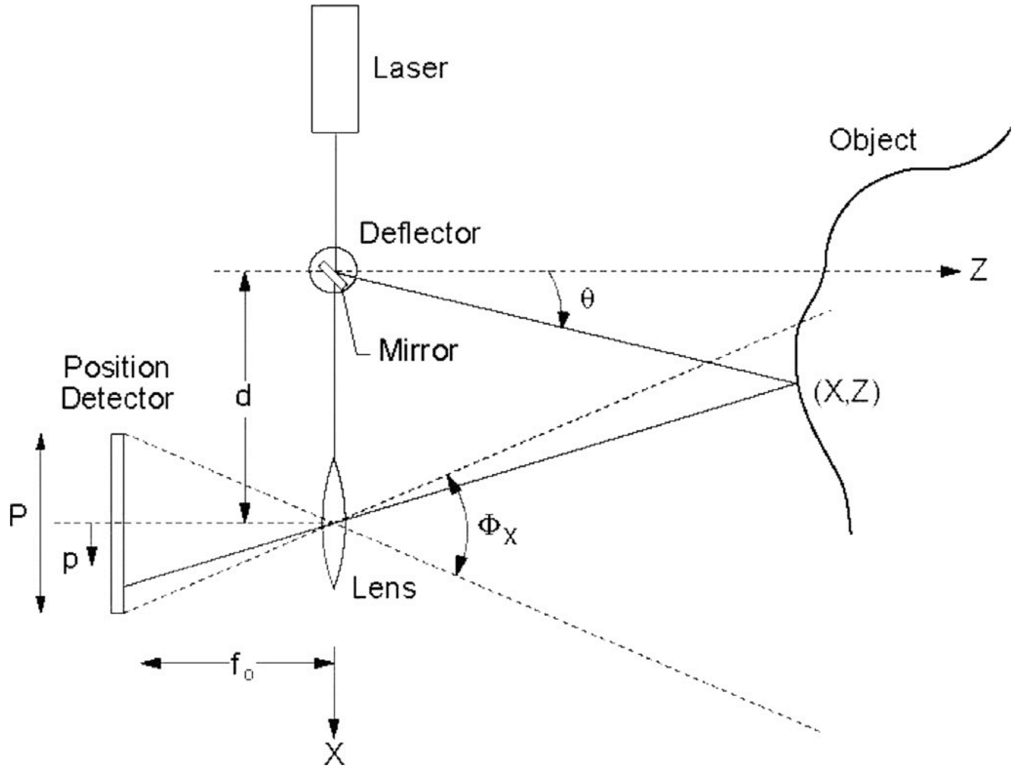
1.6.2.c Triangulation

Optical triangulation uses a laser light source, a mirror, a lens, and a light-sensitive sensor (Figure 2) (Logozzo 2014).

The laser irradiates a point, a line, or multiple lines, depending on the triangulation method, that are projected on a specimen/object through the mirror. The image reflected from the object will be captured by the sensor at different distances depending on their relative separation with the light source (El-Hakim 1995)

The laser, the sensor, and the specimen to be digitized form a triangle. The distance from the sensor to the surface is then calculated by determining the position of the image and the baseline angles and length involved by trigonometry (El-Hakim 1995). The principle of triangulation has been used for centuries, but practical sensors became available for industrial applications in the '70s (Ji 1989).

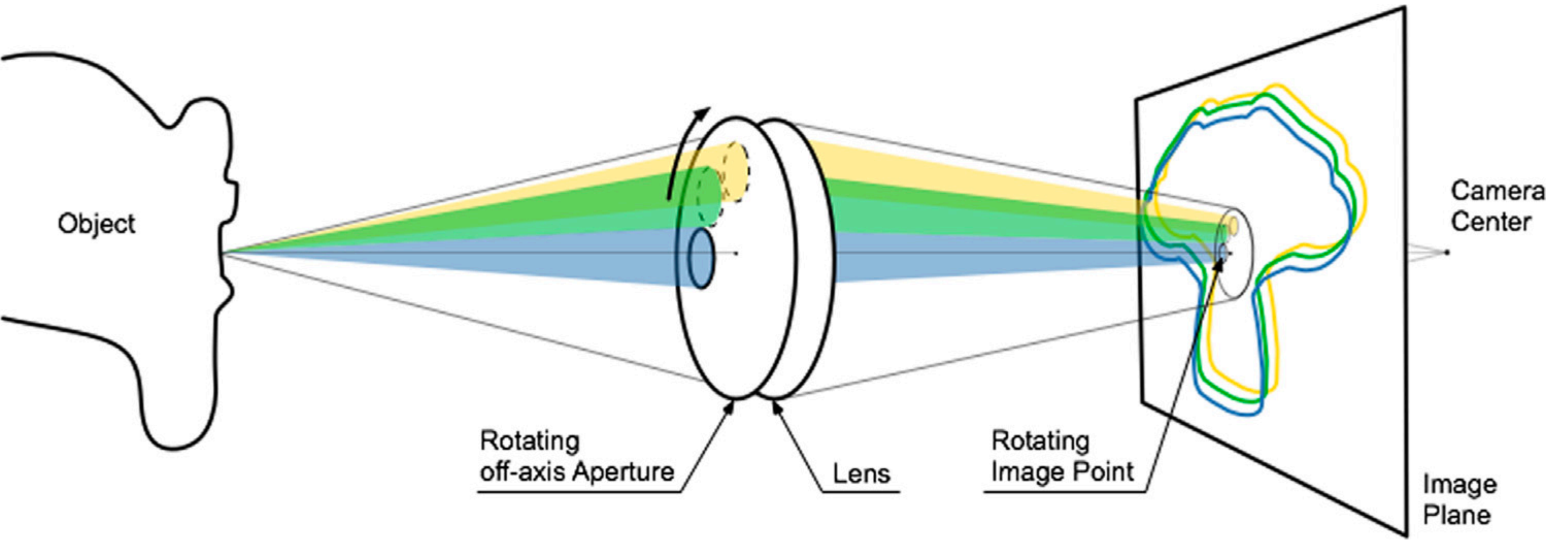
Figure 2: Active triangulation method (Logozzo 2014):



1.6.2.c Active Wavefront Sampling (AWS)

Active Wavefront Sampling (AWS) is a 3D surface imaging technique, which uses a single camera as a light source, and an AWS module (Frigerio 2013). An AWS module is an off-axis aperture that moves on a circular path around the optical axis (Figure 3). This movement produces the rotation of target points on a circle on the image plane. The target points depth information can be derived from the radius of the circular point pattern produced by each point (the blur-circle-radii generated by the rotating AWS module) (Heber 2013). AWS imaging allows any system with a digital camera to function in 3D. Thus, it eliminates the need for multiple cameras to acquire 3D geometries (Logozzo 2014).

Figure 3: Active wavefront principle (Heber 2013):



1.6.3 Technical characteristics

Other than the acquisition method, the available IOSs have different technical characteristics that should be taken into consideration, and are described below.

Depth of field (DOF)

It refers to the maximum range of distance between the wand sensor and the structure to be digitized. Systems using active wavefront sampling usually have a narrow range of DOF, while systems with confocal microscopy provide a wider range, allowing the wand to be in contact with the tooth without losing focus (Hwang 2020). In the case of a narrow range of DOF, scanning a surface becomes more challenging, as the wand tip is required to maintain a constant distance to the object during image acquisition, otherwise interrupting the scanning process (Park 2016, Robles-Medina 2021). With the general objective of facilitating scanning, new IOSs incorporate extended DOF ranges, such as Primescan (Dentsply Sirona Inc, York, PA, USA), with a DOF of 20 mm.

Powder requirement

Not all restoration materials and dental tissues are equally easy to digitize due to their different light refraction indexes. Consequently, some IOSs require contrast powder coating (titanium oxide) for surface opacification. A light powder coating has been shown to result in highly accurate impressions (Richert 2017). It is nevertheless a highly technique sensitive procedure, as only a thin uniform layer is required, and controlling this inside the moving, salivating patient may prove challenging (Richert 2017). For this reason, newer IOSs tend to eliminate powder requirement.

Lighting conditions

The impact of lighting conditions on the scanning accuracy has been evaluated recently in an in-vitro (Revilla 2020.a) and a clinical study (Revilla 2020.b).

The lighting conditions evaluated were:

- (CL) chair light 10000 lux
- (RL) room light 1003 lux
- (NL) natural light 500 lux
- (ZL) no light 0 lux.

Three IOSs were tested in-vitro: TRIOS 3 (3 Shape, Copenhagen, Denmark), iTero, and CEREC Omnicam (Dentsply Sirona Inc, York, PA, USA); while only TRIOS 3 was evaluated in-vivo. The findings from these studies reveal that lighting conditions significantly influenced accuracy, but the lighting condition showing the highest accuracy was different for the different IOS systems.

For iTero, CL and RL resulted in better accuracy. For CEREC Omnicam, ZL resulted in better accuracy, and for TRIOS 3, RL improved accuracy overall (Revilla 2020.a, Revilla 2020.b).

iTero and TRIOS 3 use confocal microscopy, while CEREC Omnicam uses active triangulation technology (Revilla 2020.a, Revilla 2020.b). It remains uncertain whether systems using the same technology will benefit from the lighting conditions tested in these studies. Additional studies are recommended to fully understand the impact of lighting conditions on the accuracy of the available IOSs (Revilla 2020.a, Revilla 2020.b), and meanwhile, as with other parameters, may it be generally recommended to follow the manufacturers' instructions.

Scanning strategy

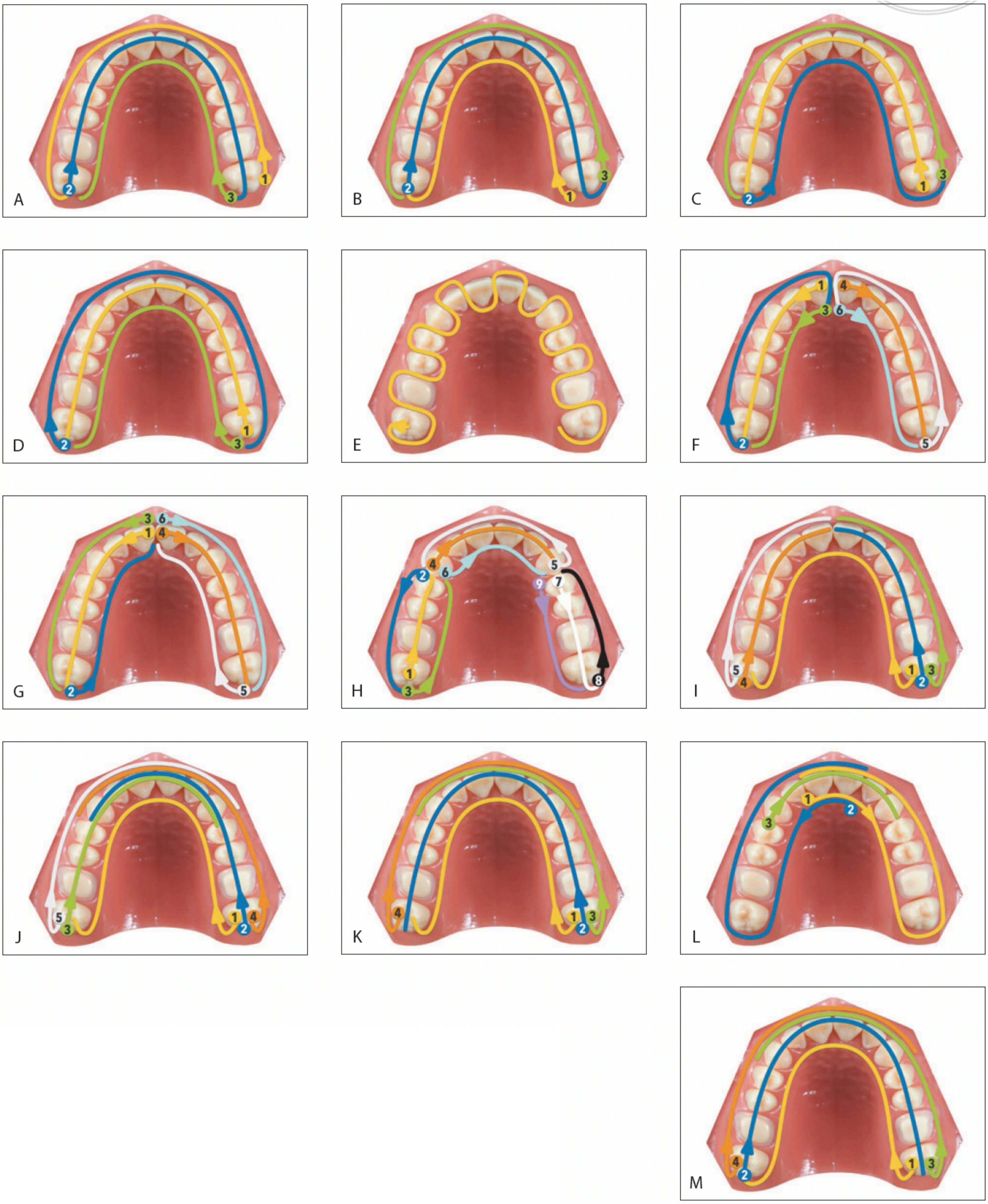
Manufacturers recommend specific scanning strategies for each intraoral impression device.

Scanning strategies may refer to several factors implied in the scanning sequence, such as the scanning path, the number of scans proposed for the scanning strategy, and the resolution.

There is a consensus that the scan strategy should begin preferably at broad surfaces, e.g., the occlusal surfaces of posterior teeth (Medina-Sotomayor 2018, Passos 2019, Revilla 2020.a, Revilla 2020.b). This provides the scanning software with enough information for the initial stitching of images and to easily recapture the scanning flow if the tracking is lost.

Figure 4: Graphic representation of the scanning paths proposed by Passos et al. (Passos 2019).

Reprinted from Passos et al. (Passos 2019) with permission granted by the author and the publisher (Quintessence Publishing Co, Inc):



Other studies also reported on the following scanning strategies, which are all included within the proposed scanned strategies published by Passos et al. (Passos 2019):

- to scan 1st the occlusal facets (creating a digital scaffold), then vestibular or lingual/palatal, and vice-versa (Güth 2016, Kachhara 2020, Medina-Sotomayor 2018, Miyoshi 2020, Müller 2016, Passos 2019).

- to complete one sextant (Medina-Sotomayor 2018, Passos 2019), or quadrant (Gintaute 2019, Medina-Sotomayor 2018, Muallah 2017, Passos 2019), then continue to the next.

- to zigzag the occlusal or incisal sections from vestibular to lingual/palatal (Gintaute 2019, Kachhara 2020, Medina-Sotomayor 2018, Müller 2016, Passos 2019), or to swipe smoothly one part (e.g., vestibular), and then complete the other sections (Gintaute 2019, Güth 2016, Kachhara 2020, Medina-Sotomayor 2018, Müller 2016, Passos 2019).

Scanning strategies may also refer to the number of scans that are taken and superimposed, or to the scan resolution:

- a one-step approach, by scanning both the scan body and or tooth preparation and surrounding structures together (Motel 2020).

- a two-step approach, by scanning an initial scan without the scan body and with provisional crown or pre-preparation, and adding a final scan with the scan body in place and or the preparation (Motel 2020).

- standard resolution (Chiu 2020).

- high resolution (Chiu 2020).

In an in-vitro study assessing the impact of four scanning strategies (Figure 4: D, E, F, H) in the in-vitro accuracy of a complete maxillary arch scanned using four IOSs, the results supported that each IOS performed better results with a specific strategy, yet only iTero showed a significant difference between the accuracies of the different strategies, favoring a zigzag strategy (Figure 4: E). CEREC Omnicam, True

Definition (3M, St. Paul, MN, USA), and TRIOS 3 revealed a tendency for better accuracy with strategies F, H, E (Figure 4), respectively, yet without significant differences. Additionally, accuracy differences were not statistically significant among IOSs. It was concluded that some IOSs are more reliant on the scanning protocol than others (Medina-Sotomayor 2018). In agreement with these findings, Müller et al. (Müller 2016) revealed that the accuracy of TRIOS Pod (3 Shape, Copenhagen, Denmark) was not significantly affected by their three tested scanning strategies (Figure 4: A, B and E), although strategy E, in zigzag, showed the worst accuracy.

Passos et al. (Passos 2019), analyzed the influence of different scanning strategies (Figure 4) on the accuracy of complete arch STLs taken with Primescan (Dentsply Sirona Inc, York, PA, USA) and CEREC Omnicam. The findings of their in-vitro study revealed an influence of the scan strategy on the accuracy of both IOSs. Strategy M showed the best outcomes for both scanners. It is important to note that strategy M is similar to strategy B (Güth 2016, Kachhara 2020, Medina-Sotomayor 2018, Miyoshi 2020, Müller 2016), with the difference that it overlaps scanning of the anterior section with a partial fourth vestibular scanning swipe until the canine. Passos et al. find a significant difference between scanning strategy B and M with CEREC Omnicam. Other studies that do not include strategy M in their scanning strategies fail to find a significant difference between scanning strategies when analyzing CEREC Omnicam (Medina-Sotomayor 2018).

Motel et al. compared the difference in accuracy between two strategies for implant impression using the TRIOS 3 scanner in an in-vitro study (Motel 2020). The first strategy involved a one-step approach by scanning both the scan bodies and surrounding structures together, whereas the second strategy combined an initial scan without the scan bodies and a final scan with the scan bodies in place. The authors concluded that the one-step scanning strategy achieved significantly higher accuracy compared to the two-step approach.

Chiu et al. (Chiu 2020) evaluated whether the resolution (high vs. standard resolution) impacted the accuracy of STLs recorded with TRIOS 3. No significant differences were observed between standard resolution and high resolution; hence standard resolution was recommended.

Partial vs. full arch scan

Since an intraoral digital impression system cannot capture the whole dental arch with a single image, as happens with the optical laboratory scanner, multiple images of limited areas are connected and stitched together to construct the whole image. It has been shown that the accumulation of errors increases as the range of the impression expands (Abduo 2018, Ahlholm 2018, Ender 2016, Ender 2019, Mangano 2017, Robles-Medina 2021).

When using an IOS, limiting the extension of the impression limits the cumulative errors, and increases the accuracy of the registration (Ender 2016). For this reason, limiting the extension of the impression, when possible, for example, when the indication of the impression is a single reconstruction, may improve the outcome of the treatment (better fit of the reconstruction, improved contact points, or occlusion). On the other hand, partial scans also have disadvantages, such as reduced options for articulator mounting or reduced information about the contralateral teeth.

1.7 Accuracy

Accuracy is one of the main research interests in prosthodontics, material science, and also in the field of IOSs (Abduo 2018, Ender 2016).

As discussed in the introduction, many factors may play a role in the accuracy of STLs resulting from an intraoral digital impression, such as: the IOS system used, the use of powder, the lighting conditions, the scanning strategy, or the experience of the operator.

When discussing accuracy, we need to consider what is clinically acceptable for each treatment. The accuracy or fit required for an orthodontic aligner or for a bleaching appliance may not be clinically acceptable for a crown or for an implant fixed dental prosthesis (FDP). It may be assumed that fixed prostheses (onlays, veneers, crowns on teeth, or implants) require the highest accuracy, and hence the clinical acceptability of discrepancies should be relatively limited. This needs to be taken into consideration when choosing an impression method, and for this reason, the accuracy of the conventional and the digital impression methods are frequently investigated (Abduo 2018, Ahlholm 2018, Ender 2016, Ender 2019, Mangano 2017, Mangano 2019, Medina-Sotomayor 2018, Passos 2019, Robles-Medina 2021).

Classically, the accuracy of techniques and materials to fabricate crowns was accomplished by evaluating the marginal fit (McLean 1971, Martínez-Rus 2011, Pak 2010).

1.7.3 Marginal fit

Marginal fit is one of the most important criteria in establishing the long-term functional success of restorations (Pak 2010). It is necessary to minimize the marginal gap since a significant space between the tooth and the restoration exposes the luting material to the oral environment, thus resulting in a more aggressive rate of cement dissolution caused by oral fluids and chemo-mechanical forces (Jacobs 1991). The consequent micro-leakage may result in inflammation of the periodontal tissues, secondary caries, and subsequent crown failure (Martínez-Rus 2011).

