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Cobotized intra-oral digitization: a preliminary study

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1. INTRODUCTION

New digital technologies have now enhanced healthcare and more specifically dental care. This has led to the emergence of a CAD/CAM dental chain, which competes with or sometimes replaces the traditional dental chain. One of the major technological advances is the use of intra-oral scanners (IOS) in oral imaging for dental restorations.

The use of IOS in the daily practice offers many advantages including digital files' dimensional and geometric stability over time; patient comfort improvement, eased communication between practitioners and prosthetists, and time reduction in chairside.

Practitioners need high quality STL files, as a starting point of the CAD/CAM process [1-2], but digitization is an operator dependent activity [3-5]. In addition, today's students are not trained in the use of this tool during their studies and learn empirically through their own practice, which also creates errors. Created errors will accumulate with those generated throughout the whole workflow. Consequently, some produced prostheses are poorly fitted and must be manually chairside adjusted by milling and polishing, thus reducing their quality and lifespan. Nevertheless, using IOS requires repetitive movements and awkward postures and increases the risk of musculoskeletal disorders for clinicians even more for heavy IOS [6].

Since the early 80's, the use of robotics has become increasingly widespread to limit the impact of the human factor and reduce operational time in industry and more recently in dentistry [7-8], leading in odontology, to the ability to isolate the most factors as possible linked to the practitioner. In a context of immediate proximity between the patient and the practitioner, the use of cobot handling the IOS instead of the practitioner takes on its full meaning and can be a solution to:

- Increase, stabilize and make repeatable the level of quality of images and data generated by IOS,
- Reduce the risk of musculoskeletal disorders for practitioners when using IOS,
- Freeing up time for the practitioner, highly demanded and/or in insufficient numbers,
- Become a useful teaching tool for learning how to use appropriately IOS in dental training units.

To this end, the aim of this article is to introduce an in-vitro preliminary study which explore the feasibility of a cobotized intra-oral digitization and to objectively compare results to those obtain by a manual operator (practitioner).

2. STATE OF THE ART

2.1. Cobot in dental care

Robotic technology applied in healthcare has reached advances and offers various use [9, 10] whose most common are the assistance and the monitoring of patients or the assistance of paramedical staff in non-critical tasks. However, interventional robots dedicated to help practitioners to perform efficient and safe procedures is a hot and disruptive topic. In dental care, research studies are carried out in oral rehabilitation and implantology with a focus on the development of robots able to increase the accuracy of the practitioner's work, in particular for dental preparations [11]. Results showed that the use of a poly-articulated robot (UR5e cobot) trained to reposition itself in an in-vitro patient environment enabled accurate and repeatable positioning for drilling operations [12], even for small spaces like the oral cavity with adaptive control strategies [13]. The performance of robots for dental applications would therefore be appropriate for intra-oral scanning, insofar as the experimental biases associated with the robot are relatively low. However, it needs to be proven that handling a IOS (a cumbersome

object compared with the tools used in the other studies) in the confined environment of the mouth is realistic and leads to results similar to those obtained with practitioners. To this end, it is necessary to look at how the quality of intraoral scans obtained with cobot or manually is assessed.

2.2. Accuracy measurement in dentistry

IOS are not only used for in vivo digitization but also for finished products such as dental restorations or aligners. It is also essential to compare the STL files of these scans in order to determine which clinical protocols, which biomaterial or which manufacturing parameters perform better. Several comparison methods exist based on STL superimposition [14].

A first solution uses physical artefacts such as cubes, hemispheres [15] or cuboids [16] placed on to the samples to be compared. By reconstructing these elementary geometries using their canonical models, it is possible to define reference entities on which the STL are aligned. Nonetheless, while canonical models help in assessing reference values [17] it is not adequate for the dental arch due to its complex horseshoe shape. Indeed, without modifying the arch itself, it is challenging to set up a standard reference coordinate system, which is essential for evaluating deviations and calculating the trueness and precision according to the International Standards Organization (ISO) 5725-1:2023 [18].

