Selective Laser Sintering versus Selective Laser Melting and Computer Aided Design – Computer Aided Manufacturing in Double Crowns Retention

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**Abstract**

**Purpose:** This in vitro study aimed at ascertaining the retention forces for telescopic crowns fabricated with Selective Laser Manufacturing (SLM) and Selective Laser Sintering (SLS) additive technologies, and Computer Aided Design – Computer Aided Manufacturing (CAD–CAM) subtractive technology, by using suitable materials for each.

**Materials and Methods:** Full-factorial design was employed for experimental testing, considering the following three factors: (a) inner crown material – technology (zirconia – CAD–CAM; metal-alloy – SLS; metal-alloy – SLM); (b) tooth type (canine or molar); (c) wet vs. dry conditions (i.e. either with or without artificial saliva). The roughness of the inner crowns was analyzed through atomic force microscopy. Three-way analysis of variance (ANOVA) was applied for statistical analysis, followed by Tukey’s post-hoc comparisons between the crown types.

**Results:** The retention force mean values were between 3.8 N (dry, SLM) and 14.8 N (artificial saliva, SLS), with statistically significant (p<0.001) differences between the three types of inner crowns and interaction with the tooth type. No significant interaction was found between crown or tooth types and the wet vs. dry testing conditions. The zirconia crowns’ retention force was significantly (p<0.001) higher compared to similar SLM crowns, with 95% CI (-5.19; -4.06) N for the differences. The roughness decrease and subsequent loss of retention force was the largest in zirconia.

**Conclusions:** The SLS inner crowns showed the best retention, followed by zirconia and SLM inner crowns.

**Keywords:** Selective laser sintering, Selective laser melting, Computer aided design, Retention force, Telescopic crown

1. Introduction

A challenge in dentistry research is finding suitable combinations of materials and technology for prostheses fabrication. Subtractive manufacturing is still prevailing in dental practice, in parallel with the increasing interest for the additive manufacturing (AM) processes, such as Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Melting (SLM), and 3D printing [1]. Selective Laser Sintering (SLS) is another AM technique, which uses a laser as the power source to sinter powdered material (e.g. a metal), automatically aiming the laser beam at points in space, guided by a 3D model to agglutinate the material for creating a solid structure. Though similar to Direct Metal Laser Sintering (DMLS), the two differ in terms of technical details [2]. SLM also employs a comparable concept, the material being fully melted rather than sintered, leading to different final properties (e.g. crystal structure and porosity) [2]. Laser melting machines deposit liquefied layers of fine metal powder to create complex and accurate 3D geometries directly from Computer Aided Design (CAD) files, in a controlled environment (under inert gas and shielded from external influences) [3,4]. The SLS technology is suitable in prosthetic dentistry due to the wide range of dental materials that can be employed for manufacturing the dental constructions, such as thermoplastic polymers, waxes, ceramics and thermoplastic composites, metals and alloys, e.g. Titanium, Titanium alloys, Cobalt-Chromium (Co-Cr), Co-Cr alloys, or stainless steel [5-7]. SLS has proved its efficiency in realizing margin-fit, well adapted crowns [8,9]. Summing up, the innovative additive technology has been reported to...
offer many advantages compared to the casting and milling fabrication techniques, with enhanced mechanical and electrochemical properties, quickly providing less expensive dental prosthetic restorations.

In prosthodontics, telescopic crowns are valid treatment options in cases of removable dentures on natural teeth or on implants. Double-crown-retained removable partial dental prostheses were recently reported as having the highest increase in German elderly population (about 15% to 20%) [10], though good prognoses for conical crown-retained removable partial dentures had also been reported in Kennedy Classes I, II, and III arches [11]. The most frequent complication of telescopic dentures was de-cementation of the primary crowns [12-14], which would be remediable in the context of long term studies emphasizing that patients’ satisfaction mainly depended on the adequate retention of the double-crowns in time [15,16].