However, no consensus exists on what constitutes a maximum clinically acceptable marginal gap width. Values in the range of 50–200 μm have been reported, suggesting the absence of an objectively accepted threshold (Martínez-Rus 2011). Most investigators use the criteria established by McLean and von Fraunhofer, who, after examining more than 1000 crowns, concluded that 120 μm was the maximum tolerable marginal opening (McLean 1971, Martínez-Rus 2011, Zarauz 2016).

1.7.4 Digital accuracy

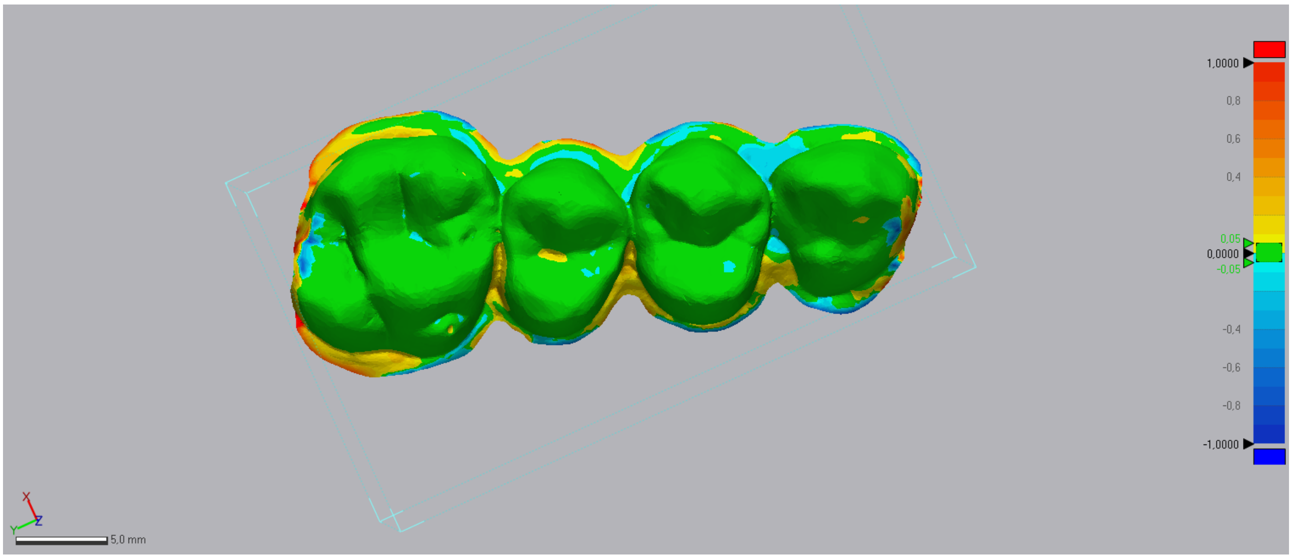
When evaluating digital *accuracy*, two independent factors have to be considered: *trueness*, defined as the closeness of agreement between a measurement result and a real value, and *precision* describing the closeness of multiple repeated measurements (ISO 12836:2015) (Ender 2019).

The most common method for measuring digital accuracy is by calculating the deviation of the test scan from the reference scan after a best-fit alignment process, where the reference and test scans are superimposed using an iterative closest point algorithm in a metrology software (Abduo 2018, Medina-Sotomayor 2018).

The deviation of a test scan from the reference scan may be considered equivalent to evaluating the marginal fit in classical accuracy analysis. Nevertheless, some differences need to be understood for the interpretation of digital accuracy analysis.

When the test scan and the reference scan are superimposed, the deviation at each point may be either positive or negative, as the superimposition method is done by best fit, where the two scans fit in the closest agreement possible (Abduo 2018, Medina-Sotomayor 2018). The metrology softwares report a series of parameters (reported below: parameters for digital accuracy analysis), and a color map which allows a visual evaluation of the magnitude and the direction of the deviation (Figure 5).

Figure 5: 3D compare color map visualization from software Geomagic Control X:



Accuracy values reported in different studies, range between 2 – 903 microns (Abduo 2018, Amin 2017, Canullo 2021, Chebib 2018, Chiu 2020, Doukantzi 2020, Ender 2016.a, Ender 2016.b, Ender 2019, Kim 2018, Medina-Sotomayor 2018, Mehl 2009, Müller 2016, Nagy 2020, Passos 2019, Revilla 2020.a, Revilla 2020.b, Revilla 2021, Waldecker 2021.b, Yilmaz 2021).

The accuracy of IOSs was initially significantly worse than conventional impressions (De Oliveira 2020, Mangano 2017). Over the last decade, technological developments have allowed a significant improvement in the accuracy of IOSs (De Oliveira 2020), to comparable levels of conventional impressions on single-unit and short-span FDP on teeth (Hasanzade 2019, Zimmermann 2020) and implants (Mühlemann 2018, Ahlholm 2018, Mangano 2019).

However, it may be noted that the range of accuracy is wider for digital impressions (2 - 903 microns) than for conventional impressions (50 - 200 microns). Factors influencing the accuracy of digital impressions need to be carefully considered to limit inaccuracies.

1.7.5 Parameters for digital accuracy analysis

Average absolute deviation

The average absolute deviation (AAD) is the average of the sum of deviation values between the predicted values and observed values.

It is a straightforward parameter, with many research groups reporting this value, which is advantageous for comparability purposes (Ender 2016, Ender 2019, Nagy 2020, Revilla 2020.a, Revilla 2020.b, Waldecker 2021). However, in the case of digital accuracy analysis, where the test scan and reference scan are superimposed by the best fit method, the positive and negative deviations cancel each other, reducing the AAD value, and diluting the interpretative capacity of the parameter overall.

Positive and negative averages

Positive and negative averages are similar to AAD, averaging the sum of the deviations, with the difference that it reports two separate values, on the one hand, the average of the positive deviations, and on the other the average of the negative deviations.

It is a fairly straightforward parameter, like the AAD, with the advantage that positive and negative deviations do not neutralize each other, and are helpful for the understanding of the direction of the deviation. This is helpful to deepen the understanding of where the IOS systems are most frequently showing inaccuracies and if these inaccuracies are positive or negative, which may also be seen in the color map visualization (Figure 5).

Root Mean Square (RMS)

RMS is defined as the arithmetic mean of the squares of a set of numbers (the errors or deviations). In estimation theory, the RMS deviation of an estimator is a measure of the imperfection of the fit (accuracy) between the predicted values and observed values or the quadratic mean of these differences (Hyndman 2006).

The RMS deviation aggregates the magnitudes of the errors in predictions for various data points into a single measure of predictive power, it is scale-dependent, always non-negative, and a value of 0 (rarely achieved in practice) would indicate a perfect fit to the data. In general, a lower RMS is better than a higher one (Hyndman 2006).

In IOS accuracy studies, it is a frequently used value (Chebib 2018, Doukantzi 2020, Revilla 2021).

One of its advantages is that the negative and positive deviations do not cancel each other (which dilutes the interpretative capacity of a parameter as discussed previously for the AAD) as the formula transforms the negative deviations into positive values by applying the square root, and then all the squared root errors are averaged.

Removal of extreme outliers

Removal of the outliers is proposed in many studies (Ender 2016, Ender 2019, Mehl 2009, Müller 2016, Revilla 2020.a, Revilla 2020.b).

There are several ways to remove outliers: eg. to remove the error values that lie more than 3.0 times the interquartile range below the first quartile or above the third quartile (Revilla 2020.a, Revilla 2020.b); or report the mean deviation between the 90 and 10 percentile values (Ender 2016, Ender 2019, Mehl 2009, Müller 2016).

Removing the outliers has statistical advantages, as overall, the evaluation and discussion of the accuracy values centered in the digital impression is of most importance, as it is where the reconstructions will usually be fitted, and removing outlier values, which usually are located in the margins of the digital impressions allows us to focus on the accuracy where it mostly matters.

However, as the positive and negative values remain to neutralize each other (unless the 90/10 positive and negative percentile values are reported), this strategy, together with removing high deviation values, may dilute the outcomes considerably, with reported values being low and making it difficult to find differences between groups; hence interpretation should consider this factor.

1.7.5 Challenges for accuracy evaluation

Accuracy evaluation, whether it be analog or digital, has several challenges.

Choosing the parameter to analyze, from the multiple options available, choosing the study design (in-vivo or in-vitro), determining the methodology, choosing the most suitable reference model, etc.

The parameters to analyze digital accuracy were described in the previous section.

In the next section, the determinants involved in the choice of the reference model and study design, in-vivo or in-vitro, will be introduced.

Reference model / in-vivo or in-vitro model

One of the challenges for accuracy measurements, is rendered by the 'impossibility' to measure 'real' trueness in-vivo. For real trueness measurements, the real dimensions of the test subject must be known (ISO 5725-1) (Ender 2016). For this purpose, the structure to be evaluated should be scanned with the highest accuracy, provided by a reference scanner (Ender 2016). In in-vivo research, the patient's mouth cannot be directly introduced and digitized in a reference scanner. Most studies investigating accuracy have chosen an in-vitro model for this reason (Canullo 2020, Chiu 2020, Doukantzi 2020, Ender 2019, Gimenez 2014, Gimenez 2015, Keul 2020, Kim 2018, Mehl 2009, Müller 2016, Nagy 2020, Revilla 2020.a, Yilmaz 2021, Waldecker 2021).

Using conventional impressions with elastomeric materials and indirect digitization of the master cast in a reference scanner has been previously utilized to create reference models for in-vivo evaluation of trueness and precision (Keul 2020, Nedelcu 2018, Sason 2018, Revilla 2020.b). When using this technique, the reference model is not perfect, as it incorporates the inaccuracies of the conventional impressions and casting techniques. Nevertheless, full-arch impressions obtained with addition silicone or polyether materials have proven high accuracy when used according to the manufacturer's instructions (Keul 2020, Nedelcu 2018, Sason 2018, Revilla 2020.b).

It can be assumed that in-vivo investigations will result in lower accuracy outcomes than in in-vitro designs (Ender 2019, Waldecker 2021).

However, findings from in-vitro research need to be corroborated in in-vivo studies, as in-vitro models are not lacking their limitations. The oral environment conditions (cheeks, tongue, saliva, breath, moving patient, limited access, especially in the retro-molar area of posterior teeth), which may negatively affect the accuracy of IOSs (Richert 2017), are lacking in the in-vitro design, only providing an insight into the actual accuracy of IOSs. Therefore, the results need to be interpreted with caution (Ender 2019).

For this reason, both in-vitro and in-vivo studies, with their respective limitations, need to be proposed and conducted to advance the overall understanding of IOSs accuracy.

1.8 Other influencing factors impacting IOS choice

Other than accuracy, or as the accuracy of IOSs improves and becomes less critical, other aspects gain relevance in the choice of the impression method.

Factors such as the costs (initial purchase, consumables and regular maintenance) (Roth 2020), the patient’s (Manicone 2021) and operator’s perception (Sivaramakrishnan 2020, Yilmaz 2021), the time required to perform an impression (De Oliveira 2020, Manicone 2021), or the learning curve (Waldecker 2021.a) may play a decisive role.

1.8.1 Costs

Purchasing costs are higher for digital impression systems initially, however less consumable materials and storing space are necessary (Mangano 2017, Mühlemann 2018). Joda et al. calculated the cost efficiency during impression taking for posterior single implant crowns to be 30 CHF and 24 CHF for digital and conventional impressions, respectively (Joda 2015).

1.8.2 Patient preference

Previously published studies comparing the patient preference between digital and analog impression systems have shown mostly consistent outcomes in favor of the digital impression systems (De Oliveira 2020, Joda 2016, Manicone 2021, Sailer 2017, Sailer 2019, Sivaramakrishnan 2020, Wismeijer 2014, Yuzbasioglu 2014).

The advantages of digital impressions mentioned previously, such as reduced gagging, and avoiding the pressure of the trays in the oral cavity (Richert 2017, Nagy 2020), may be responsible for the consistent patient preference of digital over conventional impressions. Impression time seems to have less impact, as impression times for digital and conventional have been reported to range within similar ranges (6 - 19 min) (Mühlemann 2018); hence it cannot be assumed that a faster impression is linked with a higher patient preference.

Moreover, Sirivaramakrishnan et al. (Sivaramakrishnan 2020) compared patient preference and the time required for digital and conventional impressions. While their findings revealed patient preference towards digital impressions, these findings were not linked with faster impression times, as digital impressions required statistically more time than conventional impressions.

The marketing effect that seeing the digital model on the screen has on the patient, may play a key role in such a clear preference of digital over conventional impressions. Nevertheless, this requires clarification in future research.

1.8.3 Operator preference

On the other hand, operator preference does not show such a clear advantage for digital impressions compared to conventional. Age of the operator seems to play a role in the preference towards digital or conventional impression systems (Lee 2013), when the operators are inexperienced with the digital impression system. In a study published by Lee et al., it was shown that dental students preferred digital impression procedures. Meanwhile experienced clinicians tended to prefer conventional over digital impressions (Lee 2013). In a study of the computer usage behaviours of university faculty members, Rosseau et al. (Rosseau 1998) found that although staff members, older and younger, regularly used computers in their line of work, older staff members used fewer software applications. There was no indication that older faculty members avoided using computer applications, they simply used the programs they required, leading them to be labelled 'selective' users (Rosseau 1998). It is therefor reasonable that this selectivity is applied to the impression method preferred by older clinicians, who are already acquainted with conventional impression methods, especially when they are not experienced with digital impression systems. Meanwhile, students with no experience with either digital or conventional impression systems prefer digital impressions (Lee 2013). Hawthorn et al. (2007) argues that older people are not necessarily avoidant of technology; rather they avoid making errors by limiting the tasks they attempt to perform.

1.8.4 Time efficiency

User-friendliness gains importance, and the time required to complete a task is commonly used to evaluate user-friendliness (De Oliveira 2020, Kim 2016, Mühlemann 2018, Roth 2020, Sivaramakrishnan 2020, Waldecker 2021.a). In a world where time is money, technology strives to help improve efficiency (reduce the required time for a certain task, hopefully maintaining the same quality) (Mühlemann 2018). Multiple factors have an influence on the required time to perform conventional or digital impressions.
Time efficiency of the complete prosthetic workflow includes impression taking, laboratory workflow and delivery of the reconstruction (Mühlemann 2018). In this thesis, the focus is directed at the time efficiency relevant to the impression process.

Studies evaluating the time required for conventional impression taking ranged between 4.3 and 28.47 min (De Oliveira 2020, Mühlemann 2018, Sivaramakrishnan 2020), while the studies evaluating the time required for digital impression taking showed times between 19 seconds and 30.8 min (complete, double arch and occlusion) (Chiu 2020, De Oliveira 2020, Mühlemann 2018, Passos 2019, Roth 2020, Sivaramakrishnan 2020, Yilmaz 2021, Waldecker 2021.a). As it may be observed, the range is wide for both pathways, as many factors play a role in the time required of the included studies.

For conventional impressions, factors that require clinical time in the impression workflow are: tray selection and preparation, including screw-access perforation (for implant open tray impressions), adhesive application and material setting time. The required overall time will be affected by the experience of the operator, for example, if an experienced operator can precisely anticipate the size and placement of the access hole for the impression transfer in the tray, or if on the other hand, an inexperienced operator needs to mark the tray before perforation, and make progressive adaptations before validation. Experience plays an enormous role in the overall time required to take conventional impressions, even though some aspects of the process should be predictable, like the material setting time. There is a wide variety of working and setting times available commercially, depending on the different needs of the operator, yet the manufacturer reports these working and setting times in the material instructions (Ritter 2017).

Digital impressions are affected by other factors, such as: extension (full-arch vs. quadrant impressions) or patient-related factors (cheek flexibility, tongue interference, salivary rate, breath, preparation margin depth) (Richert 2017). Other factors, as IOS system used, software version, or operator experience, may also play a role in the time required to take a digital impression, but remain unclear.

The learning curve for IOSs is a matter of recent research attention (Kim 2016, Roth 2020, Waldecker 2021.a).

Learning curve is defined as the acquisition of a skill over time until plateau performance is achieved (Pernar 2017).

Time required to complete a task is used as a measure of the learning curve in robotic general surgery (Pernar 2017). Time has also been used to evaluate the learning curve of IOSs (Kim 2016, Roth 2020, Waldecker 2021.a). Roth et al. used a hybrid model to evaluate learning curve, by measuring in-vivo scanning time and image number (count of images created by IOSs during the scanning process) (Roth 2020). Kim et al. compared model scanning times before and after four training sessions (in-vivo) (Kim 2016), and Waldecker et al. evaluated the effect of the number of training sessions (1, 2 or 3) on model scanning times of dental students (Waldecker 2021.a). It was shown that repeated practice (1-4 sessions) reduced scanning time, yet as no control group was used, it was not possible to determine if proficiency had been reached (Kim 2016, Roth 2020, Waldecker 2021.a). Studies evaluating time efficiency of IOSs were performed with either experienced operators (Chiu 2020, Yilmaz 2021), or with inexperienced operators (Kim 2016, Roth 2020, Waldecker 2021.a). Age was not controlled in any of these investigations.

1.9 Age and learning

An assumption exists within the general population, that older adults have negative attitudes and difficulty in learning new technology, specially when compared with younger cohorts (Broady 2010, Czaja 1998).

Being too old to learn to use computers or technological devices is a belief held by many older people, even before attempting to use computers (Broady 2010). However, the negative self-beliefs held by the older students may well be ascribed not solely to their poor performances, but also to the negative stereotypical views held by their tutors, as well as the fact that the tutors expected them to learn new skills not commensurate with their existing skills and knowledge more rapidly than they were capable of doing (Broady 2010).

Botwinick et al. (Botwinick 1967) found that older participants displayed more caution than their younger counterparts in responding to measures of cognitive ability, actively choosing to perform slower to increase their response accuracy. This finding may help to understand time differences in performance on computers between younger and older adults, in that perhaps older people prefer to take longer to ensure they do not make errors in completing any computer task.

During ageing, declined overall volume of hippocampus, especially in people after 60 years has been reported (Zhang 2021). The hippocampus is pivotal for cognition, memory processing, and therefor for learning in the human brain (Zhang 2021).

Individual differences in cognition and behaviors have been reported in neuroscience researches (Zhang 2021).

Additionally, no age effect is evident among experienced users (Charness 2001). The number of errors appears to be uniform across age groups, and although older experienced users perform slower than younger experienced users, the difference is smaller than that found for novice users. Extensive practice on a task diminishes age differences in reaction time (Charness 2021, Zhang 2021).

2 Justification

As discussed in the introduction, accuracy has played a central role in the validation of IOSs as an alternative to conventional impressions (Mangano 2017). Impressions, whether conventional or digital, need to be sufficiently accurate. After a long technological development, IOSs are becoming increasingly accurate (Mangano 2017). With this prospect in mind, other factors gain relevance, such as the time required to complete a digital intraoral impression, or the learning curve it may be needed to acquire the skills to perform said impression in a reasonable amount of time. Several factors affecting scanning times, learning curves and accuracy have been previously investigated and mentioned in the introduction, such as scanning path (Müller 2016, Passos 2019), lighting conditions (Revilla 2020.a, Revilla 2020.b), scanning extension (Roth 2020), or number of training sessions (Waldecker 2021.a, Waldecker 2021.b). Evaluating whether factors such as the operator's age, previous intraoral scanning experience, the scanning system itself or the software version influence the performance and learning curve of IOS operators in a clinical setting needs further clarification. As mentioned previously, older clinicians may not necessarily be averse to learning new technology, they are simply more selective with the tasks they want to learn or incorporate into their practice. Gaining a deeper, evidence based knowledge into how long it may be required to gain the skills necessary to perform adequate digital impressions, in terms of scanning time and accuracy, and if different impression systems may impact this process, acquires importance, also in consideration with the investment required to purchase these systems, and the everyday growing range of options available.