A second solution used to compare two STL files is a best-fit alignment procedure, which incorporates an iterative closest point (ICP) algorithm [20]. This solution is more suitable for dental arches since no stable anatomical features can be used to help with the alignment [18]. Results obtained with best-fit alignment show that distortions after repositioning mainly occur on occlusal surfaces [19] and interproximal surfaces [20]; moreover, second molars are found to be more affected than first molars [21].

It is therefore necessary to develop a comparison method based on current tools, but suitable for comparing STL of dental arches with complex shapes and variable tissues depending on the area scanned.

3. MATERIALS AND METHODS

3.1. Dental artefact, IOS and cobot

This study focused on the digitization of a mandibular model (i.e. a lower dental arch). An anatomical model used for dental training is selected in order to work on a standard mandible. The STL file of a Frasco ANA-4 anatomical model (later called nominal mesh) is 3D printed on a Form 3B (Formlabs), a SLA dental machine filled with the Dental Model V2 (Formlabs) resin. The printed mandible is then set on a 45 mm average mouth opening [22] articulator in order to be as close as possible to an in-vivo situation and placed in the cobot workspace.

A Dexis IS3800 wireless IOS, a compact wireless scanner, weighing 240g, is used. It is equipped with a

standard tip and has a 16 mm x 14 mm field of vision. Data acquisition is achieved using Dexis IS ScanFlow software.

A UR5e cobot from Universal Robots (HMI-MBS) equipped with the 2F-85 Adaptive Gripper is chosen. It has a maximum payload of five kilograms, a reach of 850 mm, six rotating joints (up to $\pm 360^\circ$ of working range at a speed of $\pm 180^\circ/s$) which is in line with the IOS weight and with the distance between tools and patient in a dentist's surgery. Before scanning, the cobot is programmed to recognize the IOS stored on its base with the Wrist Camera, pick it with its grip, put it back on its base and return to its initial position. The pick and place movements are programmed manually with the 3-Position Enabling Device equipped with PolyScope software.

3.2. Cobot scanning pathway

Two scanning strategies, commonly used by practitioners, are tested on the cobot.

- Occlusal-Vestibular-Lingual (OVL) pathway (Figure 1- left): The IOS starts on the second left molar then scans the occlusal face of the mandible, then it switches to the vestibular side (i.e. in contact with the lips) and ends with the lingual side.
- S-shape pathway (Figure 1- right): The IOS starts on the second left molar, and it successively scans its occlusal, then vestibular and finally lingual side and then moves to the next one.

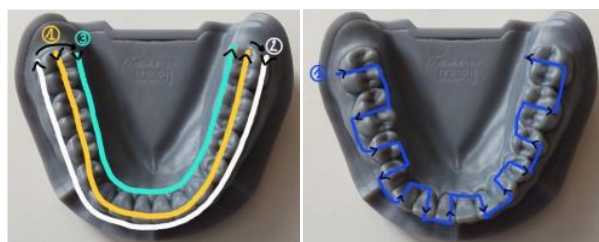


Figure 1 - Left: OVL pathway - Right: S-shape pathway

For both strategies, guide curves are created on SolidWorks above the nominal mesh. They are based on a curve to have a smooth trajectory whose control points are placed:

- Above each tooth at an average height of 2 mm for the OVL pathway.
- At the foot of each tooth on the internal and external side of the gum and above the occlusal face for the S-shape pathway with a distance range from 1 mm to 2 mm.

3.3. Virtual experimental environment

RoboDK is used to create a digital twin of the experimental environment. All elements (anatomical model, articulator, IOS, Cobot, cobot's support) are designed on SolidWorks or downloaded from the RoboDK library. In this virtual environment, the IOS is already settled in the UR5e grip (Figure 2 - left).