Telescopic crowns’ retention in removable denture is a challenge in usual dental practice, for double-crowns of different designs and materials would exhibit various retention forces and a problematic long-term retentive behavior [17]. Double-crown tooth abutments and dentures demonstrated a wide range of survival rates while implant-supported mandibular overdentures proved a rather favorable long-term prognosis [18]. In case of looseness between the inner and secondary crowns, in order to regain the optimal retention, double-crowns must be lined with a suitable composite material [19]. A recent study in Japan showed that the space settings did not have a significant effect on retentive force; telescopic crowns’ taper and the load actually affected the retentive force and the settling [20]. The reported long-term clinical performance of double-crowns removable prostheses, e.g. over a seven-year follow-up, would be 90% survival for telescopic-crown-retained removable dental prostheses, and 78.5% for conical-crown-retained removable dental prostheses and resilient telescopic-crown-retained overdentures. This good survival rate and the optimal retention certainly stimulate the clinicians to propose this type of prostheses [18,21].

Four decades ago, K.H. Körber recommended 5-10 N as retentive force per abutment in double crowns [22]. Current literature suggests a force of 3-7 N per attachment to be acceptable [20,23]. The smaller the cone angle, the higher the retention force [24,25]. Increased retention measurements were reported for increased height, in equal angles, retention also depending on the static friction coefficient and contact pressure [26].

Telescopic dentures are used both on natural teeth (for removable partial dentures and overdentures) and on implant abutments, sometimes connecting teeth and implant abutments. Survival and success rates of resilient telescopic crowns with occlusal clearance fit on natural teeth are significantly influenced by the number of abutments [27]. To ensure a higher survival rate of implants, the tendency is to place at least four implants (splinted or unsplinted) for an overdenture treatment [28]. The patients were successfully rehabilitated with removable telescopic denture in cases of lost implants [29], or maxillo-surgery interventions with bone loss [30].

Although standard cast telescopic crowns have proved their value [31], and they still are a valuable option, clinicians are eager to make evidence-based choices in each case.

The aim of this in vitro study was to measure and compare the retention force for conical double-crowns fabricated with SLM and SLS additive technology, and Computer Aided Design – Computer Aided Manufacturing (CAD–CAM) subtractive technology, by using suitable materials for each. To ascertain the significance and applicability of this research, the null hypothesis stated that all three types of double-crown-retained removable prostheses would have the same retention force, irrespective of tooth type (e.g. molar vs. canine) or saliva presence.

2. Materials and Methods
2.1. Experiment design and methods

The study had a full-factorial design and considered the following three factors: (a) inner crown material – technology (zirconia – CAD-CAM; metal-alloy – SLS; metal-alloy – SLM); (b) tooth type (canine or molar); (c) wet vs. dry conditions (i.e. either with or without artificial saliva).

For the full-factorial design with a desired power and level of significance of 0.8 and 0.05, respectively, factors’ interaction two-by-two and all three, and Cohen’s effect size f-square=0.12 [32], the necessary number of observations per cell resulted to be 7, with a total of 84 observations.

The marginal area of a virtual cast was designed with chamfer finish line (0.8 mm deep) on the left canine and left molar (Fig. 1). The primary crowns were prepared at a cone angle of 6°, by using a 3Shape design (Smilden Biotechnology Co., Taiwan) (Fig. 2). The 6° taper was chosen according to the literature recommendations [12].

Based on the digital design, area of the inner crown surface was calculated with Autodesk Meshmixer v.3.5 software (http://www.meshmixer.com) as following: a mesh of 1000 triangles was created on the designed surface; the triangles corresponding to the canine and molar surfaces were selected and the aria of each surface was determined.

Three sets of inner crowns were manufactured, corresponding to the three material – technology combinations, for the left canine and left first molar (14 replicates for each). The zirconia crowns were made by using IPS e.max ZirCAD (Ivoclar Vivadent, Lichtenstein), a material with high mechanical stability (1,200 MPa), therefore suitable for thin single-tooth crowns like the telescopic primary crowns. The inner crowns’ sintering process followed the protocol: high temperature thermal exposure at 1550°C (2822°F) and 1500°C (2732°F); hold time for 2 hours, increasing rate of temperature 10°C (18°F)/minute and decreasing rate of temperature -10°C (-18°F)/minute. The SLS inner crowns were manufactured by using the PXS system (Phenix Systems, USA), of Starbond CoS Powder 16 as the metal-alloy (Scheftner Dental Alloys, Germany). The SLM inner crowns were made of Co-Cr powder from Remanium® star rematitan CL, via Concept Laser (Dentaurum, Germany) and Mlab cusing 200R metal laser melting system (Concept Laser, GE Additive Company).

