INFLUENCE OF CAD/CAM MATERIALS ON DAMPING BEHAVIOR OF IMPLANT-SUPPORTED CROWN

Miss Charnikan Sukkasam

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Prosthodontics
Department of Prosthodontics
FACULTY OF DENTISTRY
Chulalongkorn University
Academic Year 2022

อิทธิพลของวัสดุที่ออกแบบและผลิตด้วยคอมพิวเตอร์ (CAD/CAM) ต่อความหน่วงที่แสดงออกของครอบฟันที่รองรับด้วยรากเทียม

น.ส.ชนิกานต์ สุขเกษม

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาทันตกรรมประดิษฐ์ ภาควิชาทันตกรรมประดิษฐ์
คณะทันตแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2565

Thesis Title	INFLUENCE OF CAD/CAM MATERIALS ON DAMPING BEHAVIOR OF IMPLANT-SUPPORTED CROWN
By	Miss Charnikan Sukkasam
Field of Study	Prosthodontics
Thesis Advisor	Assistant Professor KRID KAMONKHANTIKUL, D.D.S., Ph.D.
Thesis Co Advisor	Professor MANSUANG ARKSORNNUKIT, D.D.S., M.S., Ph.D.

Accepted by the FACULTY OF DENTISTRY, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Science

______________________ Dean of the FACULTY OF DENTISTRY

(Professor Pornchai Jansisyanont, D.D.S., M.S., Ph.D.)

THESIS COMMITTEE

______________________ Chairman

(Associate Professor ORAPIN KOMIN, D.D.S., Ph.D.)

______________________ Thesis Advisor

(Assistant Professor KRID KAMONKHANTIKUL, D.D.S., Ph.D.)

______________________ Thesis Co-Advisor

(Professor MANSUANG ARKSORNNUKIT, D.D.S., M.S., Ph.D.)

______________________ Examiner

(Assistant Professor WAREERATN CHENGPRAPAKORN, D.D.S., Ph.D.)

______________________ External Examiner

(Assistant Professor Pisaisit Chaijareenont, D.D.S., M.Sc., Ph.D.)

ชนิกานต์ สุขเกษม : อิทธิพลของวัสดุที่ออกแบบและผลิตด้วยคอมพิวเตอร์ (CAD/CAM) ต่อความหน่วงที่แสดงออกของครอบฟันที่รองรับด้วยรากเทียม. (INFLUENCE OF CAD/CAM MATERIALS ON DAMPING BEHAVIOR OF IMPLANT-SUPPORTED CROWN) อ.ที่ปรึกษาหลัก : ผศ. ทพ. ดร.กฤช กมลขันติกุล, อ.ที่ปรึกษาร่วม : ศ. ทพ. ดร.แมนสรวง อักษรนุกิจ

วิทยานิพนธ์นี้มีเป้าหมายเพื่อศึกษาความสามารถในการหน่วงของครอบฟันที่รองรับด้วยรากเทียม ซึ่งทำด้วยวัสดุที่ออกแบบและผลิตด้วยคอมพิวเตอร์ (CAD/CAM) ชนิดต่างๆกัน โดยการนำรากเทียมมาลงในเรซิน ครอบฟันถูกแบ่งตามวัสดุเป็น 3 กลุ่ม คือ 1. เซอร์โคเนีย 2. ลิเทียมไดซิลิเกต และ 3. พอลิเมทิลเมตะไครเลท ครอบฟันแต่ละชิ้นจะถูกแบ่งเป็นกลุ่มย่อย คือ 1. ไม่ใช่สารยึดติด 2. ใช้เรซินซีเมนต์ (n=5) ชิ้นงานทั้งหมดจะถูกนำเข้าทดสอบโดยถูกให้แรงตั้งแต่ 0-200 นิวตัน สเตรนเกจถูกยึดติดไว้ที่บริเวณส่วนบน และส่วนล่างของชิ้นงาน ความสามารถในการหน่วงของระบบแสดงด้วยความชันของกราฟแรงที่กระทำต่อเวลา, ความหน่วงต่อเวลาที่บริเวณต่างๆ และเวลาที่ใช้ถึงแรงที่กระทำสูงสุด ทำการวิเคราะห์ความแปรปรวนสองทาง, การจับคู่แบบทูกีย์ และการเปรียบเทียบแบบรวมกลุ่ม โดยกำหนดระดับความเชื่อมั่นที่ร้อยละ 95 (α = 0.05) ผลการวิจัยพบว่า ความชันของกราฟทั้งหมดและเวลาที่ใช้ ในกลุ่มของเซอร์โคเนีย และ ลิเทียมไดซิลิเกตไม่แตกต่างกัน ($p<0.05$) แต่ในกลุ่มของพอลิเมทิลเมตะไครเลทมีความชันของกราฟต่ำและใช้เวลามากกว่าในกลุ่มอื่นอย่างมีนัยสำคัญทางสถิติ ($p<0.05$) กลุ่มที่ไม่มีสารยึดติดมีความชันที่มากกว่าบริเวณส่วนบน และใช้เวลาน้อยกว่ากลุ่มที่ใช้เรซินซีเมนต์อย่างมีนัยสำคัญทางสถิติ ($p<0.05$) จึงสรุปได้ว่า ความสามารถในการหน่วงในระบบครอบฟันที่รองรับด้วยรากเทียมแตกต่างกันตามชนิดของวัสดุครอบฟันโดยวัสดุที่มีค่าโมดูลัสต่ำแสดงความหน่วงที่ดีกว่า และ การใช้สารยึดติดช่วยเพิ่มความสามารถในการหน่วง

สาขาวิชา	ทันตกรรมประดิษฐ์	ลายมือชื่อนิสิต ....
ปีการศึกษา	2565	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
		ลายมือชื่อ อ.ที่ปรึกษาร่วม ....

6370007332 : MAJOR PROSTHODONTICS
KEYWORD: Damping, Implant-supported crowns, Strain gauge, CAD/CAM, Crown material

Charnikan Sukkasam : INFLUENCE OF CAD/CAM MATERIALS ON DAMPING BEHAVIOR OF IMPLANT-SUPPORTED CROWN. Advisor: Asst. Prof. KRID KAMONKHANTIKUL, D.D.S., Ph.D. Co-advisor: Prof. MANSUANG ARKSORNNUKIT, D.D.S., M.S., Ph.D.