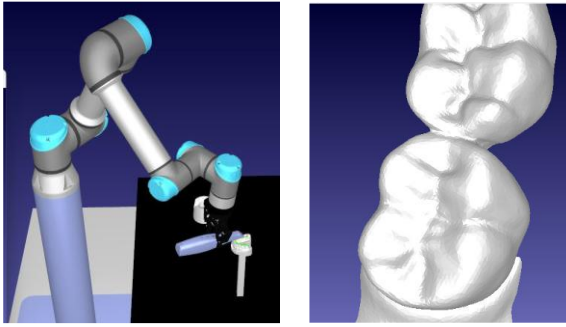


Figure 2 - Left: virtual environment on RoboDK - Right: IOS vision

The center of the IOS window is used as the piloted point. Guide curves upload into RoboDK using the RoboDK Add-In for SolidWorks, define the pathway. The IOS orientation is set manually. A Python's program is also adapted to simulate the IOS vision during the digitization to enable virtual feedback of the scanning operation (Figure 2- right). Thus, when the IOS is working, a virtual video is obtained to ensure that all the teeth and part of the gum are theoretically flown over while moving. From these data, RoboDK simulates the UR5e movement with constant scanning speeds in the different areas of the mandible for the two pathways.

These simulations help to:

- Adjust IOS position/orientation above the mandible
- Ensure that the pathway is fluid enough for the scanning
- Identify forbidden configurations during the operation (eg: collision between UR5e and elements).

To validate the final strategies, some waypoints are moved or added in order to delete crossover points incompatible with the scanning pathway. Some normal vectors are adjusted when the pathways do not ensure the whole digitization of the mandible (non-visible area). An optimal placement of the experimental elements is also found based on the cobot's capabilities:

- Accessibility through the working volume,
- Working area with less movement dispersions due to stopping time and stopping distance [23].

3.4. Manual scanning pathway

In order to compare the scans obtained with the cobot with those obtained manually, an experienced practitioner have to perform scans under the same experimental conditions (IOS, luminosity, mandible model, articulator opening, ...). The strategy adopted for this manual digitization is the OVL pathway.

3.5. Files recording and post-processing

The two strategies of cobotized digitization and the manual one are repeated 10 times each in the same conditions. All the files (3 batches x 10 = 30 files) are exported as STL files in medium resolution, which is recommended by the manufacturer for orthodontics treatments and represents an average distance of 150 μm between two vertices.

Zeiss Inspect optical 3D 2025 software is used to compare the nominal mesh with all the 30 STL files.

First of all, the scanner-generated mesh had its normal vectors automatically oriented during processing to ensure consistency. To prevent potential biases in subsequent deviation calculations, any incorrectly oriented normal vectors were manually inverted.

Then, in order to delete most of the gum part of the files (useless in this study because the restorative treatment concerns teeth only), a cutting plane is needed. To construct this plane, some studies have suggested during mesh processing to manually place points (i.e., markers) on the digital model to define a reference plane, such as from a set distance from the gingival margin, with or without performing next a parallel plane cut [19, 20, 24-26]. However, to prevent any placement bias in this study, a plane passing through 3 specific points is constructed (Figure 3). One of these 3 points is located at the inter-incisal level above the labial frenulum, while the two others are located below the vestibular surfaces of the second molars. To maximize repeatability, the coordinates of these three points are defined on the nominal mesh, as it remains constant.

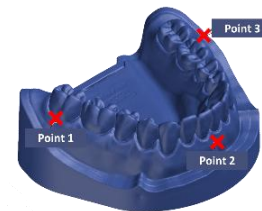


Figure 3 - 3 points cutting plan construction overview

The mean and standard deviation of the three STL batches characteristics (vertices number, facets number, total surface and points density) are calculated.

Each STL file is then superimposed on the nominal mesh for its comparison. The alignment is achieved in two steps: first, an automatic pre-alignment between nominal mesh and scanned mesh; second, a local best-fit on mesh points whose calculated Euclidian distance after the pre-alignment stage is lower than 0.01 mm.

3D color maps are then created by an orthogonal projection of the vertices of scanned mesh on the nominal mesh. Vertices with a projected distance greater than 0.1 mm are excluded. For each map, two indicators are automatically calculated by Zeiss Inspect software:

- the area of valid distance (AVD) i.e. the area of the surface of comparison
- the integrated absolute distance (|ID|) which represents the absolute value of the inscribed volume of the surface comparison i.e. the sum of absolute volumetric deviation between the two meshes.