The SLS and SLM inner crowns were heat treated to remove the residual stress: (i) after removing the surplus of metallic powder, they were put on a plate in the oven; (ii) the temperature was raised to 10°C/minute to 450°C, where it was maintained for 45 minutes; (iii) the temperature was again raised 15°C/minute to 820°C, where it was maintained for 45 min; (iv) the temperature was decreased at 600°C and the oven door was progressively opened; (v) at 300°C, the crowns were removed from the oven and were left to cool. In the following stage, they were polished using a Surveyor (F1, Degussa, Germany), with a medium polishing gum (Jota, Switzerland). The zirconia inner crowns were polished, as well.

All inner crowns were then scanned using a 3Shape D700 scanner (Smilden Biotechnology Co., Taiwan) and the secondary crowns were manufactured employing the same SLM technology for all (Fig. 3): Remanium® star rematitan CL, via Concept Laser (Dentaurum, Germany) and Mlab cusing 200R metal laser melting system (Concept Laser, GE Additive Company). They had an extension with a gap to permit the fitting into the testing device (Fig 4). SLM metal abutments were also fabricated of the same metal-alloy used for the secondary crowns. Materials and technologies used for the fabrication of the abutments, inner crowns and secondary crowns are described in Table 1. The inner crowns were cemented on these metal abutments with resin cement (Filtek Ultimate dual cure, 3M ESPE).

Retention force testing was performed in displacement control at 1 mm/minute, on a universal testing machine Zwick/Roell Z005 (Zwick/
Roell, USA) equipped with tensile grips (Fig. 5), having the following characteristics: load in tensile/compression 500 N; accuracy class 0.5; crosshead speed from 0.0005 to 1500 mm/minute; maximum error ± 1 μm in differential movement measurement between two measuring points in a range from 10 to 200 μm. The testing setup and data post-processing was performed using the TestXpert II testing software package (https://www.zwickroell.com/en). For each combination-set of primary crowns and type of tooth, seven independent retention tests were performed either with or without artificial saliva.

Before and after the retention testing, the primary crowns’ morphologies were investigated by atomic force microscopy on Easyscan AFM (Nanosurf EasyScan2 Advanced Research) using a scanning sample size of 1.1 μm x 1.1 μm, locally flat to within 570 nm x 570 nm. The surface roughness was calculated using the equations (Eq.1) and (Eq.2) for the average roughness and mean square root roughness, respectively:

\[
S_a = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} |y_j(x_i) - y_j(x_{i-1})|
\]  
(Eq.1)

\[
S_q = \sqrt{\frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} (z(x_i,y_j) - \bar{z})^2}
\]  
(Eq.2)

In (Eq.1) and (Eq.2): N and M represent the number of crystallites on the x and y axis; z is the medium height of the crystallites.

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**Table 1.** Materials and technology used for the fabrication of the abutments, inner crowns and secondary crowns.

| Material | Technology |
|----------|------------|
| Inner crowns | Zirconia IPS e.max ZirCAD (Ivoclar Vivadent, Lichtenstein) | CAD-CAM |
| Cr-Co alloy Starbond CoS Powder 16 (Scheithauer Dental Alloys, Germany) | SLS |
| Co-Cr alloy Remanium® star CL – laser melting powder via Concept Laser (Dentaurum, Germany) | SLM |
| Secondary crowns | Co-Cr alloy Remanium® star CL – laser melting powder via Concept Laser (Dentaurum, Germany) | SLM |
| Abutments | Co-Cr alloy Remanium® star CL – laser melting powder via Concept Laser (Dentaurum, Germany) | SLM |

CAD-CAM – Computer Aided Design - Computer Aided Manufacturing; SLM – Selective Laser Melting; SLS – Selective Laser Sintering
The testing was carried out at the Department of Mechanics and Strength of Materials, Polytechnic University, Timisoara, Romania.