Additionally, it remains unclear whether scanning time has an impact on the accuracy of the resulting STLs.

3 Objectives

For this purpose, and with the previously mentioned questions in mind, the objectives of the current investigation were developed:

1. To evaluate whether the *operator's age* (≤ 25 years, ≥ 40 years) influences the performance and the learning curve of inexperienced IOS operators compared with experienced operators.
2. To evaluate whether the *type of IOS* influences the performance and the learning curve of inexperienced IOS operators compared with experienced operators.
3. To evaluate whether the *software version / study site* influences the performance and the learning curve of inexperienced IOS operators compared with experienced operators.
4. To evaluate whether the *operator's age* (≤ 25 years, ≥ 40 years) influences the accuracy (trueness and precision) of STLs registered by inexperienced IOS operators compared with experienced operators.
5. To evaluate whether the *type of IOS* influences the accuracy (trueness and precision) of STLs registered by inexperienced IOS operators compared with experienced operators.
6. To evaluate whether the *software version / study site* influences the accuracy (trueness and precision) of STLs registered by inexperienced IOS operators compared with experienced operators.
7. To evaluate whether scanning time and accuracy are correlated.

Null hypotheses

Therefore, the null hypotheses were established as:

1. The operator's age does not influence the performance and learning curve of inexperienced IOS operators.
2. The intraoral scanning system does not influence the performance and learning curve of inexperienced IOS operators.
3. The software version / study site does not influence the performance and learning curve of inexperienced IOS operators.
4. The operator's age does not influence the accuracy of STLs obtained by inexperienced IOS operators.
5. The intraoral scanning system does not influence the accuracy of STLs obtained by inexperienced IOS operators.
6. The software version / study site does not influence the accuracy of STLs obtained by inexperienced IOS operators.
7. The scanning time and accuracy are not correlated.

4 Materials and Methods

4.1 Study design

This clinical, prospective, multi-centric study was performed in the Faculty of Dentistry of University Complutense of Madrid (center 1) and the University Clinics of Dental Medicine of University of Geneva (center 2). Consequently, the study protocol was submitted and approved by the local ethical committees of the canton of Geneva (No. 2017-01717), and by el Comité ético de investigación clínica del Hospital Clínico San Carlos (No. 17/367-E).

4.1.2 Included intraoral scanners

Two IOS systems, both Conformitè Europëenne (CE), were evaluated: TRIOS 3 (3 Shape, Copenhagen, Denmark) and True Definition (3M, St. Paul, MN, USA). IOSs characteristics are shown in Table 4.

Table 4: Intra-oral scanners (IOSs) characteristics:

IOS	Study abbreviation	Software version	Technology	Description
TRIOS 3	S1	1.18.1.2 (center 1) / 1.18.1.3 (center 2)	confocal microscopy / video-based	The projection of optical slices on the object reflects focused and defocused images. The sharpness of the image determines the distance to the object, correlating to the focal length of the lens (Kachhara 2020).
True Definition	S2	5.3.1 (center 1) / 5.4 (center 2)	active wavefront sampling / video-based	Distance and depth information are derived and calculated from the pattern produced by each point formed by the rotating module around the optical axis (Logozzo 2014).

4.1.2 Study groups

In order to evaluate if age has an influence on the learning curve of clinicians inexperienced with IOSs, two test groups (with marked age difference) and one control group were established:

Test Group 1 (≤ 25): young dental students equal to or under the age of 25, with no previous experience in the use of IOSs.

Test Group 2 (≥ 40): dentists equal or over the age of 40, with no previous experience in the use of IOSs.
Control Group (control): clinicians with experience in the use of IOSs, with no age restriction. Experience was determined by the completion of at least 100 scans (Gimenez 2014).

4.1.3 Sample size calculation

A sample size calculation was performed, including an alpha error of 0.05, a 1-beta error of 0.8, for three groups, and an effect size of 0.3 (Schäfer 2019), based on the results from a similar study (Kim 2016). In that study, two groups of oral hygienists showed an improvement in time registrations of 23% and 24%, respectively, after training. The sample size calculation resulted in a minimum of 30 operators. Finally, 36 operators were included between center 1 and center 2, 18 operators per center, to compensate for potential dropouts.

4.1.4 Patient selection

An in-vivo model was chosen. Ideally, a single patient would be selected, in order to evaluate participants under exact study conditions (same cheeks, same mouth opening etc). However, as scanning a single patient would not be acceptable for ethical reasons, six volunteer patients were recruited in each center, 12 in total. Fourth-year dental students, medically healthy, free of active oral inflammation and with sufficient mouth opening, who were interested in contributing to the advancement of research, and getting acquainted with IOSs were included as test patients.

4.1.5 Study schedule

All study operators (groups ≤ 25, ≥ 40, and control), completed a 4-session study schedule (Table 5) with each IOS, including three training sessions (one on typodont models (Frasaco GmbH, Tettnang, Germany), and 2 in-vivo), and 2 test scans (baseline and final). Each study session was spaced at least a week apart.
Study introduction, training sessions, and time recording were performed in each center by a trained investigator.

For logistical purposes, study operators and patients were organized into groups, which could be managed and appointed all together by the study monitor in each center. Each group (6 per center) was composed of an operator of each (test groups ≤ 25, ≥ 40, and control group) and a patient. This way operators completed the baseline and final scans on the same patient.

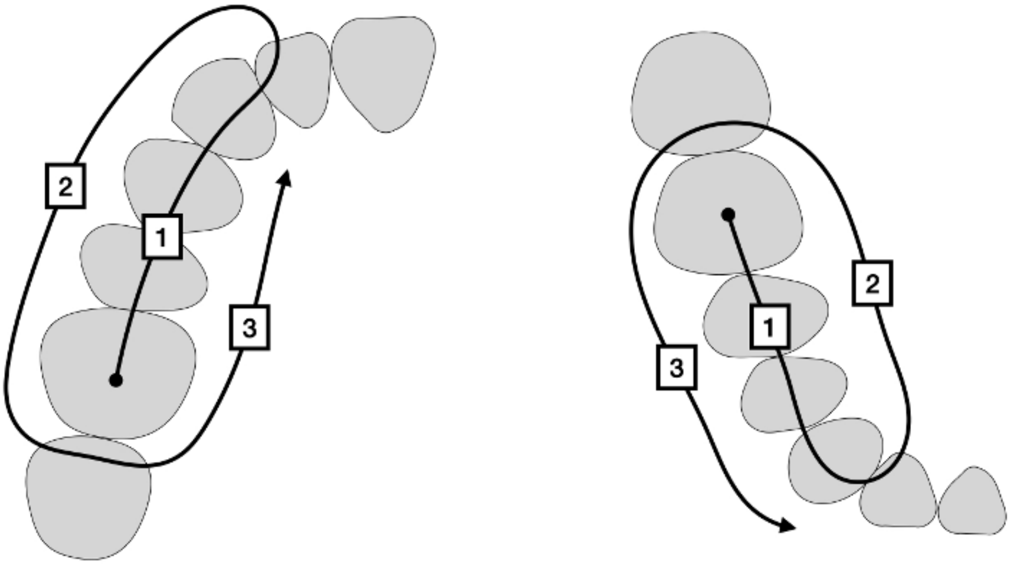
Table 5: Study schedule: task description in each session, time each operator and study subject are required to invest for study participation, per intraoral scanner (IOS):

Study session	Study task	Time needed by operator / per IOS	Time needed by subject / per IOS
1	Introduction to system and scan strategy	10 min (group)	/
1	Baseline scan with test patient	10 min (each)	30 min
1	Training with models	20 min (each)	/
2	Training with patient	20 min (each)	/
3	Training with patient	20 min (each)	/
4	Final scan with test patient	10 min (each)	30 min
Total time needed		90 min (1h, 30 min)	60 min (1h)

Single unit restorations and small fixed partial dentures (FPDs) are common indications in the dental practice (Ender 2016), and short span digital impressions have proven equally accurate to conventional impressions (Mangano 2017); hence it was considered appropriate for the current research to restrict the extension of the tested digital impressions to quadrant impressions. Additionally, it is also reasonable for inexperienced operators to begin the learning process with easier scenarios, and henceforth progress to more complex situations as they gain experience.

During the first study session, the study protocol and scan strategy (Figure 6) were introduced. Participants were requested to complete a partial scan extended from mesial of the canine to distal of the first molar of quadrants 1 and 4, including at least 3 mm of gingiva, and a bite registration, following the scan strategy (Figure 6). When S2 was being used, a thin layer of titanium dioxide powder (3M High Resolution Powder Sprayer, 3M) was applied on the surfaces to scan, as recommended by the manufacturer. The time required to apply the scanning powder was included as part of the scanning time.

Figure 6: Scan strategy for maxillary (left image) and mandibular (right image) arches, as recommended by the manufacturers of intraoral scanners:



Patients were all in a supine position, and all study scans were performed under the supervision and assistance (retraction and aspiration) of the trained investigator, with dental chair lights turned off (Revilla 2020.b). An impression was deemed satisfactory when the requested regions were registered, allowing minimal interproximal gaps. Advise was provided to follow the scanning path, keep a constant distance, and to avoid unnecessary over-scanning when possible. The time each operator spent filling in the laboratory order and scanning time were recorded in seconds (baseline computer time and baseline scan time). Following the baseline records, each operator performed a 20 minutes training of specific quadrant scanning on typodont models (Frasaco GmbH).

The second and third sessions were exclusively training sessions (20 minutes each), in which each study operator practiced scanning in-vivo by scanning each other.

In the fourth session, each study operator performed the final scan on their test patient. Again, the time required to complete the laboratory order and the scanning time were recorded in seconds (final computer time, and final scan time).

Since completing the study with the first IOS system implied some training for the inexperienced operators, which could potentially impact their performance when completing the study with the second IOS, half of the study participants initiated the study with Scanner 1 (S1) (TRIOS 3). The other half commenced it with Scanner 2 (S2) (True Definition).

Figure 7a, 7b and 7c: A clinical picture of quadrant 1 is shown (7a), and the corresponding complete scans with S1 (7b) and S2 (7c):

The STLs resulting from the baseline scanning session and the final scanning session were exported for accuracy analysis, as 'test' SLTs.

4.2 Reference model

To obtain the reference STL for each patient, a conventional impression was performed in each jaw, with 3M Stock trays (3M), and elastomeric material, polyvinyl siloxane heavy and light consistency (Wassel 2002), using a 1 step - double mix technique (Wassel 2002). The impressions were poured with type IV plaster (Fujirock EP, GC Europe, Leuven, Belgium), according to the manufacturer's instructions. Impression trays were removed from the stone model after 45 min. The models were stored at room temperature (23 °C) and ambient humidity. The models from center 1 were packaged with bubble plastic protection and sent to center 2, where all models were indirectly digitized using a laboratory scanner (Iscan D103i, Imetric 3D SA, Courgenay, Switzerland) with a reported scanning accuracy of 6 microns (Chebib 2018, Papaspyridakos 2012). Resulting STLs were imported into a metrology software (Geomagic Control X, 3D Systems Inc., Rock Hill, South California, USA) (version 2020.1.1) (Figure 8), trimmed mesial from the right canine, distal of the first molar, 3 mm from the gingival margin (Figure 9) and saved as 'reference' STLs (Figure 10).

Figure 8: Reference STL imported into Geomagic Control X:

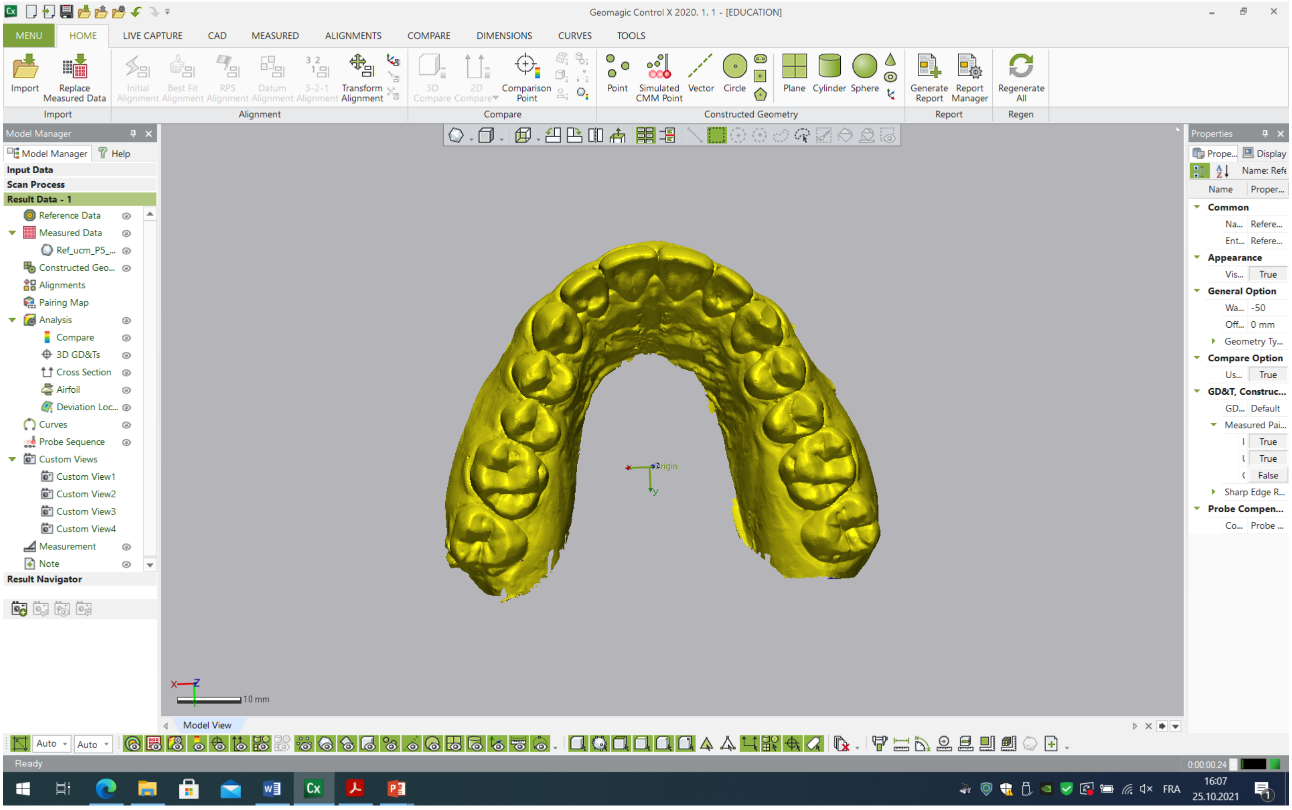


Figure 9: Trimming of STL:

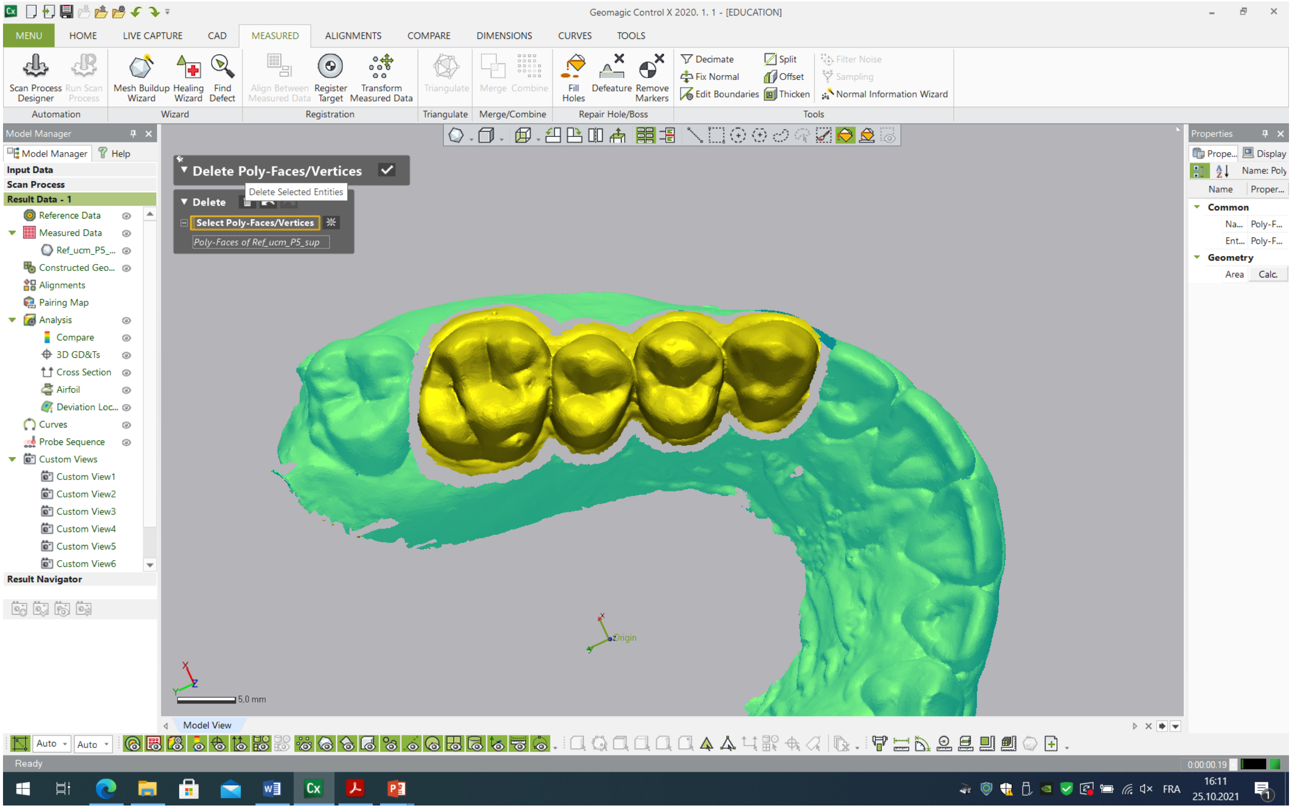
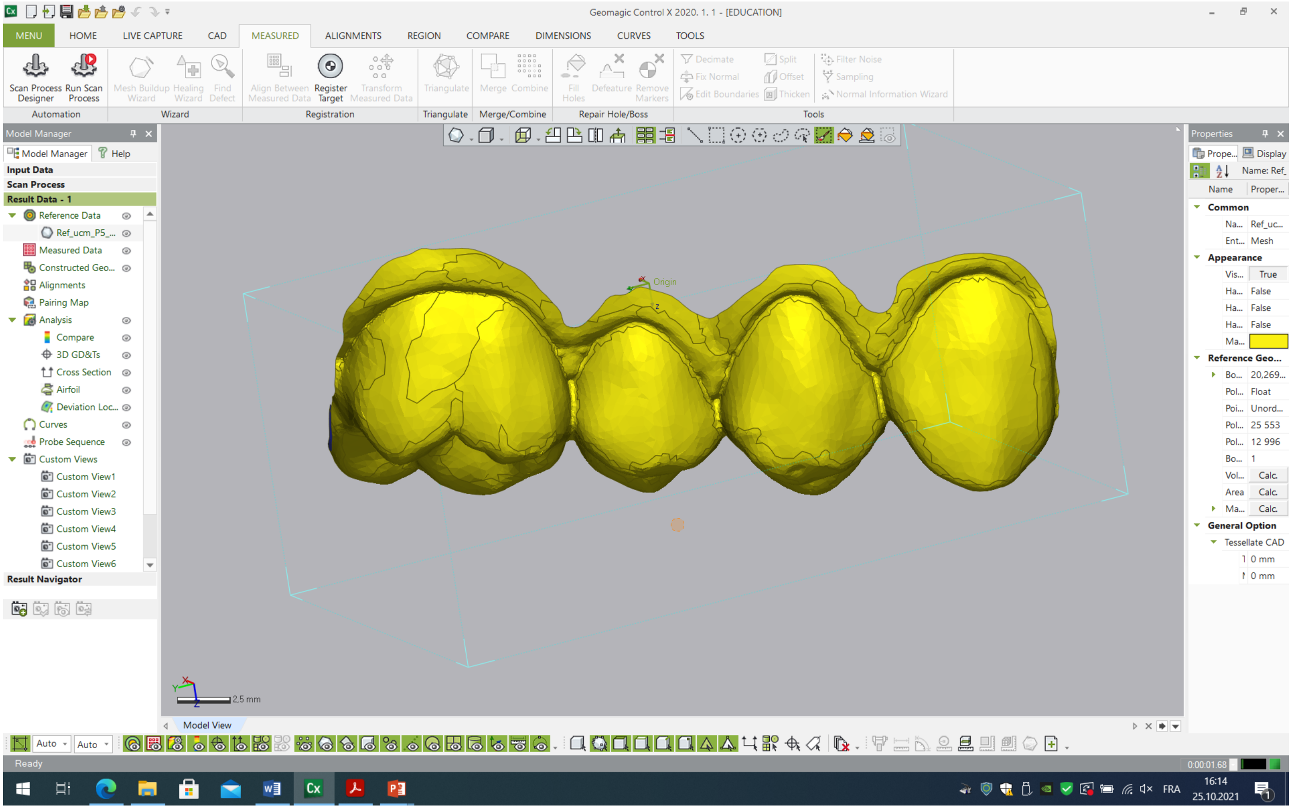


Figure 10: STL trimmed, and saved as reference model:



4.3 Assessments

4.3.1 Scanning time Performance

The performance was evaluated by comparing the time taken by each study group (≤ 25, ≥ 40, control) to complete the study tasks: (i) filling in the laboratory order (computer time) and (ii) completing a satisfactory quadrant digital impression with each IOS (scanning time), at baseline and final time-points. A clinical registry form was used to record the time required by each operator to fulfill the study tasks (Table 6).

