A butment engagement to the implant is a critical element for antirotation and the supported function in single implant restorations. Currently, the testing standard for endosseous dental implant abutment systems is the International Organization for Standardization (ISO) 14801:2007, testing guidelines for a single implant with straight or angled abutment under cyclic static fatigue loading. The common path of insertion for the prosthesis with partially engaging abutments to angled implant analogs was created by selectively reducing the abutment surface that obstructed the implant housing. A 500-N average load was applied to each sample while oscillating 30 degrees from the vertical axis at 60 Hz to failure. Prosthesis stability was measured by deflection from the initial position using a linear displacement measuring device. Sample groups were assessed using the independent-samples t test and one-way repeated-measures analysis of variance (ANOVA) with post hoc tests. Results: The mean cycles to failure for nonengaging and partially engaging abutment groups were 27,180 ± 29,420 and 457,890 ± 265,734, respectively. Failed nonengaging samples had 9 out of 10 abutment screws fracture inside the implant housing but with minimal wear to the top of the implant analog. For partially engaging samples, 8 out of 10 implant housings and 7 out of 10 abutment screws fractured at test endpoints. There was no difference in initial deflections between groups. Prostheses supported by nonengaging abutments failed before deflection measurements could be taken after loading. Prosthesis displacement of partially engaged abutments decreased significantly from the initial position after 300,000 load cycles. Conclusion: Under the experimental conditions, screw-retained splinted fixed dental prostheses supported by partially engaging abutments are 17 times more stable than prostheses supported by nonengaging abutments. Abutment screw fractures are the most prevalent mode of failure for nonengaging abutments at significantly lower cycles with minimal wear on implant analogs. Partially engaging abutment groups failed from implant housing and abutment screw fractures at higher cycles. Loading appears to concentrate preferentially on the medial side on all angled implant components. Selective removal of the abutment obstruction allows a common path of insertion for multiple implants and partial engagement to implant housings.
handling have not yet been fully investigated.\textsuperscript{6,7} Due to the irretrievability of a cemented prosthesis, frequent complications such as abutment screw loosening and overextrusion of the luting agent with bone loss around implants have resulted in the prominent use of screw-retained prostheses utilizing only nonengaging abutments in partially and edentulous restorations.\textsuperscript{8–11}

The implant abutment in a screw-retained splinted fixed dental prosthesis (FDP) is a critical component that can affect the long-term survival of the prosthesis.\textsuperscript{12} An implant abutment consists of the implant connecting end and an opposing prosthetic connecting end with an internal bore to accommodate an abutment screw.\textsuperscript{13,14} Currently, the two common methods to attach a prosthesis onto multiple implants can either be at the bone or tissue level.\textsuperscript{15,16} Bone-level attachment is when the prosthetic end of the abutment is connected or fixated to the tissue side of the prosthesis and then secured to the implant via an abutment screw. Alternatively, the implant abutment can be first connected to the implant housing via an abutment screw and a matching component can be secured to the prosthetic end of the abutment via a smaller retaining screw; this method is known as tissue-level attachment. Commercially, a nonengaging titanium (Ti) base abutment with no engagement to the implant housing can be used at the bone level. For tissue-level attachment, the prosthetic connection is conical shaped with full engagement to the implant housing, known as a multifunctional abutment.\textsuperscript{17,18} Both of these abutments were purposefully designed to avoid direct engagement to the implant to circumvent the different implant housing or abutment trajectories. The problems with using nonengaging abutments in an FDP are the difficulties in handling and increased strain on the abutment screws that can lead to increased rates of fracture and loosening of the abutment screws.\textsuperscript{20–22} Very few studies have investigated cement-retained prostheses and even fewer with screw-retained prostheses in the context of multiple implants under compressive loading simulating parafunction or bruxism.\textsuperscript{23,24} In the absence of an appropriate testing standard for multiple implants and the lack of peer-reviewed studies, abutments with nonengaging features appear to be accepted as standard components for partial and edentulous restorations.\textsuperscript{20,21,25}

Many earlier studies using photoelastic stress analysis, 3D finite element analysis, and strain gauge analysis have focused on the stability of the FDP, pre-torque values of the abutment screw, occlusion, dental biomaterials, luting cements, or marginal fit.\textsuperscript{26–35} How the abutment screw is affected at the end of testing when secured to the prosthesis directly to the implant housing without engagement of the abutments has not been fully investigated. Intuitively, the nonengaging abutment is not designed for resistance or retention due to its short or absent vertical wall height. Without the support or engagement of the abutment body, the mechanical stresses experienced by the abutment screw can lead to catastrophic failures.\textsuperscript{21} In this study, a geometric solution was introduced to allow an unobstructed seating of a prosthesis and partial engagement to all abutments in a multiple implant situation. The objective of this study was to evaluate the effects of a vertical compressive cyclic load on abutment screws and the stability of a screw-retained splinted FDP supported by bone-level nonengaging and partially engaging abutments.