This study was to investigate the damping capacity of implant-supported crowns made from various computer-aided design and computer-aided manufacturing (CAD-CAM) restorative materials. A titanium implant fixture was embedded in epoxy resin. Crown specimens were divided into three groups: Zirconia (Z), Lithium disilicate (E), and Polymethyl methacrylate (P). Each crown was subdivided into Uncement (Un) and Adhesive resin cement (RC) subgroups (n=5). Specimens were loaded (0-200N). Strain gauges were attached to measure microstrains at crestal and apical levels. Damping capacity was determined based on load-time curves, microstrain-time curves, and time required to reach the maximum load. A two-way ANOVA with Tukey post hoc test and independent t-test were conducted (α=0.05). The results showed that slopes of curves and time to reach maximum load were similar in the Z and E groups (p>0.05), but the P group exhibited less steep slopes and more time to reach maximum load (p<0.05). The UN group had significantly steeper microstrain slopes at crestal level and less time to reach maximum load compared to the AR group (p<0.05). In conclusion, the crown material significantly influenced the damping capacity, with lower modulus of elasticity materials showing higher damping capacity. Cementation enhanced damping capacity in implant-supported crowns.

Field of Study:	Prosthodontics	Student's Signature ....
Academic Year:	2022	Advisor's Signature ....
		Co-advisor's Signature ....

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my profound appreciation and gratitude to all those who have supported and contributed to the completion of this thesis, especially during the challenging times we encountered.

First and foremost, I want to express my heartfelt gratitude to my advisor, Dr. Krid Kamonkhantikul. Throughout this thesis journey, we faced numerous obstacles and worked tirelessly, often staying late into the night, to overcome them. His unwavering dedication, relentless pursuit of excellence, and willingness to go the extra mile have been truly remarkable. His commitment to my growth as a researcher and his perseverance in pushing the boundaries of this work have been invaluable. I am profoundly grateful for the guidance, support, and sacrifices he made to ensure the successful completion of this thesis.

I also want to acknowledge the tremendous efforts of my co-advisor, Prof. Mansuang Arksornnukit. His collaboration, expertise, and unwavering support were indispensable in navigating the challenges we encountered. Together, we persevered and worked tirelessly to ensure the highest quality of research. His insights, constructive criticism, and commitment to excellence have significantly contributed to the outcomes of this thesis.

I would like to extend my gratitude to the members of my thesis committee, for their valuable input, guidance, and patience during the arduous journey of completing this thesis. Their expertise and willingness to provide constructive feedback have been invaluable in refining and improving the quality of this work.

I am profoundly grateful to the members of prosthodontics department, faculty of dentistry, Chulalongkorn university for their teachings, mentorship, and support. Their dedication to academic excellence and their commitment to fostering a stimulating intellectual environment have played a vital role in shaping my research capabilities.

I would like to express my heartfelt appreciation to the staff at dental material research and development center and Kwoya company, Thailand for their assistance, resources, and technical support. Their willingness to go above and beyond to ensure that I had access to the necessary research materials and resources was instrumental in the successful completion of this thesis.

To my family, I am eternally grateful for their steadfast support, understanding, and encouragement throughout this challenging endeavor. Their belief in my abilities, their patience during my late nights, and their constant love have been my anchor and source of strength.

Lastly, I want to acknowledge the support and camaraderie of my friends and colleagues. Their encouragement, shared experiences, and understanding during difficult moments have been invaluable in keeping me motivated and focused.

In conclusion, the completion of this thesis has been a demanding journey, and it would not have been possible without the resilience, dedication, and sacrifices of the individuals mentioned above. I am sincerely grateful for their support, collaboration, and belief in my abilities.

Charnikan Sukkasam

TABLE OF CONTENTS

Chapter 1
Introduction

A dental implant is commonly utilized to replace missing teeth in individuals without teeth. The most reliable approach is through the use of a single-tooth implant or an implant-supported crown (1). Howe et al. performed a meta-analysis on the survival rate of dental implants and discovered that the estimated survival rate at the 10-year mark was 96.4%.(2). In addition to the notable success rate of dental implants, occlusal overload stands out as one of the common contributing factors. Occlusal overload is defined as a load greater than the bone-implant load-bearing capacity. Although increased bone loss around the area of relatively high stress has been reported, the causal relationship between overload and implant has not yet been established (3-8).

Occlusal loading is a significant factor affecting the success of dental implants. It is known that differences between a natural tooth and a dental implant lead to distinct biomechanical characteristics. Unlike natural teeth, osseointegrated dental implants lack a periodontal ligament (PDL) and make direct contact with the surrounding bone, thereby transferring stress to the peri-implant bone. (9, 10). PDL provides shock absorption through its physiological-functional adaptability, which helps to reduce stress on the crestal bone. (6, 11). This implies that osseointegrated implants without PDL would be more susceptible to occlusal loading (6). Therefore, it is crucial to ensure that the force transmitted at the implant-bone interface remains within the biomechanical range (11, 12).

Regarding occlusal overload, various concepts have been developed to compensate for the absence of PDL in implants, such as the intramobile cylinder (IMZ) implant system. This system aims to simulate physiological mobility by incorporating a stress-absorbing component within the implant connector. However, it is important to note that this approach requires regular follow-up and replacement of the stress-absorber component. (13).

Another concept focuses on implant prostheses, which includes abutment materials, crown materials, and luting agents. Several studies have explored the shock-absorbing capacity of abutment and crown materials, which is influenced by the elastic moduli of the materials. However, the findings regarding this matter are still inconclusive (14-18). In a study conducted by Rosentritt et al., the impact of different crown materials and luting agents on shock absorption was analyzed, revealing a significant influence of materials on the damping behavior of the implant system (19). Nevertheless, there is limited information available regarding the relationship between material type and the damping behavior of the implant complex. Therefore, the aim of this study is to investigate the damping capacity of implant-supported crowns made from various restorative material.

Research Question

Would the different computer-aided design and computer-aided manufacturing (CAD-CAM) restorative materials have an effect on the damping capacity of an implant-supported crown?