Table 6: Clinical registry form (CRF) used to record the time required by each operator to fulfill the study tasks, before and after training, and with each intraoral scanner (IOS):

CRF	Subject code		xx	
IOS	S1		S2	
Session	Computer time	Scanning time	Computer time	Scanning time
Baseline	…. sec	…. sec	…. sec	…. sec
Final	…. sec	…. sec	…. sec	…. sec

4.3.2 Scanning time Learning curve

The learning curve was assessed by comparing the time improvement of each study group before and after training (between baseline and final scanning time-points).

4.3.3 Accuracy evaluation

The accuracy analysis was performed with software metrology software Geomagic Control X.

For accuracy analysis of the test scans of each patient, the following protocol was completed: the reference STL was imported into the software (Figure 8), trimming of the gingiva to a 3 mm contour was performed, as well as mesial of the canine and distal of the first molar (Figure 9). The trimmed reference STL was subsequently saved as reference model (Figure 10). Test STLs were imported one by one into the software (Figure 11), following the protocol: initial alignment, best fit (Figure 12), 3D compare (Figure 13).

Figure 11: Imported test STL into Geomagic control X:

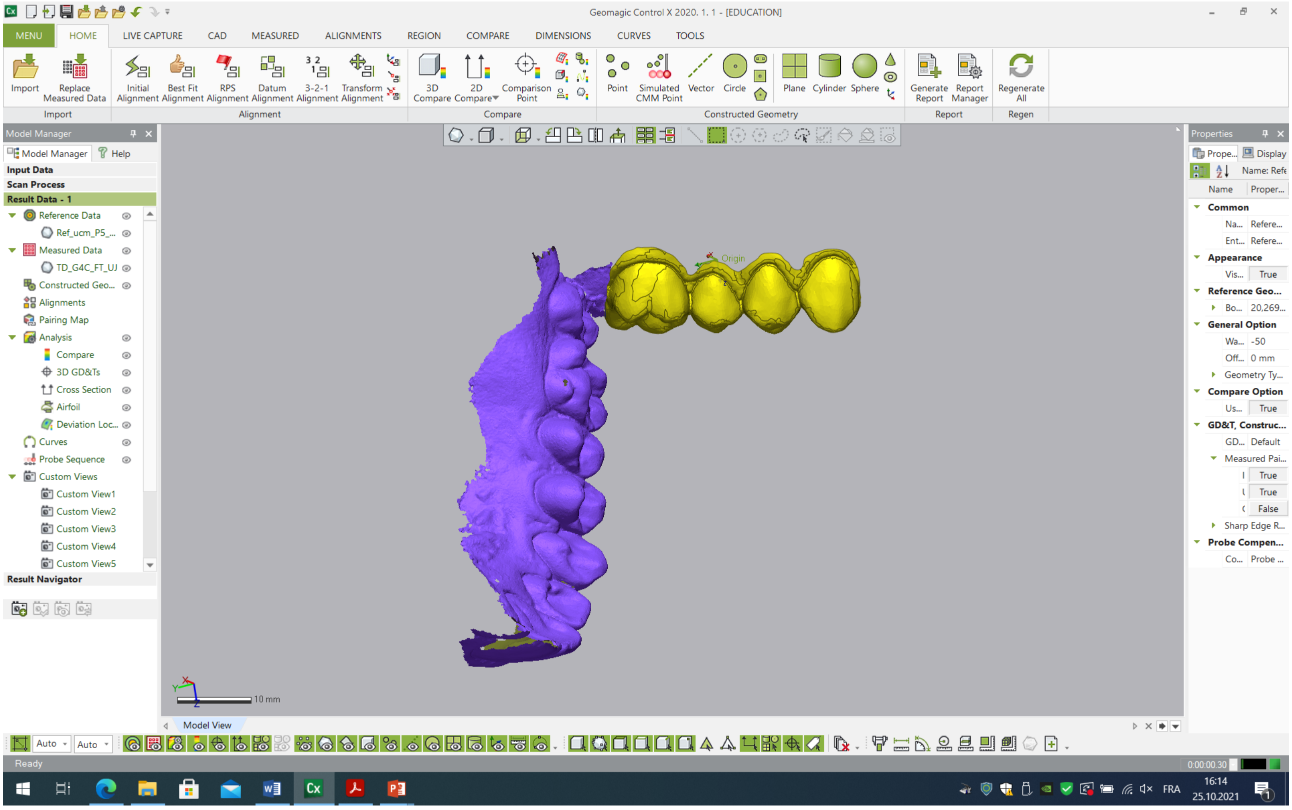


Figure 12: Best fit alignment of the reference model and test STL:

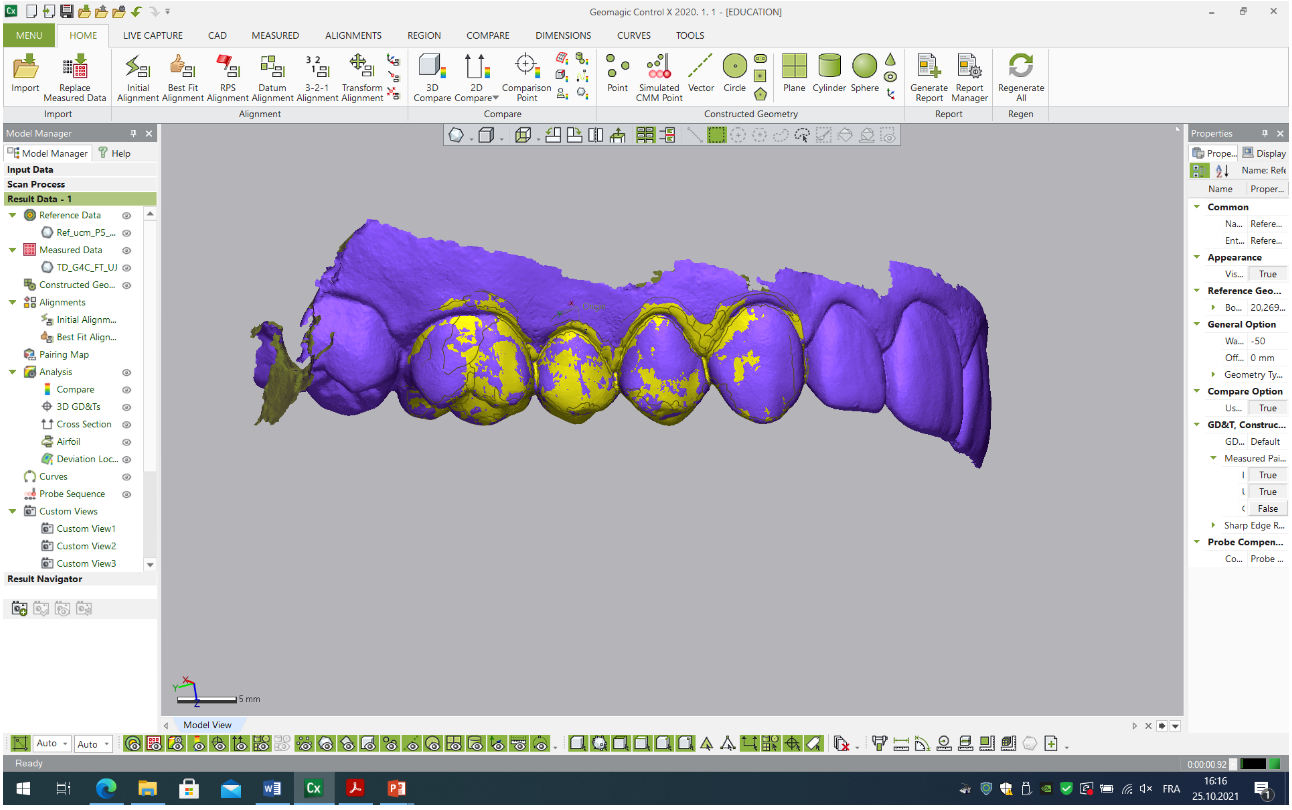
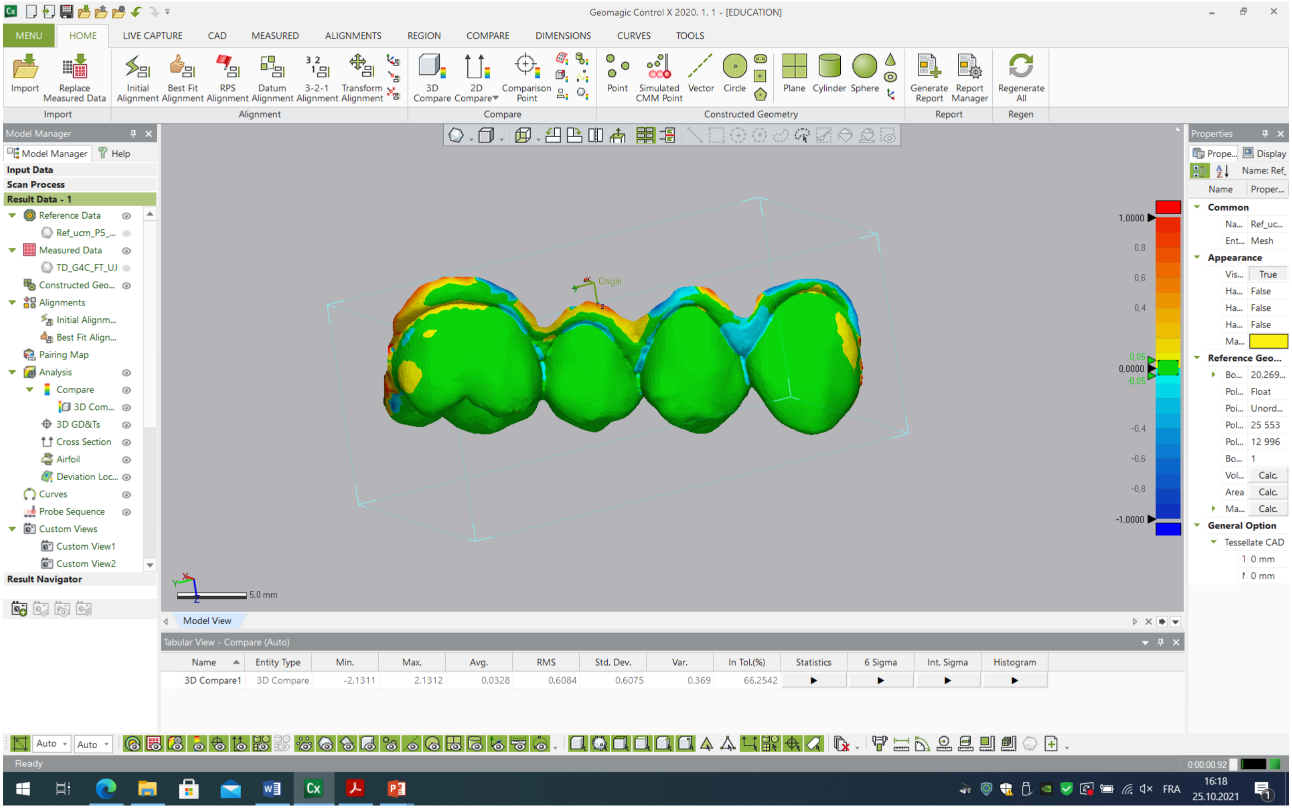


Figure 13: 3D compare:



Tabular View - Compare (Auto)

Name	Entity Type	Min.	Max.	Avg.	RMS	Std. Dev.	Var.	In Tol.(%)	Statistics	6 Sigma	Int. Sigma	Histogram
3D Compare1	3D Compare	-2,1311	2,1312	0,0328	0,6084	0,6075	0,369	66,2542	▶	▶	▶	▶

From the 3D compare data, the RMS (mean and standard deviation) were exported into an Excel file (Microsoft Excel for Mac, SV 16.52; Microsoft Corp). Root mean square (RMS) has been used for accuracy evaluations in several studies (Chebib 2018, Doukantzi 2021, Park 2019), as the outcome is a better representation of the deviation than the average deviation (which tends to 0), as positive and negative deviations neutralize each other. Another option would be to use positive and negative averages, which also do not neutralize each other, and are helpful for the understanding of the direction of the deviation. RMS was chosen due to its popularity (in comparison to positive and negative deviations), and for the fact that it simplifies an already multifactorial statistical analysis.

The mean values and the standard deviations (SD) of the RMS were utilized, which represent the trueness (RMS mean deviations) and precision (RMS SD) of the test STLs when compared to the reference model, according to ISO 5725 standards (Ender 2016). This analysis is a recognized method within accuracy studies and has been used in previous investigations (Ender 2016, Keul 2020, Medina-Sotomayor 2019, Güth 2016).

4.4 Statistical analysis

Independent variables

- Age (≤ 25 vs. ≥ 40 years old) of the operator
- Experience (inexperienced vs. experienced)
- IOS system (S1 vs. S2)
- Study site / software version (center 1/SV: 1.18.1.2 (S1) and 5.3.1 (S2) vs. center 2/SV: 1.18.1.3 (S1) and 5.3.4 (S2))

Dependent variables

- Computer time (baseline vs. final time-points)
- Scanning time (baseline vs. final time-points)
- Trueness
- Precision

4.4.1 Normality test

Normality of data distribution was tested using the Kolmogorov–Smirnov test.

4.4.2 Inferential statistics

All the statistical tests were performed at two tails and alpha = 0.05. All results were calculated with SPSS version 26 (SPSS, Chicago, IL, USA).

4.4.2.a Scanning time

A Pearson correlation was applied to evaluate the correlation: between operator's age and time performance (at baseline and final scanning), excluding group control.

An ANOVA of repeated measures test, with a Bonferroni correction, was applied to evaluate: inter-group (≤ 25, ≥ 40, control) performance (at baseline and final scanning); inter-system (S1 vs. S2) performance (at baseline and final scanning); site / software version (center 1/SV: 1.18.1.2 (S1) and 5.3.1 (S2) vs. center 2/SV: 1.18.1.3 (S1) and 5.3.4 (S2)) performance (at baseline and final scanning); and experience (inexperienced vs. experienced) performance (at baseline and final scanning).

For the intra-group learning curve evaluation (training effect), Paired student T-test was applied, evaluating changes within-group (between baseline and final scanning).

4.4.2.b Accuracy (trueness and precision)

A Kruskal Wallis test, with Dunn-Bonferroni post hoc was applied to evaluate inter-group (≤ 25, ≥ 40, control) trueness (mean RMS) and precision (RMS standard deviation), at baseline and final scanning sessions.

A Mann Whitney test was applied to evaluate the effect of experience (inexperienced vs. experienced), jaw (maxilla vs. mandible), and site / software version (center 1/SV: 1.18.1.2 (S1) and 5.3.1 (S2) vs. center 2/SV: 1.18.1.3 (S1) and 5.3.4 (S2)) on trueness (mean RMS) and precision (RMS standard deviation).

For the intra-group accuracy evaluation (training effect), a Wilcoxon signed-rank test was applied, evaluating changes within-group (between baseline and final scanning), on trueness (mean RMS), and precision (RMS standard deviation).

5 Results

5.2 Study participants

A total of 34 participants and 12 test subjects in 2 centers (center 1 and center 2), were included in this study. Two study participants initially assigned to group ≥ 40 in center 2 were incapable of participating due to agenda incompatibility with the study schedule, and were excluded from the study. Demographic (age) data of study participants is shown in Table 7. All included study participants were men.

Table 7: Operator's age distribution per center and per group:

	Mean operator's age		
Center	Grupo ≤ 25	Grupo ≥ 40	Group Control
Center 1	22	59	38
Center 2	23	54	34

5.3 Time efficiency

The efficiency was evaluated by comparing the time (in seconds (sec)) required to complete the different study tasks, such as the computer time performance and the scanning time performance, before training and after training. The results for time efficiency have been published (Zarauz 2021), and may be found annexed at the end of this thesis.

5.3.1 Normality test

The Kolmogorov-Smirnov test revealed that the data for computer time and scanning time were normally distributed.

5.3.2 Descriptive statistics

5.3.2.a Computer time

Computer time ranged between 8 and 170 sec, with a mean (± SD) baseline computer time of 62.3 (± 38.3) sec, and 57.7 (± 37.2) sec for final computer time. Neither group, scanning system, software version or training had a significant effect on computer time ($p > 0.05$). For this reason, computer time was not further analysed.

5.3.2.b Scanning time

Scanning time ranged between 50 sec (control / S1 / final scan) and 604 sec (≥ 40 / S2 / baseline scan), with a global mean (± SD) baseline scanning time of 269.4 (± 124.9) seconds, and a global final scanning time of 225.2 (± 103.2) seconds. The descriptive statistics (mean and SD) for group, IOS and site / software version (center 1/SV: 1.18.1.2 (S1) and 5.3.1 (S2) vs. center 2/SV: 1.18.1.3 (S1) and 5.3.4 (S2)) are shown in Table 8.

Table 8: Descriptive statistics table: mean and standard deviations of baseline and final scanning times, including time improvement values, are shown for test and control groups, for intraoral scanners (IOSs) S1 and S2, and for site / software version (center 1 vs. center 2):

	Baseline scanning time				**Final scanning time**		
	–	Group	Mean (sec)	Standard Deviation	Mean (sec)	Standard Deviation	Improvement (sec)
IOS	S1	≤ 25 years (y)	208.9	± 91.8	163.2	± 63.0	45.7
		≥ 40 y	217.5	± 103.5	180.7	± 90.3	36.8
		Control	156.8	± 75.6	137.9	± 54.3	18.9
	S2	≤ 25 y	339.3	± 94.8	271.1	± 57.0	68.2
		≥ 40 y	414.0	± 104.4	371.0	± 75.2	43.1
		Control	287.6	± 88.8	235.7	± 76.9	51.8
Site / software version	Center 1	–	300.4	± 121.9	248.5	± 86.8	51.9
	Center 2	–	236.6	± 121.2	200.6	± 114.2	36.0

5.3.3 Inferential statistics

5.3.3.a Scanning time performance

Operators who had better performances (shorter scanning times) at baseline also demonstrated better performances at final scanning after training ($r = 0.8$, $p < 0.01$).
Regarding inexperienced operators, age and scanning time showed a weak positive correlation for final scanning time ($r = 0.29$, $p < 0.05$). Experienced operators demonstrated a better performance than inexperienced operators at both time-points ($p = 0.016$).
When comparing groups (≤ 25, ≥ 40, control), control group demonstrated a better performance compared with ≥ 40 at baseline ($p = 0.013$) and final scanning time ($p < 0.001$). However, no differences were found between control and ≤ 25 and between ≤ 25 and ≥ 40 ($p > 0.05$).