2.2. Statistical data analysis

Descriptive statistics included the mean and standard deviation of the retention force for each combination of categorical variables (i.e. the observed factors).

Three-way analysis of variance (ANOVA) was applied for the force values across the factors, followed by post-hoc comparisons between the crown types according to the Tukey procedure.

All reported probability values were two-tailed and a 0.05 level of significance was considered, marking the highly significant values, as applicable. The statistical power calculation was performed with R v.3.6.3 software (https://www.r-project.org/; "easypower" package). Data analysis was conducted with the statistical package IBM SPSS v. 20.

3. Results

The surface values of the inner crowns were 197 mm
3 and 246 mm
2 for the canine and molar, respectively. The axial mesial and distal surfaces of the canine were 2.1 mm higher than that of the molar. The average height was 5.35 mm for canine and 3.25 mm for molar.

The overall (i.e. irrespective to the tooth type) mean values for the primary crowns retention force were: 7.5 N (dry) – 10.3 N (artificial saliva) for zirconia; 12.9 N (dry) – 14.8 N (artificial saliva) for SLS; and 3.8 N (dry) – 4.70 N (artificial saliva) for the SLM.

Table 2 shows the descriptive statistics for the retention force [N] for each of the 12 seven-value series of replicates corresponding to the combinations of the three factors assessed in the experiment: the inner crown material – technology combination (zirconia – CAD-CAM; metal – SLS; metal – SLM), the tooth, and the presence of saliva.

The results of three-way ANOVA are presented in Table 3, emphasizing the highly significant effect of all the three factors. The interaction between the type of inner crown and the tooth was highly significant, as well.

Post-hoc comparison between the inner crown types was applied employing the Tukey's procedure: the high statistical significance was assessed, and the 95% confidence intervals were calculated for the quantitative differences in retention force (Table 4).

Table 5 shows the results of the surface roughness for the tested inner crowns, measured in three points (incisal, middle and cervical) for each. The aspect of the surface roughness, before and after the retention tests, is presented in Fig. 6 (a-f).

4. Discussion

The in vitro study we report measured and compared retention force for conical double-crowns fabricated with subtractive and additive technology. In experimental conditions, we found statistically significant (p<0.001) differences between the retention forces for the three types of inner crowns. Previous findings were somehow contradictory: Stob et al. appreciated that the inner crown material would not influence the retention of the telescopic crowns [15], while Engels et al. found that the material exhibited significant influence on the retention [33].

The experimentally measured retention forces in the present study were comparable to those already reported for cast and electroformed double-crown systems [34,35]. The actual retention force values had highly significant (p<0.001) interaction with the tooth type (i.e. tooth height): the overall retention force was higher on the canine, compared to the molar for all types of telescopic crowns. Differences' balance did not change when the presence of artificial saliva was considered: there was no significant interaction between crown or tooth types and the wet vs. dry testing conditions. Previous findings also reported increased retention force values for higher teeth at equal taper angles [36].

The retention of the zirconia inner crowns was significantly (p<0.001) higher when compared to similar SLM stainless steel crowns. On the other hand, zirconia proved to be significantly (p<0.001) less retentive than the similar SLS metal-alloy crowns. Zirconia inner crowns have been reported as more advantageous than cast or SLS gold alloys in terms of retention force and wear, though only high-strength zirconia ceramics were recommended [12, 13, 15]. Concerning the SLS telescopic crowns, other studies found retention force values ranging from 4.35 N (or even lower) [37] up to 32.89 N [12], probably due to a wider spectrum of study designs, measuring conditions, and the various alloys used for manufacturing the crowns. Conventionally, cast double crowns can provide higher retention forces, while electroformed double crowns would offer more predictable results. In clinical cases with few and short abutment teeth, cast double crowns would better give the necessary retention force compared to the electroformed double crowns [33]. There is still little information regarding the metal-SLM primary crowns retention. The reduced retention value for the 6° taper SLM stainless steel inner crowns would suggest this solution in implant overdentures and slightly affected periodontal abutment natural teeth. Chamfer finishing line designs were recommended to reduce the micro-leakage and protect the teeth [38].