Rmesh i.e. the ratio between the AVD of each scanned mesh and the surface of the nominal mesh cut by the same previously constructed plane ($S = 3567.8 \text{ mm}^2$) is calculated. Rmesh is only a relative criterion and brings a preliminary comparison output, but it is not sufficient to objective the quality of the files. Hence, a smaller area of the scanned mesh could affect the values of AVD, the integrated absolute distance is normalized by the area of the valid distance to allow for comparison between the models. Thus, the weighted normalized distance (wND)

defined by Fasham & al [27] as the ratio between $|ID|$ and the product $AVD \times R_{mesh}$ is calculated. The wND criterion is suitable to quantify the discrepancies in μm : the lower it is, the closer the STL is to the nominal mesh. Thus, wND represents a magnitude comparable to the trueness defined by ISO 5725-1:2023 [18]. Finally, wND values in the 3 batches are compared with a one-way ANOVA followed by Tukey's post-hoc tests. Figure 4 summarizes the whole flowchart for preparing and processing the STL files.

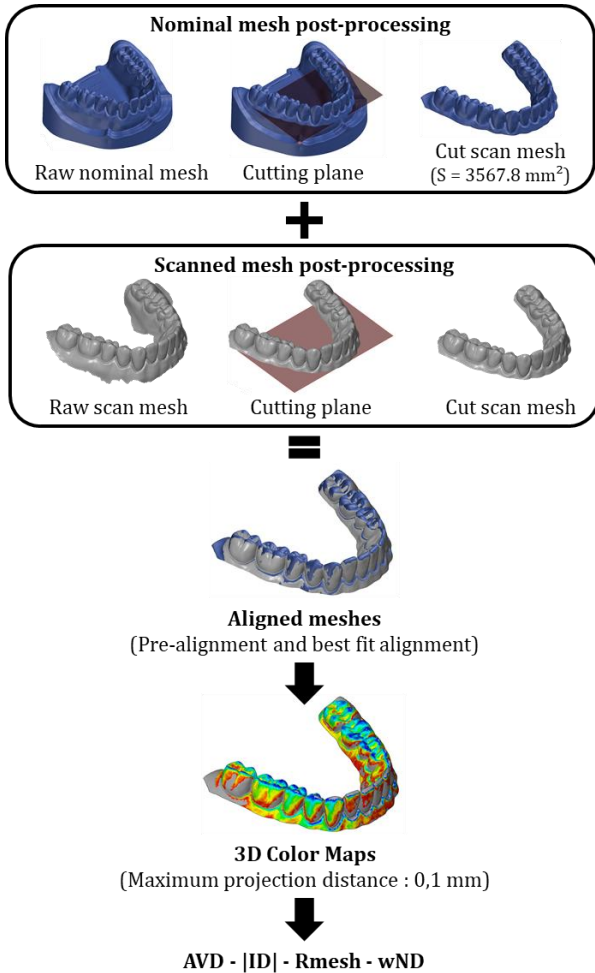


Figure 4 - Flowchart for STL files preparing and processing

4. RESULTS, ANALYSIS AND DISCUSSION

4.1. STL characteristics

Table 1 summarizes the batch keys characteristics of the digitized STL files.

Table 1 - STL files characteristics in the different batches

Batch	Number of vertices	Number of facets	Total digitized surface [mm ²]	Points density [pts/mm ²]
OVL	46449±301	91310±591	3314±4	14.01±0.09
S-Shape	46848±1043	91991±2070	3285±4	14.26±0.30
Manual	44126±476	78171±957	3380±10	13.05±0.12