**MATERIALS AND METHODS**

A total of 10 standardized prostheses for two implant bridges were designed using 3D computer-aided design software (Solidworks, Dassault Systèmes) and 3D-printed (Formlabs 2) in castable resin (Fig 1). The prosthetic ends of both nonengaging and partially engaging abutments were integrally joined to the FDP, and the implant connection ends were extended...
downwardly and outwardly 15 degrees from the tissue side of the prosthesis. The printed FDP was cast in non-precious metal (Argeloy N.P., Argen) with either nonengaging (n = 5) or partially engaging (n = 5) abutments and connected to implant analogs with conical connections (NobelReplace, Conical Connection, Nobel Biocare; Fig 1). For partially engaging abutment samples, a common path of insertion was obtained for the splinted FDP by selective removal of the obstructions on the two outer walls of the engaging abutments with conical connections using CAD software. Partially engaging abutments were purposely rotated 30 degrees to each other and placed 12 mm apart center to center at the top of the implant analogs in the resin block. For each sample, two stainless steel implant analogs with conical connections were connected to the abutment protrusions on the apical side of the prosthesis for non-engaging and partially engaging abutments prior to placement in a resin block (Fig 2). No adjustment was needed for nonengaging abutments, as they were able to be placed on the top of multiple implant housings. The implant housing refers to the implant recess with specific geometric features that connect and engage with the abutment. Abutment screws (Grade V titanium 6Al-4V) were torqued to 35 Ncm (Sealey, STS103) according to the manufacturer’s instructions.

**Vertical Compressive Cyclic Loading**

The point of contact for the load stylus (2 mm × 20.50 mm) was placed longitudinally across the center groove of the occlusal plane. The center groove was formed by the intersection of two planes at 15 degrees to the horizon, mimicking cuspal inclines. Samples were secured in a custom-designed steel holder and subjected to a continuous vertical compressive cyclic load ranging from 800 N to 200 N for an average of 500 N. The sample simultaneously oscillated 30 degrees to the vertical axis at 60 cycles per minute to simulate the eccentric forces experienced under mastication (Fig 2).

The pointed load stylus oscillated 1.0 mm from the center groove. The load cell was amplified using a Wheatstone amplifier and connected to an Arduino. LabVIEW software was used to record the time and load during sample testing (Fig 3).

Failure endpoints for all samples were defined as follows: (1) when the FDP deflection is > 2 mm; (2) any instance of prosthesis, abutment screw, or implant fracture; and (3) the sample reaches > 1 million cycles. The results were recorded within categories of number of cycles until any failure endpoint. Deflection measurements of the FDP were made prior to loading and measured every 50,000 cycles until any one of the failure endpoints was reached. Failed samples were examined under 30× magnification, and digital photos were taken (Keyence VHX-950F digital microscope).

**Prosthesis Deflection Measurement**

The displacement-measuring device consisted of a C-clamp fastener for the sample resin block. Two screw actuators were placed on either side of the sample at the
level of the FDP to record a full linear displacement of the prosthesis in both directions. The position of the FDP was mechanically translated via linkage to a dial gauge (Mitutoyo 2914S; (Fig 4). Deflection measurements were performed prior to and subsequent to compressive loading to determine the change from the initial position of the FDP. The initial position of the FDP is measured when one screw actuator is torqued to 0.50 Nm, then loosened for a repeated number of times until a consistent deflection value is obtained. The same screw actuator is then loosened so the opposing screw actuator can be similarly torqued and loosened to allow a deflection value in the opposite direction of the FDP. Subsequent deflection values during loading were recorded periodically and similarly to the initial deflection measurements. After each deflection measurement, the abutment screws were tightened and re-torqued to 35 Ncm simulating recall maintenance of the FDP.

### Statistical Analysis
Quantitative differences between groups were assessed using an independent-samples t test, one-way repeated-measures analysis of variance (ANOVA) with post hoc Tukey honestly significant difference (HSD) and descriptive statistics presented as numbers for categorical variables and means ± standard deviations for continuous variables.