The roughness of all the materials used for the inner crown fabrication decreased after the experimental testing, as shown in Table 5 and Fig. 6: the wear of the zirconia was the largest and that of SLM inner crowns was the smallest. We tested non - precious stainless steel secondary crowns; the inner crowns were made of zirconia or non-precious metal, too (either SLS or SLM manufactured). Recently, large internal porosity within the SLM-fabricated Co-Cr metal copings has been reported as affecting the marginal fit of the metal-ceramic crowns [39]. In the present study, after testing, the surface structure of the SLM stainless steel inner crowns had more gaps than SLS stainless steel and zirconia inner crowns. This might also be a reason for the lower retention of SLM versus SLS inner crowns. After repeated insertion/removal cycles, the retention decrease would be larger for zirconia and SLS inner crowns, than for SLM inner crowns. The wear of zirconia inner crown was reported when the secondary crown was made of non-precious alloy, in contrast to electroformed gold secondary crowns. Using telescopic crowns as attachments for implant-supported overdentures might be a viable treatment option [40-43], sometimes even for overdentures on teeth [44-46]. In order to maintain the retention of the telescopic crowns, a smaller taper could be recommended in case of zirconia inner crowns. Reported values of intra-orally measured retention force values for telescopic crowns did not relevantly change within the first 1.5 – 10 years [37,47] and the correlation would provide an estimative prediction of the clinically relevant forces by measuring the extra-oral retentive values [37,48,49].

In this research, a 6° taper was applied for all experimental replicates. Shiba [50] mentioned that a 4° – 8° angle might be used according to the crown height and the physiological movement of the abutment, Behr et al. [12] recommended the 6° angle, and other authors previously suggested a 2° angle would maintain accepted retention [48]. Tests made to find the retentive behaviors of double crowns with different designs and materials demonstrated reduced losses of retention force in conical crowns with 6° taper, with high-noble metal secondary crowns [19].

The limitations of the present study are generated by the experimental design, which would suggest a limited immediate clinical applicability. On the other hand, the full-factorial design allowed determinations and comparisons otherwise difficult to be performed. The single taper chosen for the conical inner crown (6°) for all tested replicates and the inherently limited number of insertion/removal experimental cycles are issues that would influence the generalizing range for the measured values of retention force. Valuable applied research would also be the retention analysis of the traditional cast double crowns, still mainstream in clinical practice, compared to the
Table 2. Descriptive statistics for N=84 observations/replicates of the retention force in [N] resulted in the experiment.

| Inner Crown(Pc) | Zirconia-CAD-CAM (n=28) | Metal-SLS (n=28) | Metal-SLM (n=28) |
|-----------------|--------------------------|-----------------|-----------------|
| Tooth           | Canine (n=14)            | Molar (n=14)    | Canine (n=14)   |
| Saliva          | m (SD)                   | m (SD)          | m (SD)          |
|                 | n=7                      | n=7             | n=7             |
|                 | 10.33 (2.90)             | 12.14 (2.61)    | 4.83 (0.56)     |
|                 | 6.90                      | 7.81            | 4.04            |
|                 | max                       | 14.44           | 15.31           |
| CAD-CAM ‒ Computer Aided Design - Computer Aided Manufacturing; m (SD) ‒ mean (standard deviation); SLM ‒ Selective Laser Melting; SLS ‒ Selective Laser Sintering.

Table 3. ANOVA three-way analysis of the full factorial experiment data.

| Factor               | F-statistic (df) | p    |
|----------------------|------------------|------|
| Main effects         |                  |      |
| Crown (Pc)           | 282.321 (2)      | <0.001** |
| Tooth                | 29.622 (1)       | <0.001** |
| Saliva               | 29.403 (1)       | <0.001** |
| Two-way interactions |                  |      |
| Crown (Pc)*Tooth     | 2.383 (2)        | <0.001** |
| Crown (Pc)*Saliva    | 2.237 (2)        | 0.114 |
| Tooth*Saliva         | 2.138 (1)        | 0.127 |
| Three-way interactions|                 |      |
| Crown*Tooth*Saliva  | 0.258 (2)        | 0.773 |
| df ‒ degrees of freedom; ** high statistical significance.