Research Objective

To investigate the damping capacity of implant-supported crowns made of different computer-aided design and computer-aided manufacturing (CAD-CAM) restorative materials

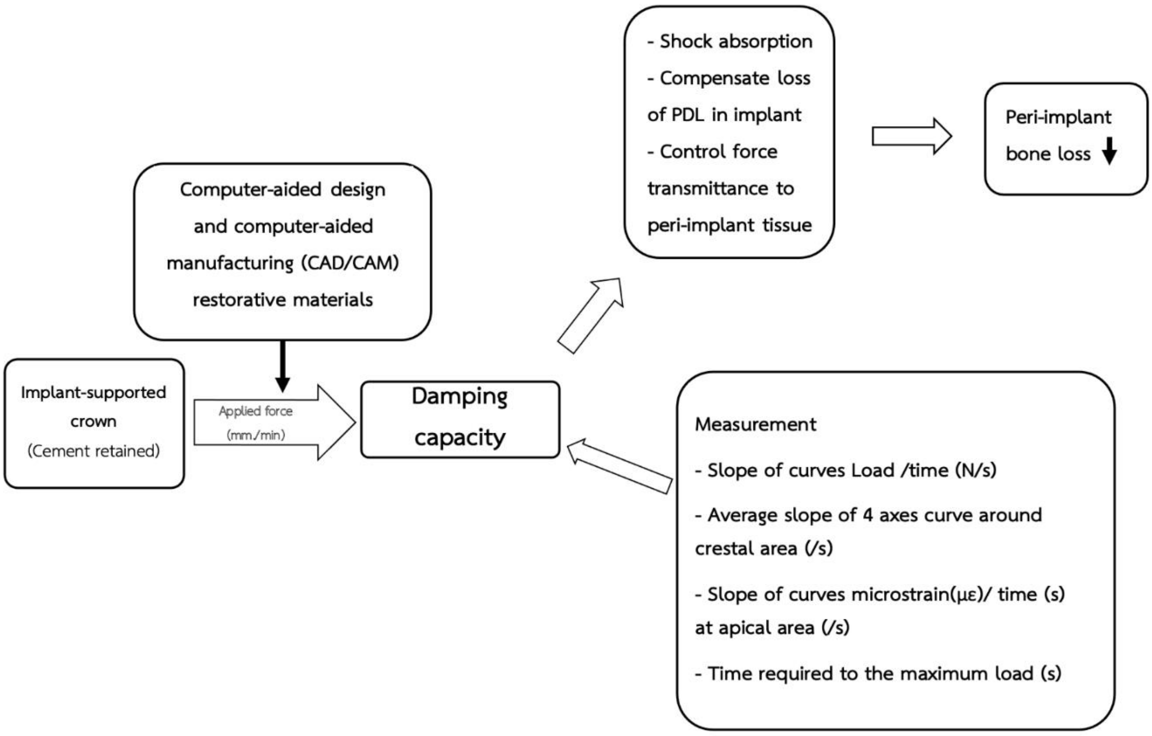
Research Hypothesis

H_0 : There are no differences in damping capacity of implant-supported crowns between each group which is made of different computer-aided design and computer-aided manufacturing(CAD/CAM) restorative materials.

Proposed Benefit

To provide information to clinicians for consideration in restorative material usage of the implant-supported crown in respect of their damping behaviors

Conceptual framework



Chapter 2
Literature Review

Implant-supported crown and CAD-CAM technology

A dental implant is a widely used treatment option for replacing missing teeth in edentulous patients. Implant-supported crowns are the most reliable method for replacing a single tooth in the posterior region (1). Goodacre et al. conducted a 20-year search of medical literature spanning from 1981 to 2001. Their literature review revealed that single-crown implants had a survival rate of 97%, surpassing other restoration types. In comparison, the survival rates for maxillary overdentures and complete dentures were 81% and 90%, respectively (20). In addition, Howe et al. conducted a study on dental implant survival rates from 1997 to 2018. Their meta-analysis revealed an estimated 10-year survival rate of 96.4% (2).

Due to the continuous advancements in computerized engineering technology, dentistry has been revolutionized by computer-aided design and computer-aided manufacturing (CAD/CAM). The utilization of digital technology is becoming increasingly prevalent in various dental specialties, including orthodontics, oral and maxillofacial surgery, and prosthodontics, particularly in the field of fixed implant prostheses (21). In the past, traditional approaches to implant treatment, such as classic impressions and plaster castings, were commonly used. However, with the advancements in technology, several treatment procedures now employ a digital workflow, offering numerous advantages, particularly for cases involving implant-supported single units and short-span reconstructions. The data is obtained through intraoral scanners, followed by virtual design and production. Many companies have developed various software, tools, and devices to facilitate and enhance the work of clinicians and technicians (22). With the digital protocol, there are several advantages, including the elimination of a master cast, improved reproducibility of reconstructions, reduced production costs, and enhanced time efficiency (23).

Furthermore, a digital protocol enables the fabrication of implant-supported restorations through subtractive manufacturing. This method involves milling the restoration from a material blank using a computer numerical control (CNC) machine (24). In this manner, the durability of the workpiece is ensured as the manufacturer pre-fabricates a material blank. Consequently, the conventional deficiencies commonly encountered in commercial laboratories, such as porosities and inconsistent homogeneity, are significantly reduced (21). In their systematic review, Kapos and Evans reported higher survival rates for CAD/CAM fabricated crowns, abutments, and frameworks compared to conventionally fabricated prostheses. The mean survival rate was 98.85% for CAD/CAM crowns, 100% for abutments, and 95.98% for frameworks (25).

Biological complications and failures

While the high success rate of the dental implants was presented, there were multifactorial backgrounds that involved implant complications and failures. In terms of biological complications, which can be defined as problems around the peri-implant soft tissue compartment and supporting bone, three major considerations have been identified as etiologic factors: infection, impaired healing, and overload (3).

The first factor is an infection that can occur during implant treatment (4). This could be induced by direct contamination of the implant surface itself or from neighboring dental structures (3). Moreover, inflammatory reactions of the tissue surrounding an implant that involves loss of supporting bone are properly defined as peri-implantitis. Based on Mombelli et al., peri-implantitis was a site-specific infection that had a remarkably similar ecosystem to those in periodontitis, in which black-pigmented Bacteroides elevated (26). There are studies stating that the risk factor of implant treatment was biofilm. Its composition was more complex in the peri-implant site compared to the normal periodontal site. Biofilm influenced implant success rates (27-30).

On the other hand, a study by Isidor F. showed different results. Five implants were inserted into the mandible of 4 monkeys, and the peri-implant bone was histologically evaluated. The results showed that in comparison to the excessive occlusal overload implants, which had a percentage of bone to implant contact of only 11%, all plaque accumulated implants were osseointegrated with a histologic marginal bone level of 2.4 mm., and a proportion of bone to implant contact of approximately 64.3% (31). Nevertheless, it remains difficult to determine whether poor oral hygiene is correlated with marginal bone loss (4).