When comparing groups, and stratifying by IOS, S1 failed to show differences between groups at final scanning time ($p > 0.05$).
With S2, control group demonstrated a better performance than ≥ 40 at baseline ($p = 0.010$) and final scanning time ($p = 0.000$), while ≤ 25 only demonstrated a better performance than ≥ 40 at final scanning time ($p = 0.005$).

Globally, the scanning system had a significant influence on baseline and final scanning times ($p < 0.001$).

When evaluating the impact of site / software version on scanning time, there was a significant difference between centers at baseline ($p = 0.032$), with significantly faster scanning times recorded at center 2 than center 1. At final scanning time, center 2 showed a tendency for faster scanning time, without significant difference ($p = 0.051$).

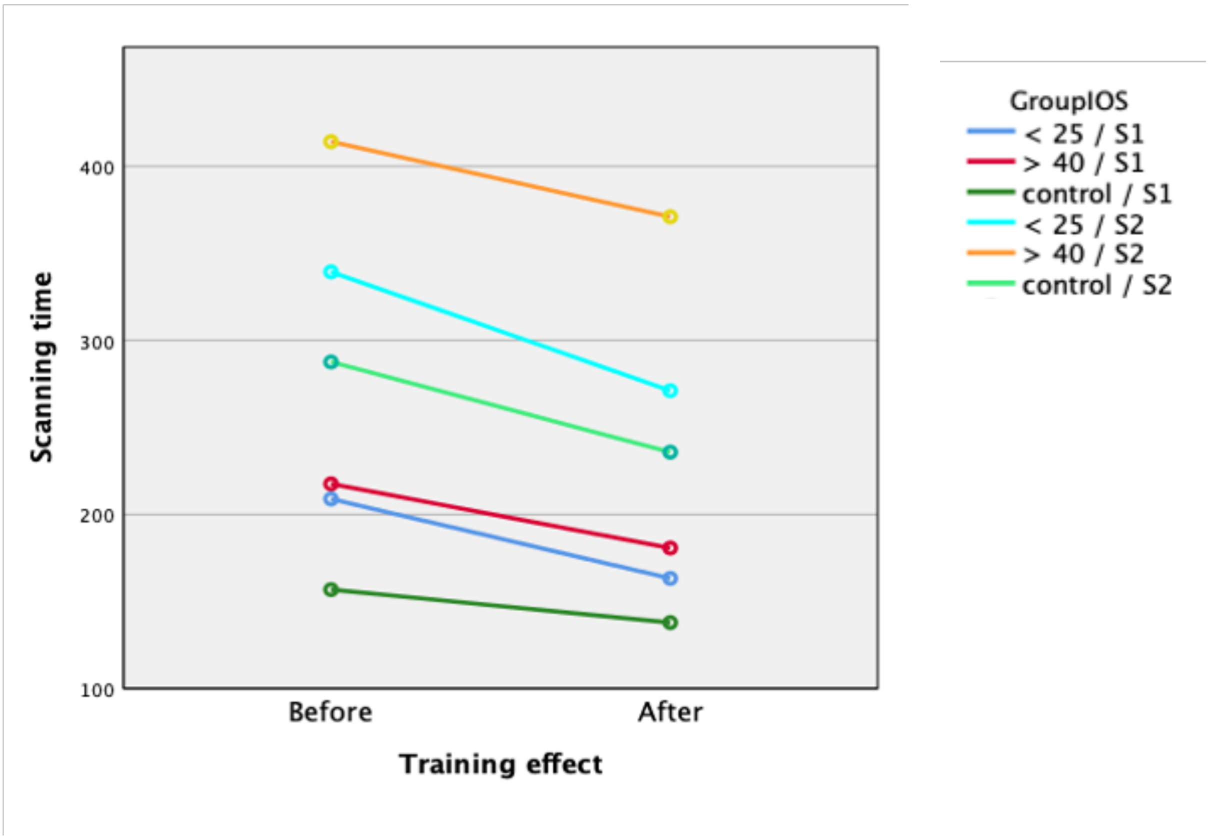
5.3.3.b Learning curve

In respect to learning curve, young operators (≤ 25) revealed a significant improvement in the scanning time between baseline and final scanning for both IOSs ($p < 0.05$), while older operators (≥ 40) only showed a significant improvement with S1 ($p < 0.05$).

Experienced operators (control) revealed a significant improvement with S2 ($p < 0.05$), but not with S1 ($p > 0.05$).

A graphical representation of the performance at both time-points and time improvement of each group and scanning system is shown in Figure 14.

Figure 14: Line graph showing the scanning time (sec) by scanning session (before and after training) stratified by group (≤ 25 years (y), ≥ 40 y, control) and Intraoral scanner (IOS) (S1, S2):



5.4 Accuracy evaluating of resulting STLs

From the 12 study subjects (volunteer test patients), 24 STLs (12 for the maxilla, and 12 for the mandible) were produced as reference STLs. The 34 study participants, produced a total of 8 test STLs each (2 jaws (maxilla & mandible) x 2 scanning sessions (baseline and final) x 2 IOSs), resulting in 272 test STLs that were superimposed with their corresponding reference STL for accuracy analysis, performed with metrology software Geomagic Control X.

The accuracy evaluation was implemented by analyzing the mean RMS to evaluate trueness, and by analyzing the standard deviation (SD) RMS to evaluate precision.

5.4.1 Normality test

The Kolmogorov-Smirnov test was applied to test the normality of the accuracy data, which revealed a non-parametric distribution. Hence non-parametric tests were applied to evaluate the effect of group (≤ 25, ≥ 40, control), experience (inexperienced vs. experienced), IOS (S1 vs. S2), software version and training effect (intra-group comparison before and after training) on accuracy (mean RMS (trueness) and SD RMS (precision).

5.4.2 Descriptive statistics

5.4.2.a Trueness

Mean RMS ranged between 45 and 84 microns. Descriptive statistics (mean, median, SD, IQ ranges) for the mean RMS values are shown in Table 8, divided by group (≤ 25, ≥ 40, control) and by jaw (maxilla, mandible).

When stratifying by IOS, S1mean RMS ranged between 47 and 96 microns, while S2 mean RMS ranged between 43 and 83 microns. Descriptive statistics (mean, median, SD, IQ ranges) for the S1 RMS values are shown in Table 9 and for S2 RMS values are shown in Table 10.

Table 8: Descriptive statistics mean RMS for global trueness evaluation: mean, median, standard deviation (SD), and interquartile (IQ) ranges:

Both intraoral scanners		RMS mean (microns)			
Jaw	Group	Mean	Median	SD	IQ range
Maxilla Baseline	≤ 25	78	77	± 24	31
	≥ 40	84	92	± 25	32
	control group	59	53	± 16	29
	Total	73	71	± 24	40
Mandible Baseline	≤ 25	67	63	± 18	30
	≥ 40	83	72	± 31	62
	control group	55	50	± 17	17
	Total	68	60	± 25	33
Maxilla Final	≤ 25	58	53	± 16	18
	≥ 40	59	53	± 16	22
	control group	45	45	± 5	5
	Total	54	50	± 14	14
Mandible Final	≤ 25	46	46	± 8	11
	≥ 40	57	53	± 18	13
	control group	45	44	± 6	6
	Total	49	46	± 12	10

Table 9: Descriptive statistics mean RMS, stratified by IOS (S1): mean, median, standard deviation (SD), and interquartile (IQ) ranges:

Intraoral Scanner 1		RMS mean (microns)			
Jaw	Group	Mean	Median	SD	IQ range
Maxilla Baseline	≤ 25	86	82	± 26	45
	≥ 40	86	92	± 32	66
	control group	52	52	± 10	15
	Total	74	66	± 28	47
Mandible Baseline	≤ 25	75	79	± 20	26
	≥ 40	96	104	± 33	64
	control group	47	50	± 5	9
	Total	72	61	± 29	40
Maxilla Final	≤ 25	58	51	± 17	24
	≥ 40	55	52	± 15	13
	control group	47	46	± 3	8
	Total	53	49	± 13	8
Mandible Final	≤ 25	48	46	± 10	11
	≥ 40	48	48	± 7	12
	control group	48	45	± 8	6
	Total	48	47	± 8	9

Table 10: Descriptive statistics mean RMS, stratified by IOS (S2): mean, median, standard deviation (SD), and interquartile (IQ) ranges:

Intraoral Scanner 2		RMS mean (microns)			
Jaw	Group	Mean	Median	Std. Deviation	IQ range
Maxilla Baseline	≤ 25	71	67	± 20	21
	≥ 40	83	92	± 18	26
	control group	65	66	± 18	34
	Total	73	75	± 19	32
Mandible Baseline	≤ 25	60	59	± 13	23
	≥ 40	71	61	± 24	39
	control group	62	57	± 21	38
	Total	64	60	± 20	24
Maxilla Final	≤ 25	59	55	± 17	16
	≥ 40	62	60	± 17	29
	control group	44	44	± 5	3
	Total	55	50	± 15	19
Mandible Final	≤ 25	44	41	± 5	9
	≥ 40	65	54	± 22	18
	control group	43	43	± 3	4
	Total	50	46	± 16	12

5.4.2.b Precision

Standard deviation (SD) RMS ranged between 43 and 78 microns. Descriptive statistics (mean, median, SD, IQ ranges) for the SD values are shown in Table 11, divided by group (≤ 25, ≥ 40, control) and by jaw (maxilla, mandible).

When stratifying by IOS (S1), SD RMS ranged between 45 and 88 microns, while S2 SD RMS ranged between 42 and 77 microns. Descriptive statistics (mean, median, SD, IQ ranges) for the S1 SD RMS values are shown in Table 12, and for S2 SD RMS values are shown in Table 13.

Table 11: Descriptive statistics for standard deviation (SD) RMS for precision evaluation: mean, median, SD, and interquartile (IQ) ranges:

Both intraoral scanners		RMS Standard Deviation (microns)			
Jaw	Group	Mean	Median	SD	IQ range
Maxilla Baseline	≤ 25	76	75	± 23	32
	≥ 40	77	78	± 21	33
	control group	58	53	± 15	29
	Total	70	67	± 21	36
Mandible Baseline	≤ 25	65	63	± 16	32
	≥ 40	78	72	± 28	56
	control group	53	48	± 16	15
	Total	65	58	± 23	32
Maxilla Final	≤ 25	57	51	± 17	19
	≥ 40	57	52	± 16	25
	control group	44	43	± 4	5
	Total	53	47	± 15	14
Mandible Final	≤ 25	45	43	± 8	37
	≥ 40	55	50	± 17	15
	control group	43	43	± 4	4
	Total	48	45	± 12	8

Table 12: Descriptive statistics standard deviation (SD) RMS, stratifying by IOS (S1): mean, median, SD, and interquartile (IQ) ranges:

Intraoral scanner 1		RMS Standard Deviation (microns)			
	Group	Mean	Median	SD	IQ range
Maxilla Baseline	≤ 25	84	82	± 24	38
	≥ 40	77	77	± 24	47
	control group	51	52	± 10	12
	Total	70	65	± 24	40
Mandible Baseline	≤ 25	71	78	± 17	21
	≥ 40	88	89	± 32	66
	control group	46	46	± 5	8
	Total	68	58	± 26	35
Maxilla Final	≤ 25	57	49	± 17	24
	≥ 40	53	51	± 15	11
	control group	45	43	± 3	6
	Total	52	48	± 14	8
Mandible Final	≤ 25	48	46	± 10	9
	≥ 40	46	46	± 6	9
	control group	45	44	± 5	4
	Total	46	45	± 7	8

Table 13: Descriptive statistics standard deviation (SD) RMS, stratifying by S2: mean, median, SD, and interquartile (IQ) ranges:

Intraoral scanner 2		RMS Standard Deviation (microns)			
Jaw	Group	Mean	Median	SD	IQ range
Maxilla Baseline	≤ 25	69	62	± 20	21
	≥ 40	77	89	± 19	31
	control group	64	65	± 17	32
	Total	70	67	± 19	29
Mandible Baseline	≤ 25	59	59	± 14	24
	≥ 40	70	61	± 23	43
	control group	60	55	± 20	35
	Total	63	58	± 19	25
Maxilla Final	≤ 25	58	54	± 17	19
	≥ 40	61	60	± 17	31
	control group	43	43	± 5	3
	Total	54	47	± 16	20
Mandible Final	≤ 25	43	40	± 5	7
	≥ 40	63	53	± 20	19
	control group	42	42	± 2	3
	Total	49	43	± 15	11

5.4.3 Inferential statistics

5.4.3.a Effect of group

The effect of group (≤ 25, ≥ 40, control) on the accuracy of maxilla and mandible STLs, before and after training, was evaluated using the Kruskal-Wallis test, with a Dunn's post hoc test for pairwise comparison.

Trueness

The results for trueness (mean RMS) are shown in Table 14 for global maxilla, in Table 15 for global mandible, and stratified by IOS in Tables 16 - 19.

Table 14: Kruskal-Wallis test to evaluate the effect of group on maxilla baseline and final mean RMS (trueness), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests:

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **RMSmaxBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.001	***Reject*** the null hypothesis.
2	The distribution of **RMSmaxFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.001	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**				
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statisti	Sig.	Adj. Sig.[a]	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
control group-< 25	15.478	5.745	2.694	0.007	0.021	18.630	5.742	3.245	0.001	0.004
control group-> 40	21.195	5.880	3.605	0.000	0.001	19.823	5.877	3.373	0.001	0.002
< 25-> 40	-5.716	5.880	-0.972	0.331	0.993	-1.193	5.877	-0.203	0.839	1.000

Table 15: Kruskal-Wallis test to evaluate the effect of group on mandible baseline and final mean RMS (trueness), and Dunn’s post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests:

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **RMSmandBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.001	***Reject*** the null hypothesis.
2	The distribution of **RMSmandFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.003	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**				
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statisti	Sig.	Adj. Sig.[a]	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
control group-< 25	13.348	5.745	2.323	0.020	0.060	1.022	5.740	0.178	0.859	1.000
control group-> 40	21.378	5.880	3.636	0.000	0.001	18.024	5.875	3.068	0.002	0.006
< 25-> 40	-8.030	5.880	-1.366	0.172	0.516	-17.002	5.875	-2.894	0.004	0.011

Table 16: Kruskal-Wallis test to evaluate the effect of group on maxilla baseline and final mean RMS (trueness), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S1):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **RMSmaxBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.007	***Reject*** the null hypothesis.
2	The distribution of **RMSmaxFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.120	***Retain*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]	Total N	32
control group-< 25	10.682	4.097	2.607	0.009	0.027	Test Statistic	4.234a,b
control group-> 40	11.182	3.999	2.796	0.005	0.015	Degree Of Freedom	2
< 25-> 40	0.500	4.097	0.122	0.903	1.000	Asymptotic Sig.(2-sided test)	0.120

Table 17: Kruskal-Wallis test to evaluate the effect of group on mandible baseline and final mean RMS (trueness), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S1):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **RMSmandBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.000	***Reject*** the null hypothesis.
2	The distribution of **RMSmandFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.881	***Retain*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]	Total N	32
control group-< 25	11.545	3.999	2.887	0.004	0.012	Test Statistic	.252a,b
control group-> 40	15.955	4.098	3.894	0.000	0.000	Degree Of Freedom	2
< 25-> 40	-4.409	4.098	-1.076	0.282	0.846	Asymptotic Sig.(2-sided test)	0.881

Table 18: Kruskal-Wallis test to evaluate the effect of group on maxilla baseline and final mean RMS (trueness), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S2):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **RMSmaxBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.041	***Reject*** the null hypothesis.
2	The distribution of **RMSmaxFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.003	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**				
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statisti	Sig.	Adj. Sig.[a]	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
control group-< 25	2.500	4.180	0.598	0.550	1.000	11.333	4.179	2.712	0.007	0.020
control group-> 40	10.398	4.274	2.433	0.015	0.045	13.091	4.273	3.064	0.002	0.007
< 25-> 40	-7.898	4.274	-1.848	0.065	0.194	-1.758	4.273	-0.411	0.681	1.000

Table 19: Kruskal-Wallis test to evaluate the effect of group on mandible baseline and final mean RMS (trueness), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S2):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmandBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.512	***Retain*** the null hypothesis.
2	The distribution of **SDmandFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.000	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Final					**Baseline**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]	Total N	32
control group-< 25	0.292	4.177	0.070	0.944	1.000	Test Statistic	1.337a,b
control group-> 40	15.061	4.271	2.927	0.000	0.001	Degree Of Freedom	2
< 25-> 40	-14.769	4.271	-0.548	0.001	0.002	Asymptotic Sig.(2-sided test)	0.512

Precision

The results for precision (SD RMS) are shown in Table 20 for global maxilla, in Table 21 for global mandible, and stratified by IOS in Tables 22 - 25.

Table 20: Kruskal-Wallis test to evaluate the effect of group on maxilla baseline and final SD RMS (precision), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests:

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmaxBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.003	***Reject*** the null hypothesis.
2	The distribution of **SDmaxFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.001	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**				
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statisti	Sig.	Adj. Sig.[a]	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
control group-< 25	15.826	5.745	2.755	0.006	0.018	19.283	5.742	3.358	0.001	0.002
control group-> 40	17.970	5.880	3.056	0.002	0.007	19.317	5.877	3.287	0.001	0.003
< 25-> 40	-2.144	5.880	-0.365	0.715	1.000	-0.034	5.877	-0.006	0.995	1.000

Table 21: Kruskal-Wallis test to evaluate the effect of group on mandible baseline and final SD RMS (precision), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests:

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmandBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.001	***Reject*** the null hypothesis.
2	The distribution of **SDmandFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.001	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**				
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statisti	Sig.	Adj. Sig.[a]	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
control group-< 25	13.739	5.745	2.392	0.017	0.050	2.196	5.742	0.382	0.702	1.000
control group-> 40	21.157	5.880	3.598	0.000	0.001	19.790	5.877	3.367	0.001	0.002
< 25-> 40	-7.418	5.880	-1.262	0.207	0.621	-17.594	5.877	-2.994	0.003	0.008

Table 22: Kruskal-Wallis test to evaluate the effect of group on maxilla baseline and final SD RMS (precision), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S1):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmaxBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.004	***Reject*** the null hypothesis.
2	The distribution of **SDmaxFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.064	***Retain*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]	Total N	32
control group-< 25	9.909	4.098	2.418	0.016	0.047	Test Statistic	5.499a,b
control group-> 40	12.545	3.999	3.137	0.002	0.005	Degree Of Freedom	2
< 25-> 40	2.636	4.098	0.643	0.520	1.000	Asymptotic Sig.(2-sided test)	0.064

Table 23: Kruskal-Wallis test to the evaluate effect of group on mandible baseline and final SD RMS (precision), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S1):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmandBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.000	***Reject*** the null hypothesis.
2	The distribution of **SDmandFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.717	***Retain*** the null hypothesis.

Pairwise Comparisons of Group

	Baseline					**Final**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.^{a}	Total N	32
control group-< 25	11.364	3.998	2.842	0.004	0.013	Test Statistic	.664a,b
control group-> 40	15.427	4.097	3.766	0.000	0.000	Degree Of Freedom	2
< 25-> 40	-4.064	4.097	-0.992	0.321	0.964	Asymptotic Sig.(2-sided test)	0.717

Table 24: Kruskal-Wallis test to evaluate the effect of group on maxilla baseline and final SD RMS (precision), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S2):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmaxBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.210	***Retain*** the null hypothesis.
2	The distribution of **SDmaxFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.007	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Final					**Baseline**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.^{a}	Total N	32
control group-< 25	10.167	4.179	2.433	0.015	0.045	Test Statistic	3.123a,b
control group-> 40	12.508	4.273	2.927	0.003	0.010	Degree Of Freedom	2
< 25-> 40	-2.341	4.273	-0.548	0.584	1.000	Asymptotic Sig.(2-sided test)	0.210

Table 25: Kruskal-Wallis test to evaluate the effect of group on mandible baseline and final SD RMS (precision), and Dunn's post hoc test for pairwise comparison at baseline and final time-points adjusted by the Bonferroni correction for multiple tests, stratified by intraoral scanner (S2):

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of **SDmandBL** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.376	***Retain*** the null hypothesis.
2	The distribution of **SDmandFinal** is the same across categories of Group.	Independent-Samples Kruskal-Wallis Test	0.000	***Reject*** the null hypothesis.

