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Original Article

In-Vitro Assessment of Articulation Precision in Digital vs. Traditional Stone Cast Models

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ABSTRACT

With the integration of digital workflows in dentistry, digital models can now be articulated inter-occlusally through different digital techniques. The Cadent iTero intraoral scanner records the maxillomandibular relationship via a buccal scan taken in maximum intercuspation. This in-vitro research evaluated the occlusal accuracy obtained from traditional stone cast articulation compared with that of digitally articulated quadrant-milled models. Thirty pairs of stone casts made from full-arch polyvinyl siloxane impressions (Group A) and thirty polyurethane quadrant models milled from digital impressions (Group B) were used. The full-arch casts were manually articulated and mounted on semi-adjustable articulators, while the digital models were pre-mounted by the milling center using buccal scan data. Bite registrations for both groups were acquired using a T-scan sensor. The occlusal data collected from both groups were compared to a master model to assess reproducibility. A statistically significant variance in contact surface area was detected on tooth #11 of the digitally articulated models relative to the master. Force distribution analysis also revealed a greater load tendency on the anterior #11 tooth in digital models. Within the study's limitations, digitally articulated quadrant systems may lose occlusal accuracy, particularly in anterior restorations. Attention to potential error sources in the digital workflow is essential to optimize restorative precision and efficiency.

Keywords: Intraoral scanner, Digital articulation, Milled model, T-scan

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Introduction

A variety of methods and materials have been developed to articulate conventional dental casts in the desired maxillomandibular position. Typically, wax or polyvinyl siloxane materials are used to transfer this relationship to the casts. However, achieving clinical precision can be difficult due to the dimensional instability of these materials or incomplete seating of the record on the casts. Several studies have reported vertical and horizontal inaccuracies associated with conventional registration materials. These substances are susceptible to dimensional changes caused by variations in temperature, moisture, and time [1–6]. Because of this instability, when stable occlusal stops are present, manual articulation of casts has been found to more accurately replicate the true interocclusal relationship [7, 8]. The accuracy and dimensional reliability of dental casts have been widely investigated and are influenced by factors such as the type of impression and stone materials used, impression technique, and duration of storage [9, 10].

With the continuous development of computer-aided design and manufacturing (CAD-CAM), the demand for digitally fabricated restorations has significantly increased. Studies have demonstrated that these restorations produce comparable clinical results, with digital workflows offering improved efficiency and preference among both clinicians and patients [11–15]. The quality of CAD-CAM restorations depends on the precision of the scanning, model creation, articulation, and milling or 3D printing steps. Some reports indicate that digital casts and articulation using buccal scans can achieve equal or greater accuracy than conventional methods [16–18]. Nevertheless, limited data exist on the reliability of occlusal relationships derived from digitally articulated quadrant scans and models.

Accurate evaluation of occlusal contacts and forces is essential when comparing mounted casts. Various materials—such as articulating foils, papers, waxes, silicone, and photocclusion—have been employed to record occlusal contact areas [3, 19]. Yet, most of these rely on visual interpretation rather than measurable data. The T-scan III system, a digital occlusal analyzer, employs a pressure-sensitive sensor to simultaneously record and display force distribution and contact timing. The device generates quantifiable percentage-based data, avoiding the subjectivity of visual markings. Earlier versions of the T-scan produced mixed results concerning precision and reproducibility [20, 21], possibly due to sensor placement or sensitivity. However, later studies reported improved precision and consistency in measuring relative force distribution and contact numbers [22–26]. In this investigation, occlusal data from the T-scan sensor were refined through imaging software to remove sensitivity artifacts and isolate true contact points accurately.

The purpose of this in-vitro experiment was to assess the precision of digital articulation of milled polyurethane quadrant models using buccal scans compared with conventionally mounted stone casts, analyzed via a digital occlusal measurement system. The null hypothesis proposed that no significant difference would exist in occlusal accuracy between digitally articulated milled models and conventionally articulated stone casts.