A failure from impaired healing is generally discovered in the second operation in a 2-stage system (3). The biological processes occur at the bone-implant interface, including inflammatory and regenerative processes. The healing process at the site of surgical trauma displays several tissue differentiation and regulation features (32). Whenever the processes of normal bone healing are perturbed to a certain unknown threshold, the inserted implant will be encapsulated by fibrous tissue instead of bone. These processes lead to the instability of implanted devices. Even though the mechanism of soft tissue encapsulation is not clearly known, it is assumed that both biochemical and biomechanical are involved, such as micromotion, surgical trauma, and systemic characteristic of the host (5).

Another common factor of failures is overload. Once the functional demand exceeds the load-bearing capability of the protheses, implant components, or tissue interfaces, it is referred to overloading (5, 33). In general, the maxilla and mandible bones act as other bones that carry mechanical loads and adapt to applied forces, which are mainly derived from muscles. Frost hypothesized that the bone cells respond to mechanical stress. In a steady state, bones adapt to a certain strain unless the strain exceeds a certain threshold, at which point fatigue fractures may occur. In this theory, it is important to remind that the load is not the key, but rather the resulting strain on the bone. This is because the strain that happened is also dependent on the properties of the bone itself. In addition, Frost also stated that if greater than 3000 microstrains ($\mu\varepsilon$) were applied to the bone, it will lead to a microdamage (MDx) (34).

Based on a study by Miyata et al. conducted in monkeys, it was found that supra-occlusal contact heights of approximately 180 microns or more caused bone resorption around implants (35). In the same way, Isidor F. found that in monkeys, implants with excessive overload lost the osseointegration (31, 36). Conversely, Heitz-Mayfield et al. evaluated the effect of overloading titanium implants in 6 Labrador dogs and found that in 8 months, there was no significant change at the marginal bone of loaded and unloaded implants on radiographic (37).

For the clinical experiment, several studies showed that the marginal bone loss around the oral implant has been associated with a great occlusal stress (36, 38, 39). For instance, Quirynen et al. suggested that there was a correlation between excessive marginal bone loss and the presence of occlusal overload after the first year of loading (39). Even so, Naert et al. published a systematic review concluding there is insufficient evidence to support the relationship between implant overload and bone loss in clinically osseointegrated implants (40). Nonetheless, it appears to be important to provide the forces in order to maintain biomechanical balance. Although the relationship between occlusion and implant is not fully understood (3-8).

Implants are not teeth.

Osseointegration was defined by Brånemark as a direct contact at the light microscope level between living bone and load-carrying endosseous implant (41). And this referred to the point. There was no cushion layer of fibrous tissue (9, 10, 41).

Therefore, osseointegrated implants directly transfer stress to peri-implant bone (11, 41). Skalak R. attempted to describe a biomechanical behavior of a titanium implant in terms of stress distribution and load transfer. This article proposed that the first structure to be failed was a bone interface rather than the titanium implant due to a lower elastic modulus of bone. Implant-bone construct had a relatively stiff connection which allowed the stress to transmit without any shock resistance. To prevent the bone from being overstressed, if a large impact load is suddenly encountered while chewing, materials with a low modulus of elasticity and internal damping capacity would be recommended. However, there was no experimental data to substantiate this model (11).

On the contrary, A natural tooth is contributed by a periodontal ligament which provides shock absorption due to physiological-functional adaptability to occlusal stress. A rotational movement of a natural tooth when the lateral force is applied could diminish forces from the crestal bone. But the dental implants are directly transferred stress to the peri-implant bone (6, 11). Moreover, PDL has a periodontal mechanoreceptor that provides proprioceptive motion feedback in the early phase of occlusal forces. This issue implied that osseointegrated implants without PDL would have more susceptibility to occlusal loading (6). Robison et al. had developed and validated a finite element (FE) model of the first premolar with PDL and the dental implant, which used identical crown morphology. To assess their mechanical behavior to occlusal loading, strain-gauge measurement was used. The result showed that the strains prediction from FE stimulation was correlated to the experimental strain-gauge measurement. Both stresses and strains were substantially higher in the bone surrounding the dental implant than the natural tooth socket. Thus, the study suggested that PDL played the role of off-centering and bending stress in a natural tooth. And because of the stiffness, the dental implant should provide a light occlusal contact (42). Other studies also agreed that PDL had a crucial role in the dissipation of

masticatory force (43, 44). More recently, Dastgerdi et al. used the FE models to compare the momentum transferred to implant-bone and tooth-PDL-bone under the impact loading. The outcome appeared in the same direction as other studies, which found that the linear momenta transferred to implant-bone were greater than tooth-PDL-bone under the same impact load and the von Mises stress. Besides, This study also suggested that implant prostheses should improve the damping capacity which might allow the implant to maintain the
natural tooth behavior (45).

To compensate shock-absorbing function of PDL in implant.

In the literature, various ways have been proposed to produce a stress-absorbing element for compensating PDL function in the implant complex. Two main concepts have been developed on this subject. The first concept attempts to focus on intrastructural component by using intramobile resilient connector. The second one focuses on the suprastructure as a prosthesis component.

In 1983, the intramobile cylinder implant system (IMZ) began (46). Since then, there have been ongoing studies, in which an intramobile element (IME) is used in the connection between the prosthesis and the implant. This IME is fabricated by material with the viscoelastic property that provides the implant physiological mobility (13, 47-49). Rossen et al. designed a FE model of a free-standing single implant with and without a stress-absorbing element. The result showed that the stress-absorbing element could not act as a stress distributor in a single implant even with a low elastic modulus (49). Mehdi et al. inserted two elastomers as stress absorbers between implant, screw, and abutment, and then analyzed the stress distribution using a 3D-FE model. The analysis showed that the stresses around the bone-implant interface are lower in the elastomeric model than in the conventional model but the compressive stress in the implant increased sharply (48). However, this stress absorber must be replaced for long-term use (13).