Pairwise Comparisons of Group

	Final					**Baseline**	
Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]	Total N	32
control group-< 25	0.208	4.177	0.050	0.960	1.000	Test Statistic	1.958a,b
control group-> 40	15.152	4.271	3.548	0.000	0.001	Degree Of Freedom	2
< 25-> 40	-14.943	4.271	-3.499	0.000	0.001	Asymptotic Sig.(2-sided test)	0.376

5.4.3.b Effect of experience (trueness and precision)

The effect of IOS experience (experienced vs. inexperienced) on the accuracy of STLs (trueness (mean RMS) and precision (SD RMS)), was evaluated using the Mann-Whitney U test. Results are shown in Table 26 (overall, and stratified by IOS).

Table 26: Mann-Whitney U test evaluating the effect of IOS experience (experienced vs. inexperienced) on mean RMS (trueness) and SD RMS (precision), overall, and stratified by intraoral scanner (S1 and S2):

	Hypothesis Test Summary				
IOS		Null Hypothesis	Test	Sig.	Decision
S1 & S2	1	The distribution of **mean RMS** is the same across categories of **IOS Experience**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **IOS Experience**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
S1	1	The distribution of **mean RMS** is the same across categories of **IOS Experience**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **IOS Experience**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
S2	1	The distribution of **mean RMS** is the same across categories of **IOS Experience**.	Independent-Samples Mann-Whitney U Test	0.001	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **IOS Experience**.	Independent-Samples Mann-Whitney U Test	0.001	***Reject*** the null hypothesis.

5.4.3.c Effect of training (trueness and precision)

The effect of training (before / time point 1 vs. after training / time point 2) on the accuracy of STLs (trueness (mean RMS) and precision (SD RMS)), was evaluated using the Mann-Whitney U test. Results are shown in Table 27 (overall, and stratified by IOS).

Table 27: Mann-Whitney U test evaluating the effect of training (before vs. after training) on mean RMS (trueness) and SD RMS (precision), overall, and stratified by intraoral scanner (S1 and S2):

	Hypothesis Test Summary				
IOS		Null Hypothesis	Test	Sig.	Decision
S1 & S2	1	The distribution of **mean RMS** is the same across categories of **Time point**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Time point**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
S1	1	The distribution of **mean RMS** is the same across categories of **Time point**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Time point**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
S2	1	The distribution of **mean RMS** is the same across categories of **Time point**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Time point**.	Independent-Samples Mann-Whitney U Test	0.000	***Reject*** the null hypothesis.

5.4.3.c Effect of jaw (trueness and precision)

The effect of jaw (maxilla vs. mandible) on the accuracy of STLs (trueness (mean RMS) and precision (SD RMS)), was evaluated using the Mann-Whitney U test. Results are shown in Table 28 (overall, and stratified by IOS).

Table 28: Mann-Whitney U test evaluating the effect of Jaw (maxilla vs. mandible) on mean RMS and SD RMS, overall, and stratified by intraoral scanner (S1 and S2):

	Hypothesis Test Summary				
IOS		Null Hypothesis	Test	Sig.	Decision
S1 & S2	1	The distribution of **mean RMS** is the same across categories of **Jaw**.	Independent-Samples Mann-Whitney U Test	0.014	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Jaw**.	Independent-Samples Mann-Whitney U Test	0.007	***Reject*** the null hypothesis.
S1	1	The distribution of **mean RMS** is the same across categories of **Jaw**.	Independent-Samples Mann-Whitney U Test	0.128	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Jaw**.	Independent-Samples Mann-Whitney U Test	0.063	***Retain*** the null hypothesis.
S2	1	The distribution of **mean RMS** is the same across categories of **Jaw**.	Independent-Samples Mann-Whitney U Test	0.032	***Reject*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Jaw**.	Independent-Samples Mann-Whitney U Test	0.035	***Reject*** the null hypothesis.

5.4.3.d Effect of IOS (trueness and precision)

The effect of IOS (S1 vs. S2) on the accuracy of STLs (trueness (mean RMS) and precision (SD RMS)), was evaluated using the Mann-Whitney U test. Results are shown in Table 29 (overall, and stratified by time-point (TP) (before / time point 1 vs. after training / time point 2).

Table 29: Mann-Whitney U test evaluating the effect of IOS (S1 vs. S2) on mean RMS and SD RMS, overall, and stratified by time-point (TP) (before / time point 1 vs. after training / time point 2):

	Hypothesis Test Summary				
TP		Null Hypothesis	Test	Sig.	Decision
1 & 2	1	The distribution of **mean RMS** is the same across categories of **IOS**.	Independent-Samples Mann-Whitney U Test	0.822	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **IOS**.	Independent-Samples Mann-Whitney U Test	0.987	***Retain*** the null hypothesis.
1	1	The distribution of **mean RMS** is the same across categories of **IOS**.	Independent-Samples Mann-Whitney U Test	0.784	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **IOS**.	Independent-Samples Mann-Whitney U Test	0.929	***Retain*** the null hypothesis.
2	1	The distribution of **mean RMS** is the same across categories of **IOS**.	Independent-Samples Mann-Whitney U Test	0.995	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **IOS**.	Independent-Samples Mann-Whitney U Test	0.572	***Retain*** the null hypothesis.

5.4.3.e Effect of site / software version (trueness and precision)

The effect of site / software version (center 1 / software 1.18.1.2 (S1) ; software 5.3.1 (S2) vs. center 2 / software 1.18.1.3 (S1); software 5.4 (S2)) on the accuracy of STLs (trueness (mean RMS) and precision (SD RMS)), was evaluated using the Mann-Whitney U test. Results are shown in Table 30 (overall, and stratified by IOS).

Table 30: Mann-Whitney U test evaluating the effect of site / software version (center 1 / software 1.18.1.2 (S1); software 5.3.1 (S2) vs. center 2 / software 1.18.1.3 (S1); software 5.4 (S2)) on mean RMS and SD RMS, overall, and stratified by intraoral scanner (S1 and S2):

	Hypothesis Test Summary				
IOS		Null Hypothesis	Test	Sig.	Decision
S1 & S2	1	The distribution of **mean RMS** is the same across categories of **Site**.	Independent-Samples Mann-Whitney U Test	0.077	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Site**.	Independent-Samples Mann-Whitney U Test	0.256	***Retain*** the null hypothesis.
S1	1	The distribution of **mean RMS** is the same across categories of **Site**.	Independent-Samples Mann-Whitney U Test	0.085	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Site**.	Independent-Samples Mann-Whitney U Test	0.221	***Retain*** the null hypothesis.
S2	1	The distribution of **mean RMS** is the same across categories of **Site**.	Independent-Samples Mann-Whitney U Test	0.389	***Retain*** the null hypothesis.
	2	The distribution of **SD RMS** is the same across categories of **Site**.	Independent-Samples Mann-Whitney U Test	0.652	***Retain*** the null hypothesis.

5.4.3.f Correlation between scanning time and accuracy (trueness and precision)

The Pearson correlation test showed a weak positive correlation between scanning time and mean RMS (trueness) ($r = 0.25$, $p < 0.003$), and a moderate positive correlation between scanning time and SD RMS (precision) ($r = 0.44$, $p < 0.000$).

6 Discussion

Gaining knowledge on how different aspects, such as operator's age, experience, IOS system or software version influence the learning curve to IOSs is relevant due to the financial and strategical impact associated with the acquisition of an IOS.

In the learning process of an IOS operator, the goals are both to reduce the time required for impressions and additionally, to produce an accurate digital impression.

The findings of this multi-centric clinical study performed for this thesis are presented, discussed and interpreted in two main sections, time efficiency and accuracy.

6.1 Summary of findings

The findings of the present clinical study showed that the operator's age had an impact on the scanning time performance and learning curve of novel IOS operators, displayed by the general tendency of younger operators to perform faster scans before and after training than older novel operators with both IOSs, and by the steeper learning curve they demonstrated with both IOSs.

The IOS system also demonstrated to have an impact on the scanning time performance and learning curve of novel and experienced IOS operators. Hence the first and second null hypotheses were rejected. The software version had an impact on scanning time before training, but not after training, hence the third null hypothesis was partially retained.

Concerning accuracy, the operator's age had an impact on trueness and precision, while the IOS system or their respective software versions did not impact the trueness and precision of scans performed by IOS novel operators. Therefore, the fourth null hypothesis was rejected, while the fourth and sixth null hypotheses were retained.

A correlation was stablished between scanning time and accuracy, rejecting the fifth null hypothesis.

6.2 Interpretation of the findings

6.2.1 Time efficiency

As mentioned in the introduction, the time required to complete a certain task has been used both in general medicine research (Pernar 2017), and specifically in IOS studies (Kim 2016; Waldecker 2021.a, Roth 2020), to evaluate the learning curve of inexperienced operators. The time required to complete a digital impression can be divided in: a) the time taken to complete the computer order (computer time), and b) the time taken to complete the intraoral digital scan (scanning time). The time efficiency of a digital impression will be therefor the combination of an easy and fast registration of the computer form (computer time), and an uneventful and also fast digital registration of the required hard and soft tissues (scanning time).

6.2.1.a Computer time

Computer times revealed acceptable performance for all groups and systems even before training. One of the IOS (S2), and the younger operators showed a tendency for shorter computer times. However, no significant differences were found before and after training, or between groups, probably because computer times were generally short. For this reason, computer time was not further addressed, and the bulk of the study centered on scanning time.

One study (Roth 2020) reported the global digital impression time, measured from the first step of recording patient data to the sending of the case to the lab. Scanning time was not reported independently from computer time. The findings of this thesis, which did report computer and scanning time independently, would indicate that, reporting computer times together with scanning time, should not have a major impact on the evaluation of overall digital impression time. However, as younger operators showed a tendency to faster computer times, in future research, it would be advisable to report computer and scanning times independently, or to forgo the recording of computer times entirely.

Most studies (Chiu 2020, Yilmaz 2021, Kim 2016, Passos 2019) reporting on the time required to complete digital impressions mentioned they recorded scanning time, but they did not specify if this included the computer time. Waldecker et al. (Waldecker 2021.a) specified scanning time as the time between activation and termination of scan mode. This could be considered as the appropriate time to measure; hence it could be recommended for future research to clarify what is meant by scanning time, leaving out filling out the computer form, or registering it separately.

6.2.1.b Scanning time

The relevance of having a control group:

Studies in the medical field used experienced operators to provide the benchmark for performance and evaluate the learning curve of novel operators (Di Pietro 2018, Bedi 2020), as was done in the present study. The control group, integrated by IOS expert operators, would be expected to show plateau performance before and after training, or in other words, should not show an improvement in scanning time performance after training, as their learning curve should be flat. In line with this expectation, the control group showed the best performance with both IOSs, and no improvement with one of the IOS (S1). Unexpectedly, the control group showed a significant improvement with S2, which was also the steepest improvement of all groups and IOSs. Participants in the control group were required to have performed at least 100 scans (Gimenez 2014) to be included in this study. However, it was not specifically controlled what IOS had been used to acquire such experience. In fact, members of the control group were more experienced with S1 than with S2, which is reflected in their flat learning curve with S1 and their steep learning curve with S2. Interestingly, these findings indicate that once an operator is experienced with one IOS, the learning curve for another IOS may be expected to be steep.

Impact of the operator’s age on scanning time

To the author's knowledge, no previously published studies evaluated the impact of the operator’s age on scanning time. They evaluated the impact of other factors on scanning time, such as the resolution mode (Chiu 2020), the effect of training (Roth 2020, Waldecker 2021.a), the extension (Yilmaz 2021), or the scanning path (Passos 2019). Hence this study is the first report to evaluate the effect of operator’s age on scanning time (Zarauz 2021).

The impact of the operator’s age on scanning time was non-existent before training, and minor after training, shown by a weak positive correlation between age and final scanning time. This means that both young and older operators performed slower scanning times before training, and after training, younger operators performed faster scanning times.

Kim et al. (Kim 2016) found no difference between the learning curve of two groups of operators. Both groups were composed by oral hygienists, one group had 3 - 5 years of clinical experience, and the other group had more than 5 years of clinical experience, both inexperienced with IOS. The clinical experience difference presented by both included groups; 3 - 5 and more than 5 years, may have been too narrow to reveal differences in the scanning performance and learning curves. Furthermore, the operator’s age was not controlled. For this reason, in the present study, the clinical experience and age difference between the two test groups was spaced out considerably (≤ 25 years old, and more than 40 years old). To the authors’ knowledge, there are no previous studies indicating what would be the appropriate age gap to investigate the influence of age in learning curves within the field of dentistry. Within the field of phycology, only a handful of studies have contrasted learning-related activity in younger and older adults (Czaja 1998, Merestein 2021). A study evaluating the impact of age in learning (Merestein 2021), included a wider range of age than the current investigation: younger than 23, and older than 66 years old. Such a wide range of age is not feasible for the evaluation of age impacting dentistry related tasks, as in most countries the age of retirement is 65 years. In other words, it may be clinically not relevant to investigate the learning curve of retired dentists. The age for the present study was spaced out as far as posible, allowing for the inclusion of mature dentists with sufficient years of clinical practice.

In the present study, the baseline and final scanning times within the same operator were also correlated, showing a strong positive correlation. In other words, operators who were fast before training were also faster after training. The correlation between scanning times was more robust within the same operator, than between scanning time and age (weak positive correlation). This indicates that the personal skill of the operator, are influenced by age, but more so by personal talent or previous experiences that weren’t accounted for in this study. Individual characteristics such as talent or previous experience using other technological devices (such as video games), could be hypothesized as possible factors to influence the performance and learning curve of inexperienced operators (Green 2003, Anguera 2013).

Impact of IOS on scanning time

Overall, the impact of the scanning system was evident, with S1 showing faster performances and learning curves for both young and older operators.

Additionally, the impact of age just discussed in the previous section, was shown specifically for S2, where younger and experienced operators showed a better performance for final scanning times than older operators, and less so for S1, where no operator factors (age or experience) had an impact on scanning time after training.

Several studies in cognitive psychology have shown that after appropriate training, the benefits of learning plasticity presented by youth are diluted, and older people achieve similar performance and attitude towards computer tasks (Broady 2010, Czaja 1998). Even though older people may reveal slower learning rates, they maintain their brain plasticity and can retain the benefits of training as much as young adults (McKendrick 2013). The present study's findings may therefore indicate that, while three training sessions are sufficient for novel operators (no matter the age) when S1 is used, older operators might need additional training sessions with S2. This indicates that depending on the user-friendliness of the scanner, the personal capacity of the operator (younger, more experienced or talented operators) may play a greater or lesser role on the learning curve necessary to complete intraoral scans in similar scanning times as the target operators (experienced IOS operators).

Kim et al. (Kim 2016) also reported a steeper learning curve with one scanner (iTero), than with the other (S1 in this study). iTero demonstrated slower scanning times, but a steeper learning curve, in comparison with S1. In our study, S1 showed faster scanning times and learning rates than S2.

Passos et al. (Passos 2019) evaluated the impact of different scanning strategies on scanning time, using two different IOSs (Primescan and CEREC Omnicam). Both scanners showed faster scanning times with strategy M (Figure 4), and when comparing both scanners, Primescan showed a tendency for faster scanning times, with no significant difference. While Primescan and Omnicam are produced by the same manufacturer, the most recent (Primescan), is not just a software update from the former (Omnicam), but rather a new scanner, with a novel technology called High frequency contrast, that is currently in the patenting process, and has therefor not been clearly described by the manufacturer. Omnicam uses triangulation technology, which is a common technology used by other IOSs. With respect to scanning times, the newer scanner has made improvements, but not significant.

However, their scanning times were faster than the scanning times reported in this study, also when filtering the control group, and taking into consideration that partial scans were completed in this study, in comparison with full arch scans performed in their investigation (Passos 2019). An important difference is their design was in-vitro, hence their findings yet need to be corroborated in an in-vivo study. However, the differences are high enough to consider that the impact of the scanning system in the scanning time is prime importance, also revealed by our findings, with S1 reporting faster scanning times and learning curve than S2.

Waldecker et al. (Waldecker 2021.a), scanning a complete arch in-vitro with CEREC Omnicam, with dental students, reported however longer scanning times than those shown by Passos et al. (Passos 2019). Even after training, which our study showed may erase the differences with the scanning times of the control group, the scanning times remained higher, with their lower scanning times after training at 233 sec (Waldecker 2021.a). This may be due to Omnicam requiring a longer training schedule than the proposed 3 session program evaluated in their study, which was enough for S1 in our study, or to the fact that they did not use the same scanning strategy (M: Figure 4), which showed significantly faster scanning times in complete arch scanning (Passos 2019). The scanning strategy used by Waldecker et al. (Waldecker 2021.a) was described in a previous publication by the same team (Waldecker 2019), and involves scanning the full arch in quadrants, first the occlusal part, then the palatal/lingual, and then the vestibular (G: Figure 4), which in the study performed by Passos et al. still performed low scanning times, between 35 - 55 sec for both scanners. Hence the remarkable improvements in full arch scanning speed could be due to the software version, 4.5 (Waldecker 2021.a), and 5.1 (Passos 2019).

Studies evaluating the scanning times, and using S1, revealed scanning more in agreement with our outcomes (Chiu 2020, Yilmaz 2021, Roth 2020). Chiu et al. and Yilmaz et al. reported mean scanning time ranges between 35 - 155 sec, with in-vitro design and performed by experienced operators. Roth et al. reported mean scanning times between 23 - 15 min (before and after training) for both complete arches scanned by dental students in an in-vivo design. In this study, 3 factors play a role in the significantly higher scanning times, the fact that both complete arches are being scanned, the inexperience of the operators, and the in-vivo design. However, in our study, after the training sessions, the inexperienced operators reported similar scanning times to the control group (with this scanner: S1).

Impact of software version on scanning time

Several software versions were used, as one center performed the study during one academic year (2017–2018) and the other center during the following year (2018–2019), and the software was updated in that time. Ideally, the study should have been performed simultaneously in both centers, with the same software version.

On the other hand, the factor 'software version' of both included IOS was evaluated. Several studies have evaluated the impact of software versions on the accuracy of IOSs (Ender 2016, Ender 2019, Nagy 2020), but no previous study has evaluated the impact of software versions on scanning time.

The included IOS systems were based on different technology, confocal microscopy, and active wavefront sampling. Although both IOSs use light as a light source, they present some differences, such as the need for powder coating (for S2 and not for S1), camera size and weight (S2 has a smaller hand-piece than S1), and distance to the scanning object (S2 requires a specific scanning distance (1 cm), while the S1 hand-piece may be in contact with the occlusal surfaces to be scanned) and image acquisition mode (ultrafast imaging (S1) and continuous video sequencing (S2)). It may be challenging to evaluate how they independently affect scanning time, as systems can only be tested as a whole, and each system has a combination of characteristics.

The newer software versions used in center 2 demonstrated a faster scanning performance, with a significant difference at baseline scanning time, and only a tendency after training. This may indicate that after training, the advantage of the updated software is lost, or rather, that with the updated software versions, the scanners were able to facilitate faster scanning times to novel operators without previous training, hence improved user-friendliness from the beginning. This is favorable, as ideally, the scanning systems are easy to operate and are less impacted by the talents and training of the operator, and the findings of this study reveal that the updated software versions of the included scanning systems, made progress in this direction.