Table 4. Post-hoc multiple comparisons of crowns’ retention force in [N] with Tukey procedure. The 95% confidence intervals for the estimated differences between the three types of inner crowns, in terms of the retention force, are also provided.

| Difference                  | p    | m (SD) | 95%CI with Tukey’s HSD correction |
|-----------------------------|------|--------|-----------------------------------|
| Metal-SLM ‒ Zirconia-CAD-CAM| <0.001** | -4.58 (0.40) | (-5.55; -3.62) |
| Metal-SLM ‒ Metal-SLS        | <0.001** | -9.61 (0.40) | (-10.58; -8.64) |
| Zirconia-CAD-CAM ‒ Metal-SLS| <0.001** | -5.02 (0.40) | (-6.09; -4.06) |

CAD-CAM ‒ Computer Aided Design - Computer Aided Manufacturing; m (SD) ‒ mean (standard deviation); SLM ‒ Selective Laser Melting; SLS ‒ Selective Laser Sintering; Tukey’s HSD ‒ Tukey’s Honestly Significant Difference; ** high statistical significance.

Table 5. Roughness of the inner zirconia and metal crowns before and after the retention tests. S_a and S_q are shown in (Eq. 1) and (Eq. 2), respectively.

| Sample                     | Zone | Aria (pm²) | S_a (nm) | S_q (nm) | Aria (fm²) | S_a (nm) | S_q (nm) |
|----------------------------|------|------------|----------|----------|------------|----------|----------|
| Zirconia before retention tests | Incisal | 1.326      | 24       | 29       | 331.5      | 8.8      | 10.2     |
| Zirconia after retention tests | Incisal | 1.326      | 15.6     | 20       | 331.5      | 7.7      | 9.1      |
| SLS before retention tests  | Incisal | 1.326      | 5.4      | 6.4      | 331.5      | 2.2      | 2.6      |
| SLS after retention tests   | Incisal | 1.326      | 1.4      | 2        | 331.5      | 0.77     | 1.2      |
| SLM before retention tests  | Incisal | 1.326      | 4.7      | 5.8      | 331.5      | 1.4      | 1.7      |
| SLM after retention tests   | Incisal | 1.326      | 4.4      | 5.4      | 331.5      | 1.3      | 1.5      |

S_a ‒ femto (10⁻¹⁵) meter; nm ‒ nano (10⁻⁹) meter; pm ‒ pico (10⁻¹²) meter; SLM ‒ Selective Laser Melting; SLS ‒ Selective Laser Sintering

5. Conclusion

This in vitro investigation aimed at demonstrating that CAD-CAM subtractive technology and SLS or SLM additive technologies could be valuable alternatives to the classical casting technology in fabricating telescopic crowns.

The stainless steel SLS inner crowns showed the best retention, followed by zirconia and SLM inner crowns. The retention was dependent on the abutment teeth height (higher on the canine). The presence of the artificial saliva increased the retention force, though it did not significantly interact with the inner crown design or the tooth type. The roughness decrease and subsequent loss of retention force was the largest in zirconia, followed by SLS and SLM stainless steel.

double crowns fabricated by using additive and subtractive technologies.
Fig. 6 a. 3D Atomic Force Microscopy (AFM) surface images and the particle size distribution for Zirconia before retention testing.

Fig. 6 b. 3D Atomic Force Microscopy (AFM) surface images and the particle size distribution for Zirconia after retention testing.

Fig. 6 c. 3D Atomic Force Microscopy (AFM) surface images and the particle size distribution for SLS before retention testing.

Fig. 6 d. 3D Atomic Force Microscopy (AFM) surface images and the particle size distribution for SLS after retention testing.
Declaration of competing interests

None.

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