About the total digitized surfaces, those obtained by manual scanning are slightly larger ($S_{\text{manual}} = 3380 \pm 10 \text{ mm}^2$) than those obtained with the

cobot ($S_{\text{OVL}} = 3314 \pm 4 \text{ mm}^2$, $S_{\text{S-Shape}} = 3285 \pm 4 \text{ mm}^2$). This difference comes from the use by the practitioner of the Dexis ScanFlow software's screen feedback, in real time, to identify the non-digitized areas and therefore go over them again, while for the two-cobotized strategies this was not foreseen. However, this additional digitized surface accounts for only 1.9% to 2.8% and is confined to the gum, which is not considered in this study. Moreover, the standard deviation of S_{manual} is 150% higher than that of $S_{\text{OVL}}/S_{\text{S-Shape}}$, indicating greater variability in the manual scan. In addition, the points densities are higher with the cobotized batches (14.01 to 14.26 pt/mm^2 vs 13.05 pt/mm^2). That is to say, even if their digitized surfaces are smaller, the density of vertices and facets in the STL obtained with the cobot is higher than manually.

These results highlight the clinical interest of using a cobot since it will not be subject to tiredness where even an experienced practitioner can have his performance vary during his working day. Using a cobot can therefore be an interesting option to reduce the variability of the STL characteristics by replacing or assisting practitioners for intra-oral digitalization.

Measurements were conducted over a 25-minutes period per batch to minimize external disturbances such as light and temperature variations. The standard deviations observed across the different STL batch characteristics are low relative to their mean values. Nevertheless, the S-Shape pathway exhibits higher standard deviations compared to the OVL. Similarly, the manual pathway also shows greater standard deviations than those observed with the OVL. These preliminary findings further support the repeatability of the cobotized digitization process, especially if the OVL pathway is used.

For future tests, obtaining files without gum holes will be the subject of close attention. To do this, a better adjustment of the scanner altitude, which is slightly too high, compared to the one used by the practitioner (almost in contact with the tooth) will be tested. This will require the new pathways to be carefully validated on the offline simulation to also avoid collisions.

4.2. Files quality evaluation

The indicators extracted from 3D color maps and the calculated attributes for the three batches are given in Table 2.

Table 2 - 3D color maps attributes in the different batches

Batch	AVD [mm ²]	$ ID $ [mm ³]	R_{mesh} [%]	wND [μm]
OVL	2402±18	142±1	67.3±0.5	87.9±0.9
S-Shape	2368±60	142±2	66.4±1.7	90.6±3.4
Manual	2565±72	145±4	71.9±2.0	78.7±3.0

Concerning AVD criterion, AVD_{manual} is 6.35% superior to AVD_{OVL} and 7.68% superior to $AVD_{\text{S-Shape}}$. It means that the area of surface that respects the 0.1 mm projection distance is larger when the manual scan is made. On other words, the practitioner has digitized a larger surface, and this has not affected the file's quality, since the area satisfying the comparison criterion ($d < 0.1 \text{ mm}$) is also

higher. However, AVD_{manual} has a larger standard deviation, which highlights the difficulty of a practitioner making 10 repeatable scans. At this stage, we may wonder about the results obtained in the case of novice practitioners, who would probably have larger standard deviations and perhaps smaller comparison areas due to their lack of experience with IOS.

Since AVD_{manual} is higher in absolute values than the cobotized AVD , then R_{manual} is also higher in the same ratio than the two other R_{mesh} . Thus, according to this indicator, there is a better matching after a manual scanning than after cobotized scanning. During dimensional analysis of scanned meshes, AVD is prone to discrepancies, making wND the preferred criterion to be used.