Passos et al. (Passos 2019) and Waldecker et al. (Waldecker 2021.a) both evaluated complete arch scanning times, using the same scanning strategy (G: Figure 4), the same IOS but different software versions. One study reported scanning times between 35 - 55 sec (Omnicam software version 5.1), and the other 233 sec (Omnicam software version 4.5). While Waldecker et al. (Waldecker 2021.a) evaluated the effect of training in scanning times performed by dental students, Passos (Passos 2019) evaluated the impact of scanning strategies, performed by 1 trained operator. This significant time difference between studies is impacted by both the experience of the operators and potentially also by the software version.

6.2.2 Accuracy

Other studies evaluating the accuracy of IOS revealed great variability in the reported trueness and precision. As reported in the introduction, the accuracy for IOSs ranges from 2 - 903 microns (Abduo 2018, Amin 2017, Canullo 2021, Chebib 2018, Chiu 2020, Doukantzi 2020, Ender 2016.a, Ender 2016.b, Ender 2019, Kim 2018, Medina-Sotomayor 2018, Mehl 2009, Müller 2016, Nagy 2020, Passos 2019, Revilla 2020.a, Revilla 2020.b, Revilla 2021, Waldecker 2021.b, Yilmaz 2021).

Previous studies with in-vitro designs (Mehl 2009, Müller 2016, Amin 2017, Ender 2019, Chiu 2020, Canullo 2021, Waldecker 2021.b), and with quadrant evaluations (Mehl 2009, Ender 2016.a, Sason 2018, Ender 2019, Chiu 2020, Canullo 2021), showed higher accuracy than in-vivo/complete arch studies (Ender 2016.b, Chebib 2018, Revilla 2020.b).

A clear exception to this general trend is shown by Passos et al. (Passos 2019), who report less than 5 microns mean accuracy for in-vitro complete arch scans. And Revilla et al. (Revilla 2021), who report 2 microns mean trueness and 5 microns mean precision in an in-vivo investigation, for quadrant scans.

The common denominator of these two publications may be using recently launched intraoral scanners, with newer software. Passos et al. obtain these results with Primescan. Also using Primescan (Ender 2019), Ender et al. showed mean accuracy for complete arch in-vitro scans ranging 30 microns. They used software version CEREC v.5.0.0, while Passos et al. used CEREC v.5.0.2.

Revilla et al. reported on the TRIOS 4 (3 Shape, Copenhagen, Denmark), which up to date remains the only publication with accuracy results for this system.

The lowest accuracy (903 microns) was reported by Nagy et al. (Nagy 2020) with the Planmeca scanner, and Chebib et al. (Chebib 2018), who reported mean trueness of 700 microns, with TRIOS 3, but for the border of edentulous impressions, which within the field of complete dentures, remained clinically acceptable.

Overall, trueness in this in-vivo study ranged between 45 - 84 microns, and precision between 43 - 78 microns.

These findings are in similar ranges as previous studies reporting on the accuracy of in-vivo quadrant scans; 21 - 49 microns (Ender 2016.a), and 76 - 97 microns (Revilla 2020.a), performed with the same scanners as were used in this investigation. Slight differences may be accounted for the use of inexperienced operators in our investigation, of the evaluation of different lighting conditions in Revilla' report (Revilla 2020.a).

Within the findings of our investigation, accuracy was not impacted depending on IOS, in agreement with previous reports (Ender 2016.a, Ender 2016.b), showing similar accuracy outcomes for both scanners (S1 and S2). The updated software during the course of the study had a small impact on the accuracy of the retrieved STLs. When considering the overall findings of this investigation, and the previously published investigations, regarding hardware and software, there seems to be a tendency for improvements in the accuracy outcomes, yet these improvements are not linear (Ender 2016.a, Ender 2020.b, Nagy 2020, Passos 2020, Revilla 2021).

Age of the operator cannot be compared with previous investigations, as no study controlled the age of the included operators.
The findings of this investigation revealed that age of IOS novel operators had an impact on both trueness and precision, depending on training, the IOS used, or on the jaw.
As with scanning time, S1 revealed a difference in accuracy of the test groups with the control group before training, and not after training.

With S2, control group showed same levels of accuracy as test groups when scanning the mandible before training, and also with younger operators for the maxilla after training. Younger operators, with S2, showed a tendency for more accurate scans than older operators, especially after training when scanning the mandible, where they obtained more accurate scans than their older colleagues.
So while the operator's age impacted accuracy, depending on a combination of the used IOS, the training status, and the jaw, experience had a significant impact on accuracy, both on trueness and precision, with both scanners.

Jaw had an impact on trueness and precision with S2, but not with S1. Overall, the mandible showed a better accuracy, both trueness and precision, than the maxilla. When stratifying by IOS, S1 did not show this difference between jaws, and S2 did. This again reflects on the higher sensitivity of S2 to operator's skills, or the location. The mandible showing higher accuracy than the maxilla was not an expected finding. Only quadrant scans were evaluated, hence the accuracy may again differ if full arch scans had been taken. No previous investigation compared the accuracy of mandibular and maxilla STLs.

6.2.3 Time and accuracy

Previous studies reporting on scanning time and accuracy (Passos 2019, Waldecker 2021.a, Waldecker 2021.b), did not perform a correlation between the two outcomes. However, Passos et al. (Passos 2019) did show that their fastest scanning strategy (Figure 4: strategy H), showed the best accuracy results.
Yilmaz et al. did correlate scanning time and accuracy (Yilmaz 2021), and their results showed no correlation between the two outcomes.

Our findings revealed a weak positive correlation for trueness and scanning time, while precision and scanning time showed a moderate positive correlation. Our study was performed partially by inexperienced operators, so this could have played a role in these results. In principle, faster scanning, at least when over-scanning unnecessarily is avoided, but the required surfaces are completed in an efficient scanning process, should result in improved accuracy. Novel operators will tend to over-scan, and this may result in longer scanning times as well as lower accuracy.
As shown in previous studies, other factors, such as the scanning path may have an impact on the accuracy (Passos 2019, Müller 2016), and the experienced operator can better follow the most accurate scanning strategy, and complete the digital impression in less time. A novel operator may find it difficult following the proposed scanning path, even after instruction. Additionally, having the experience or the training to choose the correct lighting condition (Revilla 2020.a, Revilla 2020.b) may also influence the scanning times and accuracy outcomes. The importance of experience is recognized by most studies performing their investigations with expert operators (Chiu 2020, Chebib 2018, Doukantzi 2020, Passos 2019, Yilmaz 2021). However, the findings of this investigation reveal that a short training program of 3 sessions may be enough to close the gap between novel and experienced operators, for certain IOSs (S1), in the context of dentate and quadrant scans, while for S2, a more extended training program may be required.

No previous investigation included inexperienced and experienced investigations; hence the findings of this study are relevant in pointing at the magnitude of training that may be expected for novel operators to perform scans in similar times and accuracy ranges as experienced operators.

Our investigation revealed that one scanner was easier to learn than the other. In the scanner that was less user-friendly regarding learning curve, operator factors, such as age, personal talent, or experience had a bigger impact than on the scanner that was promptly learned by all inexperienced operators (younger and older). This was reflected both in the scanning time and in the accuracy outcomes. These findings, reflect the impact that the scanning system has overall on scanning time and accuracy. As IOSs continue to evolve, operator skills will progressively reduce their impact on scanning times and accuracy. These findings are limited to the investigated IOSs and softwares, and need to be corroborated in further in-vitro and in-vivo investigations.

6.3 Limitations and suggestions for future research

Limitations of the present investigation include:

- The use of several patients, instead of one sole patient, to make the obstacles experienced by all the participants equal. This was however not feasible due to ethical considerations. Patients were included if they were medically healthy, had a complete dentition, were free of active intraoral inflammation, and presented sufficient mouth opening evaluated subjectively. Mouth opening may have an impact in the performance and learning curve of novel and potentially experienced IOS operators, specially when the posterior region is being scanned. Further steps could be taken in future research, with efforts oriented at better standardising the mouth opening for example, by establishing a minimal mouth opening threshold in mm, and recording this mouth opening. The registration of more accurate mouth opening data could increase the collective knowledge and understanding of IOS limitations, and their objective thresholds.

- Only men were included as study participants. This may, or may not have had an impact on the study outcomes. For future research, may it be recommended that gender inclusion be controlled, in order to achieve gender balance.

- True values need to be interpreted with caution, as the in-vivo model does not allow to place the patient under a reference scanner. The advantages and necessity to conduct in-vivo studies account for the use of this model.

- In order to obtain an STL file to use as a reference model, conventional models from conventional impressions were scanned in a laboratory scanner. Arguably, an industrial scanner could have been used to digitize these conventional models, instead of a laboratory scanner, limiting inaccuracies by using the most accurate scanner possible. This needs to be acknowledged as a limitation of this study. However, the utilized laboratory scanner has shown a high level of accuracy (6 microns), dismissible if compared with the wider range of accumulated inaccuracies shown in the combined steps necessary to obtain a conventional model. For this reason, the convenience of using a laboratory scanner was preferred.

- Quadrant scans of fully dentate patients were evaluated in this investigation. Conclusions for more challenging cases cannot be drawn. Future research could focus on evaluating the impact of the operator's age and experience on the scanning times and accuracy of digital impressions for more challenging cases, such as completely edentulous, with or without implants, or cases with prepared teeth.

- Clinicians above 40 years old were included as older novel operators. Differences were found between the younger and older novel operators, however these differences were not always marked. In the psychology learning research field, generally, people older than 60 are considered older learners (Broady 2010, Merestein 2021, Zhang 2021). Since the objective of learning to use digital impression systems is to apply them in clinical practice, a younger cohort of older clinicians was used in the present investigation, to increase the insight in the learning capacities of mature clinicians, who still have a certain time to successfully incorporate digital technology into their clinical practice. Further research could evaluate the learning patterns of an older cohort, for example older than 50 years old., with the potential of finding greater differences, when compared to 40 year old practitioners. However, it was noted in the current investigation that recruiting older clinicians was increasingly difficult, as older dentists tended to be busier, and their inclination to participate in time consuming research may be affected, if they consider they have little to gain from learning to use new impression methods.

- The use of powder was required for one scanner and not the other. The time required to apply the powder was included in the scanning time for that scanner. This was decided as it was considered that powder application is part of the scanning process for this type of scanner, and should be taken into account. The differences in scanning time between both scanners cannot be attributed solely to the time required for powder application, as this process usually takes a few seconds. To clarify the impact of this step, to evaluate the degree to which time may be influenced by powder application and control (as continuos aspiration and potential reapplication may be necessary), future research could further stratify the scanning time to differentiate in between powder application (including measures aimed at maintaining the correct amount of powder in the surface), and real scanning time, which will analyse the scanning efficiency of the system.

- Only two intraoral scanners, and two software versions for each were tested. Technology advances so fast, these findings can only be conclusive about these scanners, with these software versions. However, on the hole picture, it allows us to gain knowledge on the direction of scanning times, learning curves and accuracy. Future research needs to further validate these findings with other intraoral scanners, with more recent software versions.

7 Conclusions

Within the limitations of the present investigation, the following conclusions may be drawn:

1. The operator's a*ge (≤ 25 years, ≥ 40 years)* had an influence on the performance and the learning curve of inexperienced IOS operators. Younger operators showed better performance and faster learning curves when compared to older operators.
2. The *IOSs* evaluated had an influence on the performance and the learning curve of inexperienced IOS operators. One system (S1) showed faster scanning times while it demonstrated to be less impacted by operator factors such as age or experience.
3. The software version had an influence on scanning time before training, but not after training, showing a tendency for updated software versions to be easier to perform and learn than older software versions.
4. The operator's a*ge (≤ 25 years, ≥ 40 years)* had an influence on the accuracy (trueness and precision) of STLs registered by inexperienced IOS operators. Younger operators registered STLs with higher accuracy than older operators.
5. The *software versions* evaluated did not influence the accuracy (trueness and precision) of STLs registered by inexperienced IOS operators.
6. The *IOSs* evaluated did not influence the accuracy (trueness and precision) of STLs registered by inexperienced IOS operators.
7. Scanning time and accuracy revealed a correlation, with faster scanning times showing a tendency for more accurate STLs.

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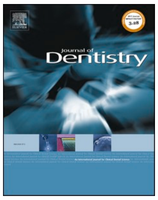

Influence of age and scanning system on the learning curve of experienced and novel intraoral scanner operators: A multi-centric clinical trial.

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ABSTRACT

Objectives: To evaluate the effect of age and intra-oral scanner (IOS) on the learning curve of inexperienced operators.

Methods: Thirty-four operators pertaining to 1 of 3 groups: (G1) students $\leq$ 25 years (y), (G2) dentists $\geq$ 40y, and (G3) a control group of experienced IOS operators (no age limitation), were included. All participants performed baseline and final quadrant scans on a volunteer subject, before and after a training program of 3 sessions, with two different IOS: TRIOS 3 (S1) and True Definition (S2). Baseline and final scanning times were registered in seconds.

A Pearson correlation was applied to evaluate the correlation between age and scanning time.

An ANOVA of repeated measures test was applied to evaluate inter-group (G1, G2, G3) and inter-system performance.

Significance level was set at $a = 0.05$.

Results: Age and scanning time for inexperienced operators showed a weak positive correlation for final scanning time ($r = 0.29$, $p < 0.05$). When comparing groups and filtering by IOS, S1 failed to show differences between groups ($p > 0.05$). With S2, the control group demonstrated a better performance than G2 ($p < 0.05$), while G1 only demonstrated a better performance than G2 at final scanning time ($p = 0.005$). Overall, the type of IOS had a significant impact on the scanning time ($p < 0.001$).

Conclusion: Results from this study indicate that age and type of IOS have an impact on the performance and learning curve of inexperienced IOS operators.

Clinical significance: Gaining knowledge on how different aspects, such as age, experience or IOS system, influence the learning curve to IOSs is relevant due to the financial and strategical impact associated with the acquisition of an IOS.

1. Introduction

Nowadays, many workflows in dentistry begin with an initial impression, a registration of the required teeth, implants, and neighboring tissues. The accuracy of this step is key for the final success of the treatment [1,2].

Traditionally, impressions were made using conventional trays and elastomeric materials. This approach is reliable and provides clinically acceptable outcomes [3]. However, conventional impressions remain technique sensitive [3,4].

Intra-oral Scanners (IOS) were introduced in the early 80 s to counteract the disadvantages of conventional impressions, such as avoidance of uncomfortable trays and impression materials in the oral cavity that were frequently associated with gagging, or logistical challenges such as storage, transportation and handling of impressions and master models [4,5]. The initial idea was to improve efficiency by avoiding the inconveniences of the analog processes [4]. For years, the accuracy of IOS remained inferior to conventional impression methods [6]. Over the last decade, technological developments have allowed a significant improvement in the accuracy of IOS to comparable levels of conventional impressions on single-unit and short-span fixed dental prostheses (FDP) on teeth [7,8] and implants [9–11].

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Once the accuracy of conventional and digital impressions is no longer an issue, other aspects gain relevance in the choice of the impression method. Factors such as the costs (initial purchase, consumables, and regular maintenance) [12], the patient's [13] and operator's perception [6,14], the time required to perform an impression [13,15], or the learning curve [16] may play a decisive role. Purchasing costs and maintenance fees are high for IOS systems, although they require fewer consumable materials and storage space than conventional impressions using elastomers [17].

Several studies have shown a patient preference towards IOS in comparison to conventional impressions [13,18,19], while operator preference might depend on the age of the operator [20]. It has been shown that dental students preferred IOS, whereas experienced clinicians tended to prefer conventional over digital impressions [20].

Multiple factors influence the required time to perform conventional or digital impressions. For conventional impressions, factors such as material setting time, tray preparation including screw-access perforation, and adhesive application contribute to the duration of the procedure. In contrast, digital impressions are affected by extension of the impression area (full-arch vs. quadrant impressions), IOS system used, software version, lighting conditions, and patient-related factors (cheek flexibility, tongue interference, salivary rate, breath, preparation margin depth) [4].

Learning curve is defined as the acquisition of a skill over time until plateau performance is achieved [21]. Time has been used to evaluate the learning curve of IOS [12,16,22]. Roth et al. used a hybrid model to evaluate learning curve, by measuring *in vivo* scanning time and image number (count of images created by IOS during the scanning process) [12]. Kim et al. compared model scanning times before and after 4 training sessions (*in vivo*) [12], and Waldecker et al. evaluated the effect of amount of training sessions (1–3) on model scanning times of dental students [16]. It was shown that repeated practice (1–4 sessions) reduced scanning time, yet as no control group was used, it was not possible to determine if proficiency had been reached [12,16,22]. Age was not controlled in any of these investigations.

Evaluating whether factors such as age, previous intraoral scanning experience or the scanning system itself influence the performance and learning curve of IOS operators in a clinical setting needs further clarification.

For this purpose, the objectives of this multicenter clinical trial were to evaluate if the operator age (≤ 25 years, ≥ 40 years) and the type of IOS influence the performance and the learning curve of inexperienced IOS users compared with experienced users. Therefore, the null hypotheses were established as: (1) operator age does not influence the performance and learning curve of IOS operators, and (2) the intraoral scanning system does not influence the performance and learning curve of IOS operators.

2. Materials and methods

2.1. Study design

This multi-centric clinical trial was performed in the Faculty of Dentistry of University Complutense of Madrid (Center 1) and the University Clinics of Dental Medicine of University of Geneva (Center 2). Consequently, the study protocol was submitted and approved by the local ethical committee of the canton of Geneva (No. 2017–01717) and by the local ethical committee of the Hospital Clínico San Carlos, Madrid (No. 17/367-E).

Two IOS systems, both Conformitè Europëenne (CE) certified, were evaluated in both centers: Trios 3 (3 Shape, Copenhagen, Denmark) and True Definitions (3 M, St. Paul, MN, USA). IOS' characteristics are shown in Table 1.

2.2. Study participants

To evaluate if age influences the learning curve of clinicians inexperienced with IOS, two analogous test groups (with marked age difference) and one control group were established in both centers:

- Test Group 1 (≤ 25): dental students aged 25 or younger with no previous experience in the use of IOS.
- Test Group 2 (≥ 40): dentists aged 40 or older with no previous experience in the use of IOS.
- Control Group (control): clinicians with experience in the use of IOS, with no age restriction. Experience was determined by the completion of at least 100 scans [25].

A sample size calculation was performed, including an alpha error of 0.05, a 1-beta error of 0.8 for three groups, and an effect size of 0.3 [26], based on a similar study [22]. In that study, two groups of oral hygienists had shown an improvement in time registrations of 23% and 24%, respectively, after training. The sample size calculation resulted in a minimum of 30 operators. Finally, 36 operators were included in total in both centers (Center 1 and Center 2,) 18 operators per center, to compensate for potential dropouts.

An *in vivo* model was chosen. Ideally, a single patient would be selected to evaluate operators under most standardized study conditions (same cheeks, same mouth opening, etc.). However, as scanning a single patient many times would not be acceptable for ethical reasons, six volunteer study subjects were recruited in each center, 12 in total. Fourth-year dental students, medically healthy, free of active oral inflammation, who were interested in contributing to the advancement of research and becoming acquainted with IOS systems were voluntarily included as study subjects.

2.3. Study sessions

All study operators (≤ 25, ≥ 40, and control) completed a 4-session study schedule (Table 2) with each IOS, including three training sessions (one on typodont models and two *in vivo*) and two test scans (baseline and final). Each study session was spaced at least a week apart. Study introduction, training sessions, and time recording were performed in each center by a trained investigator (MRM (Center 1) and AAH (Center 2)).

During the first study session, the study protocol and scan strategy (Fig. 1) were introduced. Participants were requested to complete a partial scan extended from mesial of the canine to distal of the first molar of quadrants 1 and 4, including at least 3 mm of gingiva, and a bite registration (Fig. 1). Study subjects were all in a supine position, and all study scans were performed under the supervision and assistance (retraction and aspiration) of the trained investigator, with dental chair lights turned off [27]. An impression was deemed satisfactory when the requested regions were registered, allowing minimal interproximal

Table 1
Intraoral scanner (IOS) characteristics.