Nevertheless, there have been several studies focusing on the implant suprastructure as a prosthetic component. Adell et al. had been observing cases in which fixtures were placed during 1965-1980 for 1 year. And found that controlling stress distribution was crucial for long-term maintenance of osseointegrated implant, especially in the maxilla. It was suggested that the occlusal surfaces of prostheses made of porcelain or gold were more detrimental to the viability of bone interface than acrylic resin. The acrylic resin occlusal surface could act as a shock absorber and also be successively worn to compensate for remaining minor occlusal irregularities (50). As mentioned earlier, Brånemark recommended regularly recalling the prostheses to maintain proper occlusion for a long-lived osseointegrated implant. It was also pointed out that using acrylic resin artificial teeth as an implant-supported restoration could compensate for the resilience of PDL (41). Skalak R. also theorized that covering a fixed metal partial denture with acrylic resin could lower the peak of stress and extend stress duration. Even if it would wear down, acrylic resin could be practically replaced (11). Gracis et al. compared the damping effect of five materials used to veneer the crown on implant and found that the light-cured composite resin and the heat-cured polymethylmethacrylate (PMMA) reduced about half of the peak of impact force that occurred within alloys or porcelains. However, there were concerns about other properties of these two resins such as wear resistance, tensile strength, hardness, and color stability (16). Several studies came to similar conclusions, Magne et al. examined the damping behavior of implant-supported restorations by varied implant abutment materials, crown materials, and designs. In this study, Periometer ® device was used to assess the percussion loss coefficient (LC). The LC of implant-supported restorations was compared to the LC of a natural tooth model with stimulated PDL. Multiple regression analysis revealed that the variable affecting LC was the abutment materials, the restorative materials, and the restorative designs, respectively. Anyhow, all three variables had a statistically significant effect on LC. The Dunnett t-test also showed that the only model that was not significantly different from the natural tooth group was the implant restored with zirconia abutment and composite resin restoration either crown or onlay design. Moreover, the implant was able to achieve a stronger damping effect by adding a composite resin component in the prosthetic part (17). Menini et al. conducted an in vitro study on the shock absorption capacity of implant restorative materials. Mandibular movement and the application of masticatory force were duplicated by the masticatory robot. The force transmission onto the sensor-equipped base was recorded by strain gauges. The result showed that the larger the elastic moduli of the material, the steeper the peak of the transmitted force (18). Later, there were some studies that tried to combine different crown materials with different abutment materials and investigated the damping behavior. Taha et al. combined 4 types of CAD-CAM crown materials: zirconia, PEEK, E-max, and Vita enamic with 2 types of coping abutment materials: Zirconia and PEEK. Force absorption was measured by placing a force meter at the apical of the model. The result showed that there was a significant difference in applied and resulting slope among different materials. The experiment also revealed an interesting issue, if the less rigid crown material was used, more stiff coping abutment material would be used to preserve their damping capacity (51). Omaish et al. combined resin composite veneer restoration with 2 types of new CAD-CAM inner coping restoration materials, BioHPP (bioactive high-performance PEEK based polymer) and TRINIA (glass fiber-reinforced nanohybrid polymer). The strain gauges were used to evaluate the strain developed around the implants. The models made of TRINIA exhibited significantly lower microstrains compared to models made of BioHPP (52).

However, there were contrasting results on this topic, Cibirka et al. designed a study to determine the force absorption ratio for three materials used in the implant:

gold, porcelain, and dual-cured composite resin. The self-tapping implant was inserted in a human cadaver mandible, applied force through a peanut sample, and measured microstrains with a strain gauge stuck at the lingual bone surface. This study stated that there is no statistically significant difference in the force absorption ratio between each occlusal surface materials (14). Recently, Datte et al. studied the stress distribution of the dental implant influenced by different restorative materials using in vitro study and FE analysis. The four crown materials with two abutment materials were loaded for 200 N. The results by strain gauge and FE analysis showed consistency. There was no significant difference between the crown material groups for the bone microstrains. The crown material affected stress values only in the crown and around the cervical of abutment. The analysis showed that the crown material with high elastic modulus decreased the stress in the abutment while the material with low elasticity decreased stress in the crown itself (15).

Varies of restorative materials

There are several different materials that could be used with titanium abutment in the implant complex, such as metal-ceramic material, PMMA, and all-ceramic. And because CAD/CAM technology and materials continue to improve, resulting in a wide variety of materials to choose from (25, 53).

Polymethyl methacrylate (PMMA) is a polymer most commonly used in dentistry. Due to its properties, PMMA acquired a popularity for dental applications such as denture bases, dentures, orthodontic retainers, temporary or provisional crowns on natural teeth, and also temporary or provisional crowns on implant (54). PMMA has advantageous properties including esthetics, lightweight, cost-effectiveness, and ease of manipulation. On the other hand, there are some concerns in using PMMA as a prosthesis such as durability, water absorption, poor impact, and flexural strength. Recently, CAD/CAM technologies have been used to fabricate PMMA prostheses and offer various advantages to PMMA properties which is superiority in its flexural strength, hardness, flexural modulus, impact strength, and durability (55, 56). Al-Dwairi et al. compared the mechanical properties of CAD/CAM and the conventional heat-cured PMMA and found that CAD/CAM PMMA had significantly improved flexural strength, impact strength, and flexural modulus compared to conventional heat-cured PMMA (57). Nowadays, PMMA interim crowns are increasingly used on the implant with digital workflow (58, 59).

Glass matrix ceramics are non-metallic ceramic restorative materials containing a glass phase. Currently, in clinical application, a lithium disilicate reinforcement glass matrix ceramic is the most widely used as a material for all-ceramic crowns. These improved mechanical properties as a stronger and tougher material compared to leucite-based glass ceramics make lithium disilicate ceramic benefits both highly esthetic and exceptional strength. IPS e.max CAD® is one of these materials line, the pre-heated block which formed a partially crystallized state, which is easier to mill. In 2016, the manufacturer updated the indications for IPS e.Max CAD® to use as veneering materials, inlays and onlays, partial and full crowns, three-unit fixed partial dentures (FPD) in the anterior, premolar, and posterior regions (53, 60). A 2017 cohort study investigated the survival rate of implant-supported single crown made of lithium disilicate ceramic and found that the 10-year survival rate and chipping-free rate were high at 93.8% (61).

Polycrystalline ceramics are non-metallic ceramic restorative materials that contain a fine polycrystalline grain as the main feature instead of a glass phase. These result in a ceramic with high strength and high fracture toughness ceramic, but low translucency. Among polycrystalline ceramics, zirconia ceramic in the form of yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) is commonly used for monolithic restoration. It has the highest strength and fracture toughness and can therefore overcome the problems encountered with porcelain-layering zirconia, such as chipping

(62, 63). In a systematic review in 2014, the 5-year survival rate of implant-supported zirconia crown was satisfactory at 97.1%. Furthermore, the problems that caused the most failures were chipping and fracture in ceramic veneers (64).