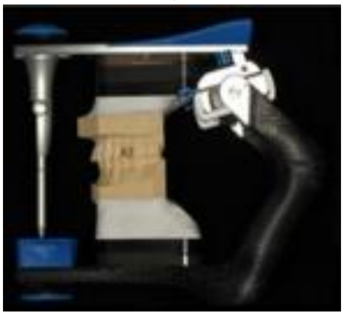
Materials and Methods

Study design

At the Harvard School of Dental Medicine, thirty individuals performed both conventional impressions and intraoral digital scans on mounted typodont master models. From these, two sets of samples were prepared: thirty full-arch polyvinyl siloxane impressions (Aquasil, Dentsply Sirona, Waltham, MA, USA) poured in Type III gypsum (Microstone, Whip Mix Corp, Louisville, KY, USA) formed Group A, and thirty polyurethane quadrant models milled directly from digital scans (Itero Cadent) comprised Group B.

For Group A, the stone casts were manually mounted on semi-adjustable articulators (Artex CR, Amann Girrbach AG, Pforzheim, Germany) using low-expansion mounting material (Whip Mix Corp, Louisville, KY, USA), ensuring consistent hinge-axis alignment with a mounting jig **(Figures 1a–1c)**. Group B consisted of digitally fabricated models mounted on prefabricated articulators (Itero Cadent Articulator, Itero, Carlstadt, NJ, USA) at the milling facility, guided by buccal scan data. Occlusal recordings were made with a digital occlusal analyzer (T-scan III, Tekscan Inc., Boston, MA, USA), with each setup positioned identically on the sensor while applying a 1.5 lb load to the articulator's upper arm **(Figures 2a and 2b)**. The same sensor was reused for consistency across all model sets. Pressure readings for teeth #11, #12, and #14 were collected, and each tooth's force value was expressed as a percentage of the total combined force on those three teeth.

a)



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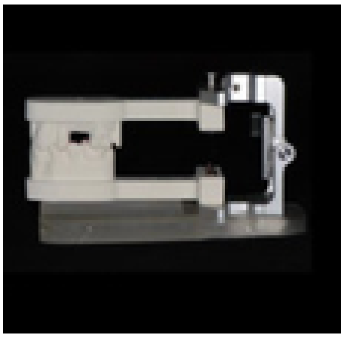
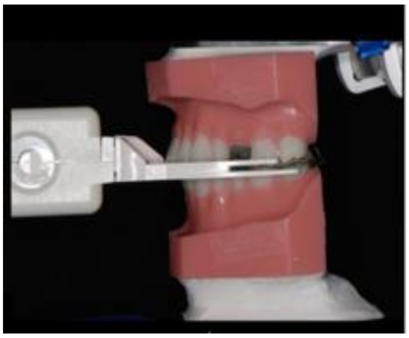


c)

Figure 1. (a) Master model and (b) conventional stone casts fixed on a semi-adjustable articulator. (c) Quadrant models milled from digital scans were pre-mounted on Itero articulators using buccal scan data.

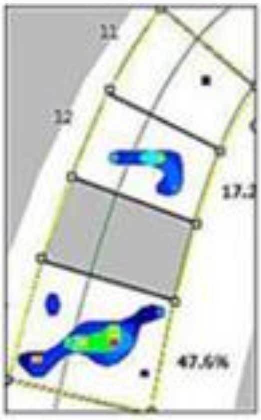
a)



b)

Figure 2. (a) Fixed-positioning jig for the T-scan sensor ensuring consistent contact alignment. (b) 1.5 lb weight applied to the articulator's top frame during occlusal data collection for all samples.

The T-scan graphical maps were processed using ImageJ software (NIH, Bethesda, MD, USA) to allow consistent analysis of tooth-specific contact zones and to remove noise. Following expert guidance, any dark-blue regions were considered digital noise and removed from all readings **(Figures 3a–3d)**. The tooth areas were cropped precisely so that the same pixel count was analyzed in each case. The pixel-based areas of remaining contact zones were then measured to quantify occlusal surface area.