### RESULTS
The mean numbers of cycles to failure for a prosthesis supported by nonengaging and partially engaging abutments were 27,180 ± 29,420 and 457,890 ± 265,734, respectively (Fig 5). The mode of failure in the nonengaging abutment group resulted in 9 out of 10 abutment screws fractured inside the implant housing but with minimal wear to the crest of the implant analog. One nonengaging abutment was dislodged from the FDP. The prosthesis supported by partially engaging abutments failed with 8 out of 10 implant housing and 7 out of 10 abutment screw fractures and at a significantly higher number of cycles. Visual inspection of all failed samples showed that vertical compressive cyclic loading caused wear facets preferentially concentrated on the medial side of implant components. The independent-samples t test showed no statistically significant difference (P > .05) in initial deflections between nonengaging and partially engaging abutments, 0.60 ± 0.04 and 0.63 ± 0.24, respectively. Prostheses supported by nonengaging abutments had failed before any deflection measurements could be taken after loading. One-way ANOVA with post hoc Tukey HSD for partially engaging abutment samples showed a significant difference (P < .05) in linear displacement values before 300,000 cycles of compressive loading and retightening of abutment screws compared with the initial deflection values. However, as loading continued past 300,000 cycles, there was a decrease in linear displacement, resulting in deflection values that were significantly different (P > .05) for partially engaging abutment samples (Fig 6).

### DISCUSSION
Abutment screw fractures and loosening were consistent complications observed in this study. Clinically, abutment screw loosening can be considered less catastrophic compared with abutment screw fracture. The vertical compressive cyclic device was designed to simulate parafunction or bruxism. Under the loading conditions, none of the samples had reached the 1 million cycle endpoint. Prostheses supported by nonengaging abutments failed on average at 27,000 cycles, with 9
out of 10 failures associated with abutment screw fractures. Interestingly, the crestal portion of the implant analog in nonengaging samples had minimal wear. In this study, the large unexpected discrepancy between the two abutment types warrants the following discussions: (1) stress concentration on abutment screws, (2) area of preferential loading on angled implants, (3) mode of failure, and (4) sample deflection and stability of the prosthesis under compressive loading.

Regardless of the abutment type, abutment screws were being leveraged at the implant housing and FDP. In nonengaging abutment samples, the abutment screws were torqued and leveraged at the top end of the implant housing and at the bottom end of the implant housing at the level of the internal threads. In the absence of contact or support from the abutment extension or implant housing, the stress concentration seemed to focus exclusively on the body of the abutment screw causing fractures in 9 out of 10 nonengaging abutment samples. The findings in this study were consistent with the results from other finite element analysis (FEA) studies investigating nonengaging abutments in a screw-retained implant-supported prosthesis.20,21 Further examination of all failed samples in both groups under digital microscopy at 30x magnification revealed evidence of wear concentrated preferentially on the medial side of the top ledge of the implant housing (Fig 7). Additionally, in one nonengaging abutment sample, the integrally joined abutment to the prosthesis had detached from the body of the FDP and with abutment screws fractured. The frequently reported debonding of the Ti base abutment from the cemented prosthesis may be related to the concentrated loading on the same areas.37

The prosthesis supported by partially engaging abutments appears to have less evidence of stress concentration; this may be due to the larger area of contact between the abutment extension and implant housing (Fig 8). The preferential loading on the medial side of implant components in this study was consistent with the results conducted by another study that had used FEA to investigate single implants of different diameters under oblique loading.38 The selective reduction of the distal aspect of the diverging partial engaging abutments appears to be of less consequence to angled implants due to the direction and preferential loading on the medial side (Fig 8).

For partially engaging abutment samples, 8 out of 10 implant housings and 7 out of 10 abutment screws had both fractured at test endpoints (Fig 9). With the assumption that the abutment extension protected the abutment screw, it could be reasonably assumed that the implant housing may have failed first followed by abutment screw fracture in the implant housing. Partially engaging abutment samples appeared to have transferred and distributed the load along the bone-implant prosthetic complex, which was not seen in nonengaging abutment samples. Empirically, there are tapered abutments that extend as deep and long as possible within multiple implant housings with different trajectories. The benefit of this approach is that it provides some degree of nonspecific engagement to the implant housing while protecting the abutment screw from load concentration.

From a regulatory perspective, the evaluation and approval of the safety and effectiveness of any dental implant and restorative code::
component is only required to show its “substantial equivalence” to a device that had been previously approved for the market known as a “predicate device.” Demonstrating the substantial equivalence to a predicate device does not require biomechanical testing of the implant and related components together for specific clinical applications. Once market clearance is obtained, the selection and use of abutments appear to be arbitrary and interchangeable based on clinical expediency. For example, the initial marketing for the clinical use of nonengaging abutments for a screw-retained splinted FDP appeared to have been based on the substantial equivalence to Brånemark’s “gold cylinder” prosthetic component or the UCLA-type abutment. The original “gold cylinder” was designed to fit on top of a standard round abutment or the UCLA abutment connected directly to an external hex implant. The current use of nonengaging abutments cannot be reasonably and safely extrapolated for their use in implants with internal-connection implants. It is important to examine many of the approved and accepted implant components and concepts due to the lack of direct scientific evidence for their efficacy. Biomechanical testing must not only be conducted on individual components but on the entire system including the implant, abutment, abutment screw, and prosthesis.