Damping behavior

Damping is an influence within an oscillatory system that reduces or prevents the amplitude of vibration in its oscillation. Damping is a result of the system causing dissipation of energy. When damping in the system is increased, the response can be modified to reduce the oscillation (65). However, it is one of the uncertain and challenging properties to measure due to the complexity and diversity of its physical origin. Damping can arise from several sources. There are many types of damping. The damping that arises mainly from the attractive electrostatic forces between the dry sliding surfaces is called “mechanical damping or Coulomb friction”. The energy loss that occurs in liquid lubrication is “viscous damping”. And the energy loss that occurs in all vibrating systems with elastic restoring forces due to the repeated internal deformation of the molecules themselves is called “hysteresis damping” (66). In dentistry, damping is a phenomenon that can predict viscoelastic behavior over a wide range of strain rates and is an essential parameter in determining the viscoelastic properties of both teeth and materials. Therefore, viscoelastic tissues present a higher damping capacity (67). The damping ratio is considered a parameter determining the viscoelastic properties of various composite materials (68). In periodontic dentistry, the damping characteristic of the periodontium has been used to diagnose a periodontal disease using the Periotest, where the Periotest value is used as a biophysical parameter (69). More recent studies used damping behavior as a noninvasive method to monitor bone properties or detect bone loss (70, 71). In the same direction, Feng et al. evaluated the osseointegration of implants using the damping factor (72). In prosthodontic dentistry, damping is considered an aspect of implant-supported prostheses because it compensates for the same characteristic as the previously mentioned PDL (14, 15, 17-19).

To evaluate damping behavior of prosthesis-implant-bone complex

According to the reviews, the damping behavior is a dissipating energy in the system, which is difficult to measure accurately but in association with the strain rate. It is a significant biomechanical factor for a good implant-supported prosthesis. Therefore, researchers have been trying to find better methods to evaluate the damping capacity in the prosthesis-implant-bone complex over the last decades.

For the accurate methods, it is sure to be the in vivo experiment or direct clinical evaluation. Nevertheless, there is no denying that in vivo study of the biomechanics of intraosseous implant complex is nearly impossible. The complexity of the living structure is also involved, especially the ethical issues (73). Even though there was a study in 2019, Cozzolino et al. performed in vivo strain measurement in the completely osseointegrated maxillary implant in a male patient by directly attaching strain gauges on the buccal cortical bone at 3 different areas: coronal, middle, apical to implant. It was only a pilot study because one patient was recruited (74). Due to these limitations, many researchers used other methods to overcome the clinical experiment using tools and computation with the experimental model.

One of the devices used in the dental implant area for biomechanical evaluation is Periotest (75, 76). Periotest is a device that was first developed to evaluate damping characteristics of the periodontium and was adapted to evaluate the implant stability to help decide whether the implant is ready for loading. The principle of Periotest is to measure the reaction of the periodontium or implant-bone system to decelerate the impact load. Its function is that the metallic rod in a handpiece would be tapping the surface of the implant at a constant speed, and a small accelerometer would capture the reaction. Once the rod taps the implant, there will be denying force to decelerate the rod. The contact time per impact was used to calculate the parameter in terms of Periotest values (PTV) and presented on a ranging scale. The more contact time to tooth or implant, the more PTV, which means the more damping capacity the surrounding tissues have (76). It can suggest that if the implant is solid, the damping capacity only comes from the surrounding tissues, which means the more PTV, the less integrated bone. Therefore, Periotest is suitable for evaluating implant-bone damping capacity but not satisfactory for the implant-protheses system because its measurement focuses on the reaction back of the system but cannot represent the distribution.

Photoelastic stress analysis is another technique used for biomechanical behavior in the dental implant field. Photoelasticity uses the mathematical and visual theories that if the polarized light is passed through the transparent photoelastic model which is stressed, the refraction indices are changed. Thus, the color alteration occurs in a pattern called fringe (73, 77). This method was widely used in the implant field because of its benefit which can show qualitative information such as stress concentration, location, and distribution. By the way, this method could not provide the numeric data for building a graph or diagram. There are some researchers who tried to reference the fringe pattern to the stress concentration. In addition, some compared the photoelastic data with strain gauge analysis to convert the fringe pattern to quantitative data. However, with their limitations, further studies should be investigated (73).

Due to the swift improvement of computerization in engineering technology, the method that uses a computer to analyze the biomechanical properties is called the Finite element method (FEM) or Finite element analysis (FEA). This method is a computer-based application that started from structural analysis by the matrix method. The principle of a program used a virtual design model and divided each region into smaller and simpler elements. It then assigned each element its properties, such as stiffness and force displacement. FEA would predict the mechanical behavior of the entire structure from mathematical calculations. We can solve the problem by stimulating the situation and evaluating the mechanical behavior (78). In implantology, there widely used FEA to investigate the biomechanical properties of the bone-implant-protheses complex. FEA could provide a solution to all the components, even the interfaces (15, 42, 45). In so doing, FEA also has some disadvantages. The invention has a complex structure. FEA will make the solution possible by simplifying and assuming the elements which may affect the result. Some of living structures, such as human bone, are not that simple. They are heterogeneous and anisotropy. So, there are some doubts in studies with this method (73).

A widely used method to evaluate biomechanical behavior in implantology is called strain gauges. This method can be used both in vivo and in vitro and is clinically reliable (14, 18, 73, 77). Strain gauges are based on electrical theory, in which the strain gauge is an electric resistor. It consists of a wire or foil in the shape of a continuous grid, which alters its resistance in response to deformation on the attached surface. The electrical current change is sent to the data logger and turned into a digital signal read by the computer. A strain gauge is a sensitive instrument that could produce resistance change within a minimal component deformation, so this method is precise (73, 77). In the implant field, several researchers used strain gauges to measure the stress and strain of prostheses, implants, and especially bone. Strain gauges have been used to evaluate various of bone experiments; bone stimulated materials, human cadaver mandible, and living human maxilla (14, 73, 74). Nevertheless, the strain gauge is a very sensitive instrument, it is challenging to standardize all the samples. Therefore, the statistical data from samples in experiments are prone to have a wide variation (79).