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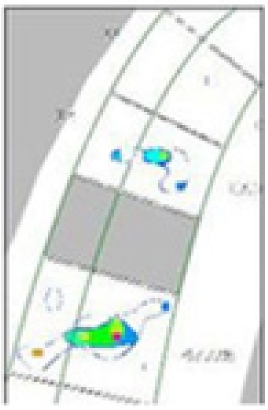

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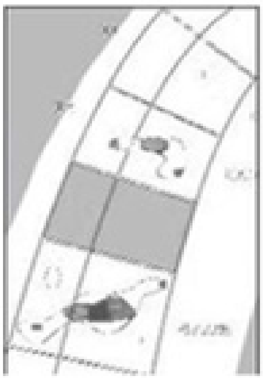

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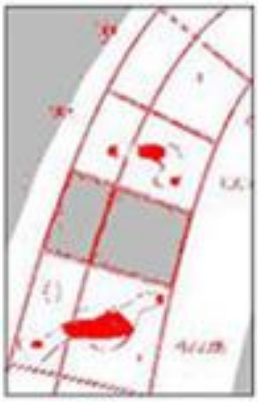

d)

Figure 3. Stepwise image cleaning (a–d) in ImageJ for removal of sensor artifacts and isolation of valid contact surfaces.

Statistical analysis

A total of 30 samples were chosen as this pilot investigation required an adequate dataset for nonparametric evaluation if normality assumptions failed. After testing for normal distribution, the Kruskal–Wallis test was performed, followed by Wilcoxon rank-sum comparisons with Bonferroni correction for multiple testing. All computations were conducted using IBM SPSS Statistics v22 (IBM Corp., Armonk, NY, USA). Descriptive data were presented as mean percentage force per tooth.

Results and Discussion

Both conventional and digital articulation groups showed occlusal contact surface areas largely similar to those of the master model, except for tooth #11 in the digital group. On this tooth, the mean contact surface reached 208.63 pixels, significantly greater than both the master model (163.27 pixels) and the conventional casts (157.60 pixels) ($p < 0.001$). The master and Group A showed no statistical difference for tooth #11 ($p = 0.778$) **(Table 1 and Figure 4)**.

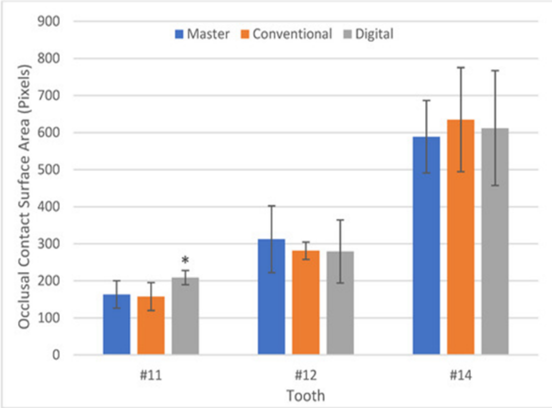

Figure 4. Occlusal contact surface area (pixels) after artifact removal. * indicates p < 0.001.

Table 1. Occlusal contact surface area (pixels).

Tooth	Reference Model	Traditional Casts	Digitally Milled Models	Statistical Significance (p-value)
#11	163.27 ± 36.92	157.60 ± 37.70	208.63 ± 19.23	p < 0.001 *
#12	312.23 ± 89.99	281.20 ± 23.43	279.13 ± 84.96	p = 0.148
#14	588.63 ± 97.78	634.77 ± 140.52	612 ± 154.94	p = 0.411

— Master vs. digital: $p < 0.001$
— Master vs. conventional: $p = 0.778$

The proportional force distribution across teeth #11, #12, and #14 is summarized in **Figure 5 and Table 2**. For the master model, the average forces were 0.17% on #11, 33.58% on #12, and 66.25% on #14. The conventional casts mirrored this trend. However, in Group B, the digitally articulated models exhibited a force concentration of 5.44% on #11—over ten times higher than that of the master model (0.17%) and markedly above the conventional casts (0.51%).

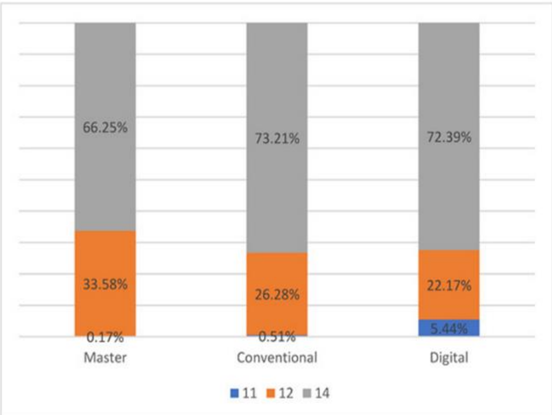

Figure 5. Distribution of occlusal forces per tooth (%).

Table 2. Mean percentage force distribution by tooth (%).