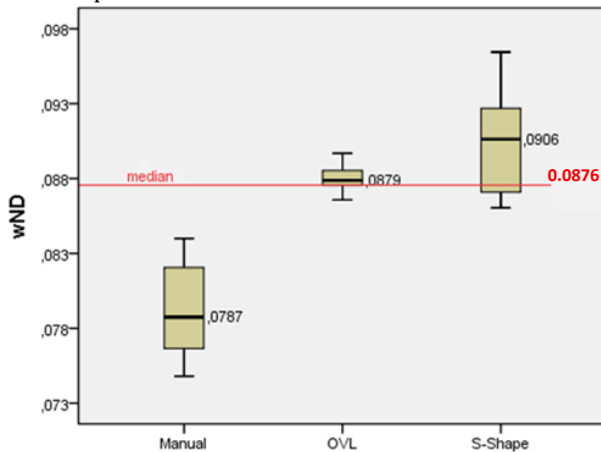


Figure 5 - wND Boxplot for the tested strategies

From a statistical point of view, for wND there is a significant difference between the manual batch and the cobotized batches. wND_{manual} batch is lower than $wND_{\text{cobotized}}$ batches. But there is no significant difference between the wND_{OVL} and $wND_{\text{S-Shape}}$ (Figure 5). Similarly, with results obtained with R_{mesh} , the use of the wND criterion keeps the ranking regarding the quality of the STL files: the quality of the files scanned with the cobot are lower than those obtained by the experiment practitioner. Although there is a significant difference, the gap between wND obtained with cobot and wND obtained with practitioner is less than $10 \mu\text{m}$, even if pathways are at this stage non-optimized. This distance represents 90% of the acceptable error for the entire dental CAD/CAM chain usually defined for a dental restoration. This quantitative indicator also brings a better understanding of potential of cobotized scanning, with better-optimized pathways that are closer to the teeth of the anatomical model.

Nonetheless, wND values may still require refinement depending on the model, as this approach assumes that deviations are uniformly distributed in the excluded mesh regions — those outside the threshold of the maximum projection distance (i.e., regions not part of the AVD). One potential solution is to determine an optimal maximum projection distance tailored to each model, ensuring that the AVD value matches the area of scanned mesh after post processing. This adjustment would enhance the accuracy of wND estimation and mitigate any additional bias caused by the overlap of misaligned facets.

If we focus on the cobotized wND values, we can see that the standard deviation of wND_{OVL} is 3 times smaller than $wND_{\text{S-Shape}}$. Thus, the OVL pathway seems more promising for obtaining STL files as close as possible to the nominal mesh than the S-Shape one. A constant distance movement in OVL pathway that is more difficult to obtain with the S-shape pathway can explain this difference. Indeed, the tooth shape is more complex and requires the scanner to be repositioned around the mandible several times during the digitization. It also requires more modifications of the cobot configuration to scan the entire mandible, which involves more mechanical joints and their inherent backlash while the repeatability announced by the manufacturer is $\pm 0.03 \text{ mm}$.

In this study, a maximum projection distance of 0.1 mm was chosen. This threshold represents the usual value of the marginal fit that ensures the clinical success of restorations fabricated by the CAD/CAM dental systems [28]. Hence, this would introduce errors in the estimation of R_{mesh} as AVD values would exceed the surface areas of the scanned meshes. Thus, the wND criteria prove to be effective in mitigating this effect. However, such errors may be limited and may primarily occur at the boundaries of the mesh. On the other hand, a greater maximum projection distance could provide a better understanding of the global outward or inward deviations by combining the analysis of ID values with $|ID|$ values. Studies have clearly [21] or indirectly [19, 24, 29-31] mentioned the maximum projection distance when assessing deviations. However, none of these studies mentioned the area of the nominal mesh analyzed or the AVD over which the projection was performed.

Another limitation of this study is that the iterative closet point (ICP) algorithm used in the local best-fit processing, may underestimate mismatches while optimizing the alignment [29]. A potential approach for future studies could involve a hybrid post-processing method that includes placing landmarks, fitting planes, and restricting the local best-fit algorithm to smaller regions. Focusing the latter on specific sectors, rather than on the entire mesh, may provide a better understanding of the gap and angular measurements along the different axes between the 2 meshes.

5. CONCLUSION

This study shows the possibility of using cobotics for dental digitization even if at this stage the experimental scope is simplified, since the digitization proves to be repeatable and the quality of the STL files is close to the values obtained by a practitioner. This makes it possible to consider the digitization strategy according to the anatomy and accessibility in the mouth. It is therefore possible to eliminate some operator bias in dental CAD/CAM. We can easily highlight the clinical interest of using a cobot since it will not be subject to fatigue and therefore, we can easily improve repeatability by removing the operator dependence parameter during digitalization.

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