Chapter 3

Material and Method

Materials

1. Abutment-implant specimen

   1.1 Titanium implant fixture (Highness Implant System; Highness Co., Ltd., Korea; HS-I 5010; ∅5 x 10 mm)

   1.2 Cemented abutment (Highness Implant System; Highness Co., Ltd., Korea; SCA6525B; Cemented 2.5 Hex system, ∅6.5mm, length 5.5 mm, cuff height 2 mm)

   1.3 Epoxy resin (Chockfast® Orange; PR-610TCF; ITW performance polymers, USA)

   1.4 Plastic block

2. Restorative materials

   2.1 Zirconia disc (High translucent; Zirlux® FC2; Henry Schein, Inc., USA; shade U1)

   2.2 Lithium disilicate block (IPS e.max CAD®; Ivoclar Vivadent, Liechtenstein; LT A3/C14)

   2.3 Polymethylmethacrylate disc (DDTempMED; DentalDirekt GmbH, Germany)

3. Luting agents

   3.1 Adhesive resin cement (Self-adhesive and dual-cure resin cement; PANAVIA™ SA Luting Plus; Kuraray Noritake Dental Inc., Japan)

4. ETC.

   4.1 Adhesive for SGs (Model: CC-33Ax5; Kyowa Dengyo Co., Ltd., Japan)

Equipments

1. Intraoral scanner (3Shape TRIOS® 3; 3Shape A/S, Denmark)
2. CAD design software program (3Shape dental system®; 3Shape A/S, Denmark)
3. CAM milling machine (InLab MC X5; Dentsply Sirona, USA)

4. Universal testing machine (EZ-S; Shimadzu Corporation; Japan)
5. Strain gauges (Model: KFG-3-120-C1-11-L1M2R; Kyowa Dengyo Co., Ltd., Japan)
6. Load cell output wire (Kyowa Dengyo Co., Ltd., Japan)
7. Fast Data logger (UCAM-550A; Kyowa Dengyo Co., Ltd., Japan)
8. Strain Unit (USM-52B; Kyowa Dengyo Co., Ltd., Japan)
9. Dynamic Data Acquisition Software (DCS-110A; Kyowa Dengyo Co., Ltd., Japan)
10. Carbide burs
11. Airotor
12. Low speed saw (Isometric)
13. Light cure unit (Bluephase N, Ivoclar Vivadent, Lichtenstein)
14. Plastic spatula
15. Stainless steel base for a plastic block
16. Parallel stainless steel jig

Table 1 Details of materials used in this study and physical properties.*

Type	Code	Material	Manufacturer	Composition (wt%)	Flexural strength (MPa)	Young's modulus (GPa)	CTE
1. High translucent ZrO_2	Z	Zirlux® FC2	Henry Schein, Inc., USA.	ZrO_2 >94.0 Y_2O_3 5.35±0.20 HfO_2 <3.0 Al_2O_3 <0.1	1,100	~200-210 (80)	10.6 (20-500°C) 10^{-6}/C
2. Lithium disilicate	E	IPS e.max CAD®	Ivoclar Vivadent, Liechtenstein	SiO_2 57.0–80.0 Li_2O 11.0-19.0 K_2O 0.0-13.0 P_2O_5 0.0-11.0	360±60	95±5	10.45±0.4(100-500°C) 10^{-6}/K
3. Polymethyl Methacrylate (PMMA)	P	DDTempMED	DentalDirekt GmbH, Germany	PMMA >99.8	78	2.98	-

*Details and physical properties provided by material's manufacturers.

Methods

Part I : Specimen preparation

Sample size calculation

Following a previous study by Taha D. and Sabet A. in 2021 (81), the sample size determined using analysis software (G*Power 3.1) was 3 samples per group. However, in the present study, we had chosen to account for any potential deviations from the calculated sample size and included 5 samples in each experimental group (Fig1.).

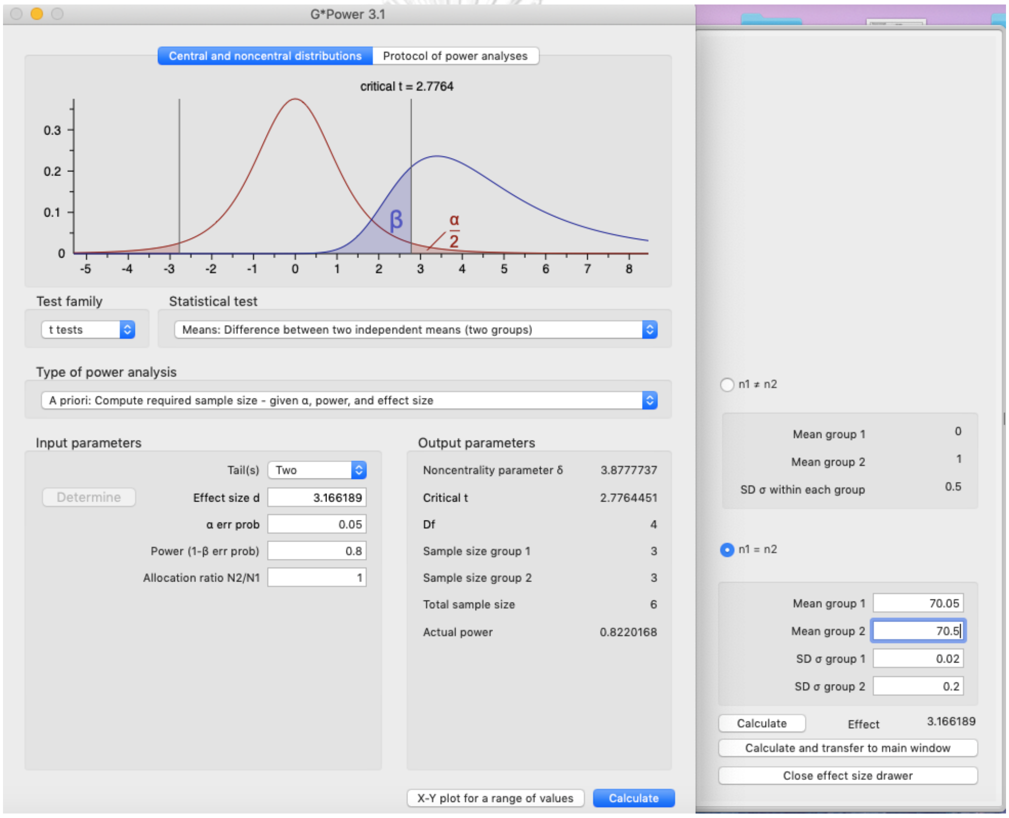


*Figure 1 Calculated sample size from G*Power 3.1*

Implant specimen

A titanium implant fixture (Highness Implant System; Highness Co., Ltd., Korea) (∅5 x10 mm) was vertically aligned using a parallel jig block and embedded in crystalline silica-reinforced epoxy resin using non-shrinkage autopolymerization (Chockfast® Orange, PR-610TCF; ITW Performance Polymers, USA; modulus of elasticity = 5.93 GPa). This epoxy resin simulated compact bone around the implant fixture. The specimens were left at room temperature for 24 hours to ensure complete setting (Fig 2.).

Figure 2 The implant fixture embedded in epoxy resin

A titanium cement retained abutment (Highness Implant System; Highness Co., Ltd., Korea) (Cemented 2.5 Hex system, ∅6.5mm, length 5.5 mm, cuff height 2 mm) was inserted into the implant fixture. The abutment-implant specimen was scanned using an intraoral scanner (3Shape TRIOS® 3; 3Shape A/S, Denmark).