Tooth	Reference Model	Traditional Casts	Digitally Milled Models
#11	0.17%	0.51%	5.44%
#12	33.58%	26.28%	22.17%
#14	66.25%	73.21%	72.39%

Achieving precise articulation of dental casts is essential for fabricating restorations that function harmoniously with the opposing dentition. Technological progress in digital dentistry has reached a point where restorations produced via fully digital workflows can match or even exceed the precision of conventional methods [27–29]. A recent meta-analysis by Tabesh *et al.* reported that intraoral scanning achieved greater marginal accuracy than traditional impression techniques for single-unit zirconia restorations [29]. Similarly, a crossover clinical study by Lee *et al.* demonstrated comparable accuracy between conventional and digital single-implant restorations [13]. Several investigations have assessed the reliability of virtual interocclusal registration for quadrant digital casts and found the outcomes to be clinically acceptable [30, 31]. Nonetheless, to date, no study has specifically investigated the occlusal precision of digitally mounted casts created from quadrant scans and printed models.

When restoring posterior single units using a digital workflow, clinicians typically obtain maxillary and mandibular quadrant scans along with a buccal bite scan to establish articulation. The laboratory then uses these records to design and mill the restoration, which is verified and adjusted on 3D-printed models attached to a simple hinge articulator. Although this approach is widely implemented, little quantitative evidence exists on its articulation accuracy—partly due to the difficulty of obtaining objective, reproducible measurements of occlusal forces. While digital pressure sensors can generate measurable data, readings often vary because of sensor positioning and the number of contacting teeth.

To address these inconsistencies, this study employed image-processing software to filter out artifacts that represented dispersed pressure rather than true occlusal contact zones. Dark-blue regions on the T-scan readouts, representing minimal pressure, were identified as artifacts and excluded by adjusting the color threshold in the image analysis program. This refinement produced more reliable pixel-based measurements of contact surface area. Similar image-based analytical approaches have been reported by Millstein *et al*., who utilized image analysis to assess bite registration transparency [19]. The forces measured by the digital pressure sensor were expressed as percentages relative to the total load recorded across the three evaluated teeth.

Based on the outcomes of this investigation, the null hypothesis—stating no difference between digital and conventional articulation—was rejected. Although posterior contacts showed no significant deviation between groups, the cuspid area exhibited a statistically larger contact size in the digitally articulated models than in the master model. Likewise, the percentage force analysis revealed that the digitally articulated group demonstrated a tenfold increase in force distribution on the canine (5.44%) compared with less than 1% in both the master and conventional casts.

This variation in occlusal accuracy may be linked to several potential causes, including discrepancies between the dimensional accuracy of milled and stone models. Limited existing research supports this observation. Vögtlin *et al*. found that conventionally produced stone casts showed higher accuracy than digitally derived full-arch models [32]. Similarly, Abduo reported lower precision in digital models compared to PVS-based gypsum casts at the full-arch level, although digital models were more precise at the individual tooth level [33].

Another factor could be the difference between articulating quadrant models and full-arch casts. The absence of contralateral contacts in quadrant models may allow greater anterior force distribution, thereby increasing contact size on anterior teeth in digital articulations. Consequently, conventional full-arch casts reproduced occlusal patterns more consistent with the master model than their digital quadrant counterparts. However, current literature lacks direct comparisons between occlusal accuracy from full-arch and quadrant articulations, indicating a need for future investigation.

Limitations of this study include its in-vitro design using a typodont setup rather than clinical patients, as well as the difference between full-arch and quadrant model types. Additionally, the use of a standardized weight across both groups may have influenced the T-scan contact readings.

Within these constraints, results suggest that digital articulation using quadrant models may lead to decreased occlusal precision for anterior restorations. Clinically, this implies that when working on anterior teeth, expanding the scanned area to include additional occlusal stops—or even the opposite quadrant—could enhance articulation accuracy and final prosthesis fit.

Conclusion

Digital techniques have greatly enhanced efficiency and patient experience in restorative dentistry, yet their accuracy does not always equal or surpass that of conventional methods. As with traditional workflows, the combination of multiple digital steps and materials introduces potential cumulative errors that can impact the fit and occlusion of restorations. Therefore, clinicians must identify and minimize these error sources to optimize accuracy and ensure predictable, effective outcomes in digital restorative procedures.

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