IOS	Software version	Technology	Description
Trios 3	1.18.1.2 and 1.18.1.3	confocal microscopy	The projection of optical slices on the object reflects focused and defocused images. The sharpness of the image determines the distance to the object, correlating to the focal length of the lens [23].
True Definitions	5.3.1 and 5.4	active wavefront sampling	Distance and depth information are derived and calculated from the pattern produced by each point formed by the rotating module around the optical axis [24].

Table 2
Study schedule: task description in each session, time each operator and study subject are required to invest for study participation, per intraoral scanner (IOS).

Study session	Study task	Time needed by operator / per IOS	Time needed by subject / per IOS
1	Introduction to system and scan strategy	10 min (group)	/
1	Baseline scan with test patient	10 min (each)	30 min
1	Training with models	20 min (each)	/
2	Training with patient	20 min (each)	/
3	Training with patient	20 min (each)	/
4	Final scan with test patient	10 min (each)	30 min
Total time needed		90 min (1 h, 30 min)	60 min (1 h)

gaps. An example case is shown in Fig. 2; a clinical picture (Fig. 2a), and the corresponding complete scans with IOS S1 (Fig. 2b) and S2 (Fig. 2c).

The time each operator spent filling in the laboratory order and scan was recorded in seconds (baseline computer time and baseline scan time). Following the baseline records, each operator performed a 20 min training of specific quadrant scanning on typodont models (Frasaco GmbH, Tettnang, Germany).

The second and third sessions were exclusively training sessions (20 min each), in which each study operator practiced scanning *in vivo* by scanning each other.

In the fourth session, each study operator performed the final scan on their study subject. Again, the time required to complete the laboratory order and the scanning time were recorded in seconds (final computer time and final scan time).

Because completing the study with the first IOS system implied some training for the inexperienced operators, which could potentially have

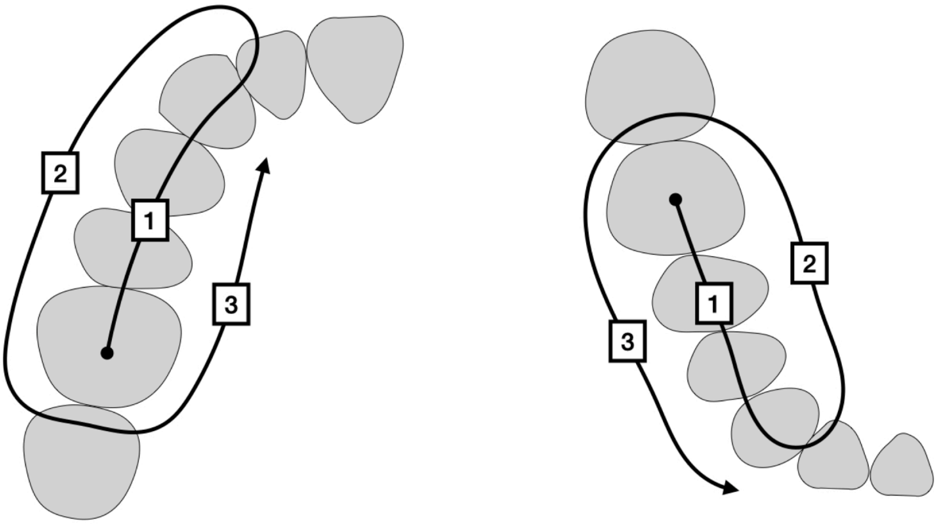

Fig. 1. Scan strategy for maxillary (left image) and mandibular (right image) arches, as recommended by the intraoral scanners' manufacturers.

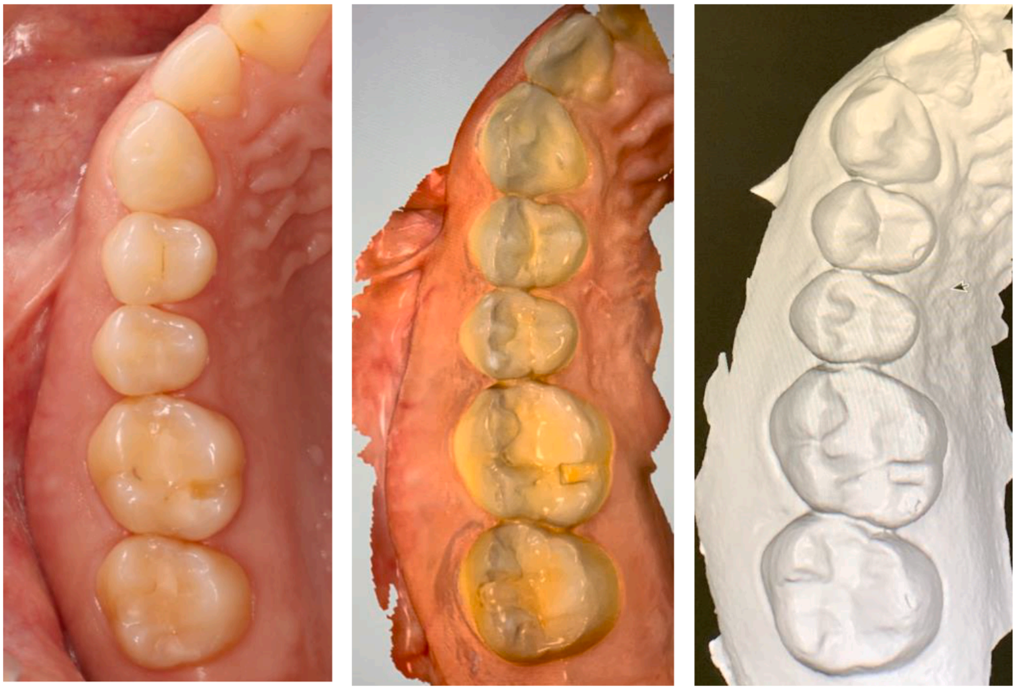

Fig. 2. A clinical picture of quadrant 1 is shown (2a), and the corresponding complete scans with S1 (2b) and S2 (2c).

an impact on their performance when completing the study with the second IOS, half of the study participants initiated the study with Scanner 1 (S1) (Trios 3 IOS), based on confocal microscopy technology. The other half began with Scanner 2 (S2) (True Definition IOS), based on active wavefront sampling technology.

2.4. Performance and learning curve assessment

The performance was evaluated by comparing the time taken by each study group (≤ 25, ≥ 40, control) to complete the study tasks: (i) filling in the laboratory order (computer time) and (ii) completing a satisfactory quadrant digital impression with each IOS (scanning time), at baseline and final time points.

The learning curve was assessed by comparing the time improvement of each study group before and after training (between baseline and final time points).

2.5. Statistical analysis

Independent variables were age (≤ 25 vs. ≥ 40 years old), experience (inexperienced vs. experienced) and IOS system (S1 and S2). Dependent variables were computer time and scanning time at baseline and final time points.

A Kolmogorov–Smirnov test was applied to test the normality of the sample, and the Levene test was applied to evaluate the homogeneity of variances.

A Pearson correlation was applied to evaluate the correlation between age and time performance (baseline and final scanning), excluding the control group.

An ANOVA of repeated measures test, with a Bonferroni correction, was applied to evaluate inter-group (≤ 25, ≥ 40, control) performance (at baseline and final scanning); inter-system (S1 vs. S2) performance (at baseline and final scanning); and experience (inexperienced vs. experienced) performance (at baseline and final scanning).

For the intra-group learning curve evaluation (training effect), the paired-samples *t*-test was applied to evaluate within-group changes (between baseline and final scanning).

The level of significance was set at $a = 0.05$. All results were calculated with SPSS version 26 (SPSS, Chicago, IL, USA).

3. Results

A total of 34 operators and 12 study subjects (patients) participated in the two centers of this study. Two operators initially assigned to group ≥ 40 in Center 2 were unable to participate due to agenda incompatibility with the study schedule and were excluded from the study. Mean age of study participants, per center and per group are shown in Table 3.

Computer time ranged between 8 and 170 s (seconds), with a mean (SD) baseline computer time of 62.3 (38.3) s and 57.7 (37.1) s for final computer time. Neither age, scanning system, or training had a significant effect on computer time ($p > 0.05$).

The Kolmogorov test revealed a normal distribution of the data for scanning times 1 and 2 ($p = 0.200$) and the Levene test revealed homogeneous distribution of variances for scanning time 1 ($p = 0.140$) and for scanning time 2 ($p = 0.069$).

Scanning time ranged between 50 s (control/S1/final scan) and 604 s ($\geq$40/S2/baseline scan), with an overall mean (SD) baseline scanning time of 269.4 (124.8) s and an overall final scanning time of 225.2 (103.2) s (Table 4).

Table 3
Mean age per center and per group.

	Mean age		
Center	Grupo < 25	Grupo > 40	Group Control
Center 1	22	59	38
Center 2	23	54	34

Operators who had better performances (shorter scanning times) at baseline also demonstrated better performances on final scanning after training ($r = 0.8$, $p < 0.01$). Age and scanning time for inexperienced operators showed a weak positive correlation for final scanning time ($r = 0.29$, $p < 0.05$).

Experienced operators demonstrated a better performance than inexperienced operators at both time points ($p = 0.016$). When comparing groups ($\leq$ 25 years (y), $\geq$ 40y, control), the control group demonstrated a better performance compared with group $\geq$ 40y at baseline ($p = 0.013$) and final scanning time ($p < 0.001$). However, no differences were found between control and group $\leq$ 25y and between group $\leq$ 25y and group $\geq$ 40y ($p > 0.05$). When comparing groups and filtering by IOS, S1 failed to show differences between groups ($p > 0.05$). With S2, the control group demonstrated a better performance than group $\geq$ 40y at baseline ($p = 0.010$) and final scanning time ($p = 0.000$), while the group $\leq$ 25y only demonstrated a better performance than group $\geq$ 40y at final scanning time ($p = 0.005$).

Overall, the scanning system had a significant influence on the baseline and final scanning times ($p < 0.001$).

With respect to the learning curve, young operators ($\leq$ 25y) revealed a significant improvement in the scanning time between baseline and final scanning for both IOS systems ($p < 0.05$). Older operators ($\geq$ 40y) only showed a significant improvement with S1 ($p < 0.05$). Experienced operators (control) revealed a significant improvement with S2 ($p < 0.05$). A graphical representation of the performance at both time points and time improvement of each group and scanning system is shown in Fig. 3.

4. Discussion

The findings of the present clinical study showed that younger operators performed faster scans than older operators with at least one of the IOS (S2). Moreover, improvements in scanning time (learning curve) were seen after training for younger operators with both IOS, while improvements were only seen with one IOS (S1) for older operators. Therefore, as the generation group (age) and the scanning system had an impact on the scanning performance and learning curve of novel IOS operators, both null hypotheses were rejected.

Computer times revealed acceptable performance for all groups and systems even before training. One of the IOS (S2), and the younger operators showed a tendency for shorter computer times. However, no significant differences were found, probably because computer times were generally short.

Studies in the medical field used experienced operators to provide the benchmark for performance and evaluate the learning curve of novel operators [28,29], as was done in the present study. The control group, integrated by IOS expert operators, would be expected to show plateau performance before and after training, or in other words, should not show an improvement in scanning time performance after training, as their learning curve should be flat. In line with this expectation, the control group showed the best performance with both IOS, in agreement with what was reported in a previous study [18], and no improvement with one of the IOS (S1). Unexpectedly, the control group showed a significant improvement with the other tested IOS (S2), which was also the steepest improvement of all groups and IOSs. Participants in the control group were required to have performed at least 100 scans [26] to be included in this study. However, it was not specifically controlled what IOS had been used to acquire experience. In fact, members of the control group were more experienced with S1 than with S2, which is reflected in their flat learning curve with S1 and their steep learning curve with S2. These findings indicate that once an operator is experienced with one IOS, the learning curve for another IOS can be expected to be steep.

The impact of age on scanning time was non-existent before training

Table 4
Results table; Mean, standard deviations of Baseline and Final scanning times, including improvement recordings are shown for test and control groups, filtered by intraoral scanner (IOS).

IOS	Baseline scanning time			Final scanning time			
	Group	Mean (sec)	Standard Deviation	Group	Mean (sec)	Standard Deviation	Improvement (sec)
S1	≤ 25 years (y)	208,9	91,8	≤ 25 y	163,2	63,0	45,7
	≥ 40y	217,5	103,5	≥ 40y	180,7	90,3	36,8
	Control	156,8	75,6	Control	137,9	54,3	18,9
S2	≤ 25 y	339,3	94,8	≤ 25 y	271,1	57,0	68,2
	≥ 40y	414,0	104,4	≥ 40y	371,0	75,2	43,1
	Control	287,6	88,8	Control	235,7	76,9	51,8

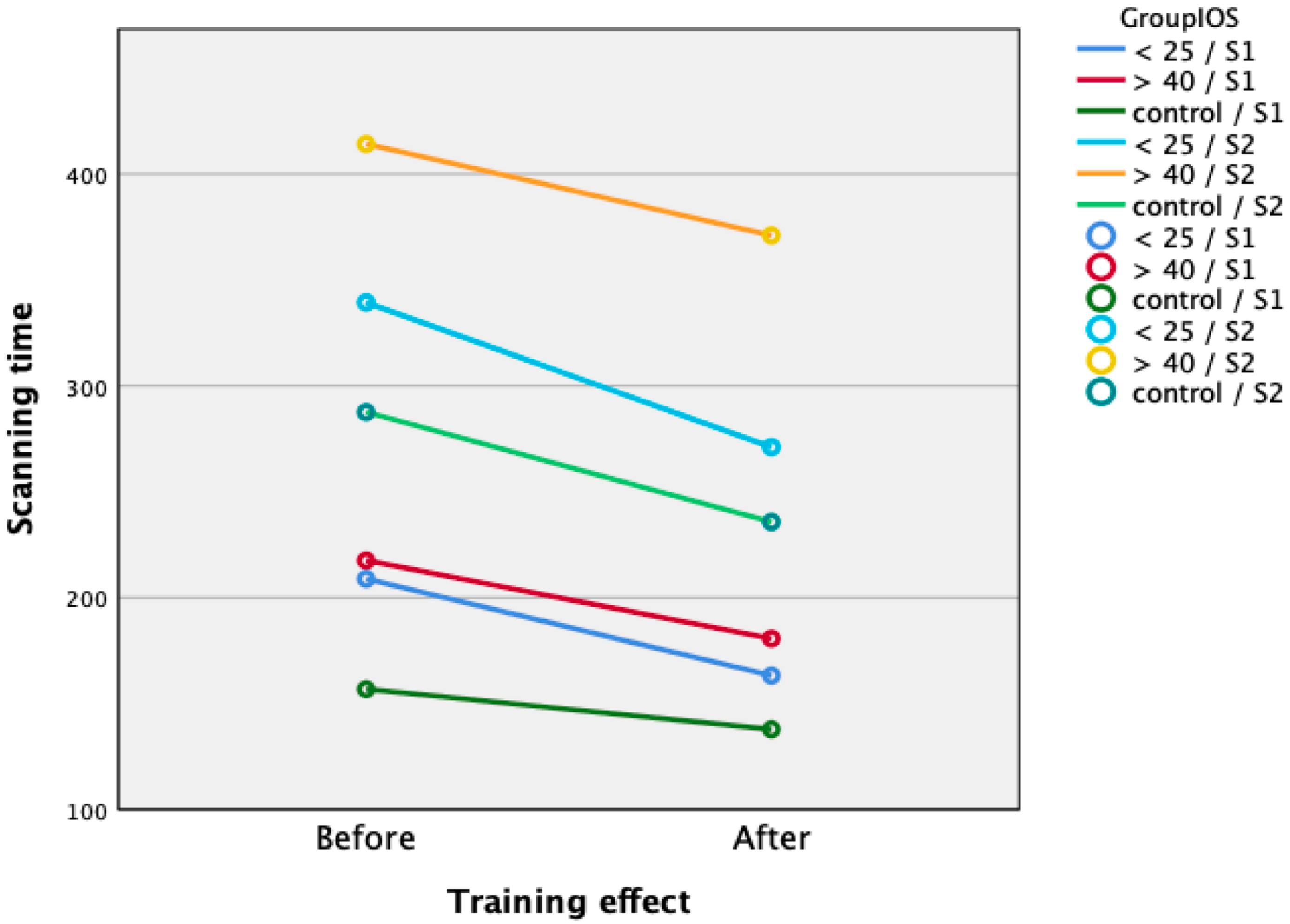

Fig. 3. Line graph: Scanning time (seconds) by scanning session (before and after training) filtered by Group (≤ 25 years (y), ≥ 40y, control) and Intraoral scanner (IOS) (S1, S2).

and minor after training, shown by a weak positive correlation between age and final scanning time. This effect was seen specifically for S2, where younger and experienced operators showed a better performance for final scanning times than older operators. Several studies in cognitive psychology have shown that after appropriate training, the benefits of learning plasticity presented by youth are diluted, and older people achieve similar performance and attitude towards computer tasks [30, 31]. Even though older people may reveal slower rates of learning, they maintain their brain plasticity and can retain the benefits of training as much as young adults [32]. The present study's findings may therefore indicate that, while three training sessions are sufficient for novel operators (no matter the age) when S1 is used, older operators might need additional training sessions with S2.

Nevertheless, the strong correlation between each operator's initial and final scanning times indicates that operators who were fast before training were also faster after training. Individual characteristics such as talent or previous experience using other technological devices (such as video games) could be hypothesized as possible factors to influence the performance and learning curve of inexperienced operators [32–34].

The impact of the scanning system was evident, with S1 showing faster performances and strong learning curves for both young and older operators. Experience only had an impact on the scanning times when S2 was used, while with S1, only experienced operators showed a tendency for faster scanning times. The greater differences between groups on the S2 IOS might indicate a higher sensitivity of this device to the operator.

Several software versions were used, as one center performed the study during one academic year (2017–2018) and the other center during the following year (2018–2019), and the software was updated in that time. Additionally, both centers have different temperature, pressure, and humidity conditions. Whether or not these confounding factors played a role in the findings of this investigation is unknown. Ideally, the study should have been performed simultaneously in both centers with the same software versions, under similar conditions.

The included IOS systems were based on different technology, confocal microscopy, and active wavefront sampling. Although both IOSs use light as a light source, they present some differences, such as the need for powder coating (for S2 and not for S1), camera size and weight (S2 has a smaller hand-piece than S1), and distance to the scanning object (S2 requires a specific scanning distance (1 cm), while the S1 hand-piece may be in contact with the occlusal surfaces to be scanned) and image acquisition mode (ultrafast imaging (S1) and continuous video sequencing (S2)). It may be difficult to evaluate how they independently affect scanning time, as systems can only be tested as a whole, and each system has a combination of characteristics. Overall, S1 showed a better performance and steeper learning curve than S2 when evaluating scanning time and additionally reflecting a lower impact of the operator (age or experience) on the scanning time, especially after training. This agrees with a previous study [22], where the same system (S1) reported a low influence of the operator on scanning time. Previous studies evaluating the accuracy of different scanners concluded that active wavefront sampling systems were as accurate as systems using confocal microscopy [1,2,35]. The correlation of scanning time on the accuracy of the resulting scans remains unclear and should be evaluated in future research.

This study was limited to two IOSs, hence the findings may not be applicable to other systems. Further research on multiple systems would be advisable to deepen the understanding of the influence of different aspects related to the operator on the learning curve of IOSs overall.

5. Conclusions

Within the limitations of this clinical study, it may be concluded that:

- Age, experience, and operator affected the performance and learning curve of novel intra-oral scanner operators when an active wavefront sampling IOS was used.
- The scanning system affects the performance and learning curve of novel intra-oral scanners operators.

CRediT authorship contribution statement

Cristina Zarauz: Conceptualization, Methodology, Writing – review & editing. **Irena Sailer:** Supervision, Writing – review & editing. **João Pitta:** Writing – review & editing. **Mercedes Robles-Medina:** Investigation, Writing – review & editing. **Abra Abdulahai Hussein:** Investigation, Writing – review & editing. **Guillermo Pradíes:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest with respect to this study. All intraoral scanners used in this multicentric clinical study were the property of the University Complutense of Madrid and the University of Geneva.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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