During routine deflection measurement, it was observed that the stability of the prosthesis supported by partially engaging abutments exhibited a biphasic type of response. Prior to 300,000 cycles, deflection values increased up to \(1.13 \pm 0.44 \, \text{mm}\) and were significantly different \((P < .05)\) compared with the initial deflection, indicating prosthesis instability. As loading continued, the prosthesis experienced a decrease in deflection values that were significantly different \((P < .05)\) compared with the deflection values prior to 300,000 cycles to \(0.75 \pm 0.05 \, \text{mm}\) indicating increased prosthesis stability (Fig 6). Similar studies with larger sample sizes need to be conducted to further validate the deflection results seen in this study. The increased stability of the FDP over long-term loading can be explained by the “settling effect” of the implant components. Other studies that used strain gauge analysis have also reported increased strain values adjacent to the implant-supported FDP when subjected to compressive loads and abutment screw tightening. In contrast, no FDP supported with nonengaging abutments survived more than 50,000 cycles to allow deflection measurements to be taken under similar testing conditions. The physical engagement of the abutment to the implant housing minimizes micromotion between the prosthesis/abutment and implant housing, which was a major contributing factor of crestal bone loss in dental implants. The failure modes for both nonengaging and partially engaging samples were both catastrophic; however, the partially engaged abutment appears to protect the abutment screw until the crest of the implant housing fractured, which failed at a much higher number of cycles.
The concept of having multiple engaging abutments in a screw-retained FDP should not be mutually exclusive. Despite high levels of surgical skill, 3D-printed surgical guides, and varied grafting techniques, parallelism in implant placement is very rare. Due to the prosthetic requirements for a common path of insertion on implants with different trajectories, a passive fit for a splinted prosthesis would require nonengaging or multiunit abutments to circumvent these trajectories. Recently, several studies have investigated and proposed the combination of engaging and nonengaging abutments in the same prosthesis.\textsuperscript{42,43} Utilizing the biomechanical advantage of a fully engaged abutment to one implant can circumvent different implant trajectories for a passive-fitting prosthesis. Dogus et al have also reported the use of implants that are most distal from high occlusal loads to be engaged while using nonengaging abutments to connect the remaining implants in the same prosthesis. The use of the single or hemi-engaged prosthesis showed better handling and a marginal increase in prosthetic stability with the eccentric forces distributed more favorably away from nonsupport ed areas.\textsuperscript{43} There have been studies that investigated using retrieval kits for abutments that have fractured in the implant housing and other solutions ranging from noninvasive procedures to specialized trephine drills.\textsuperscript{44–46} From the results of this study, the root cause of abutment screw fracture and prosthetic complications rests more closely in the design of nonengaging abutments supporting the FDP and the effects of a constant compressive load on abutment screws.

An alternative approach to the traditional dental concept for a common path of insertion was introduced in this study. Two conical engaging abutments were connected to two nonparallel implants converging at an angle of 15 degrees to the central vertical axis (Fig 1). From a geometric perspective, using CAD software for the precise selective reduction of the obstructive part of the abutment extension to the implant analog accounts for only 16.67% of the engaging abutment. The proposed method allows for the unobstructed seating of a screw-retained splinted FDP and can provide partial engagement of 83.33% to the implant housing. The results from this study also showed preferential loading on the medial side of the abutment extension, while the selective reduced distal side appeared to be less affected. The extension of the abutment and partial engagement can provide protection for the abutment screw and increase stability for the prosthesis. The unexpected large discrepancies and catastrophic failures between nonengaging and partially engaging abutments supporting screw-retained splinted FDPs underscores the need for independent studies about the claims of safety and effectiveness of dental implants and restorative systems currently on the market.

CONCLUSIONS

Under the experimental conditions, screw-retained splinted FDPs supported by partially engaging abutments are 17 times more stable than a prosthesis supported with nonengaging abutments. Abutment screw fractures are the most prevalent mode of failure for nonengaging abutments at significantly lower cycles with minimal wear on implant analogs. Partially engaging abutment groups failed from implant housing and abutment screw fractures at higher cycles. Loading appears to concentrate preferentially on the medial side on all angled implant components. Selective removal of the abutment obstruction allows a common path of insertion for multiple implants and partial engagement to implant housings.

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