Crown preparation

The crowns were manually waxed up to resemble the right mandibular first molar (crown length 8 mm, crown width (M-D) 11 mm, crown width (B-L) 10 mm) on the abutment-implant specimen, creating a space for a steel round piston at the central fossa (Fig. 3). The waxed crowns were then scanned using an intraoral scanner. Subsequently, the abutment-implant specimens with and without the waxed crowns were sent to a CAD software program (3Shape dental system®; 3Shape A/S company, Denmark) for further processing (Fig. 4). After approval of the design, the files in the standard tessellation language (STL) format were transferred to the program for crown milling using a milling machine (InLab MC X5; Dentsply Sirona, USA).

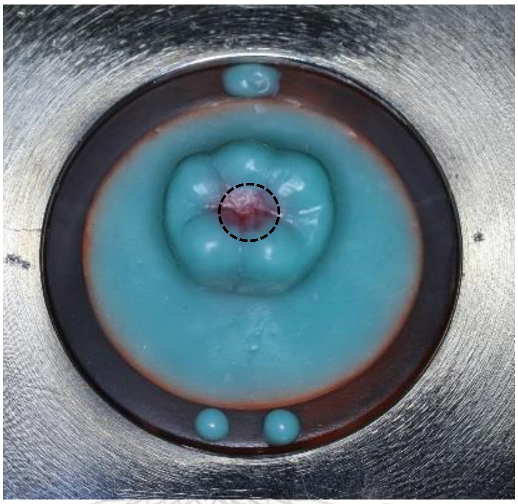


Figure 3 Waxed crown

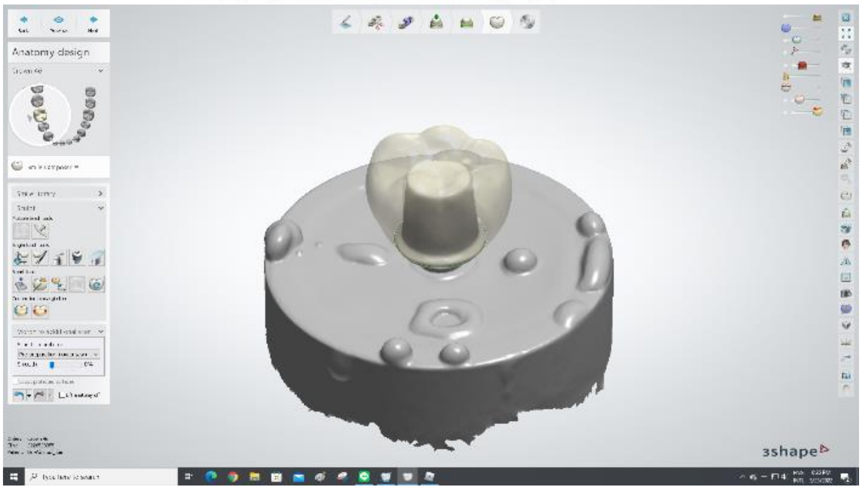


Figure 4 The crown design in the 3Shape dental system®

The crown specimens (N=30) were divided into 3 groups based on the crown material: Zirconia (Z), Lithium disilicate (E), and PMMA (P). Each crown was paired with each abutment and further subdivided into 2 subgroups (n=5) based on the cement condition: Uncement (Un) and Adhesive resin cement (RC)

After milling, all crowns were processed according to the manufacturer's recommendations. The inner surface was cleaned using a ultrsonic cleaner for 5 min. Then, each crown was tried-in on the abutment-implant specimen to evaluate proper fit using an explorer. The abutment was torqued to 35 Ncm, and the access was sealed with Teflon tape before the crown was mounted.

After mixing according to the manufacturer's instructions, the cement was loaded onto the inner surface of the crown in the appropriate amount. Tag curing was performed for 2 sec on each surface before removing any excess cement. Subsequently, full light curing was conducted for 40 sec on each surface and the crown was rested under a loading apparatus for 6 min. After that, the crown was left without any load for 6 min more to ensure complete chemical curing. The crowns of each material were connected to the corresponding abutment-implant specimens using adhesive resin cement in a random order.

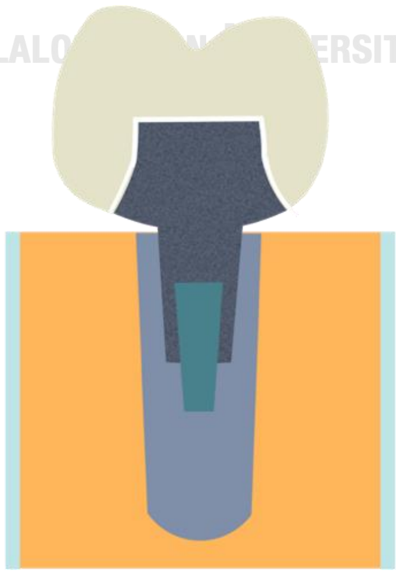


Figure 5 The framework of crown-abutment-implant embedded in the stimulated bone

Part II: Testing

All specimens were loaded into a universal testing machine (EZ-S; Shimadzu Corporation; Japan) and subjected to an increasing force at a velocity of 1 mm/minute. The force was applied on the occlusal surface of the crown at the central fossa, following the long axis of the specimen, using a loading piston (a steel ball with a diameter of 4 mm). The load was applied from 0 to 200 N, 3 times for each specimen. Additionally, a control test was conducted without an abutment, using the covering screw.

The strain gauges (Model: KFG-3-120-C1-11-L1M2R; Kyowa Dengyo Co., Ltd., Japan) were used to measure the resulting microstrains. Four strain gauges representing buccal (B), lingual (Li), mesial (M), and distal (D) areas were attached to the crestal level of the implant model. Additionally, one strain gauge was placed below the specimen to represent the apical (A) level (Fig. 6.). After 24 hours, all bonded strain gauges were coated with a vinyl mastic tape (Scotch VM Tape, 3M, Saint Paul, MN, USA) to protect moisture during testing.

To capture the output voltage from the strain gauges and transform it into load measurements in Newtons (N), a fast data logger (UCAM-550A; Kyowa Dengyo Co., Ltd., Japan) was linked to the universal testing machine using an output linker. All data, including load (N), resulting microstrains (με), and time (s), were recorded using dynamic data acquisition software (DCS-110A; Kyowa Dengyo Co., Ltd., Japan).

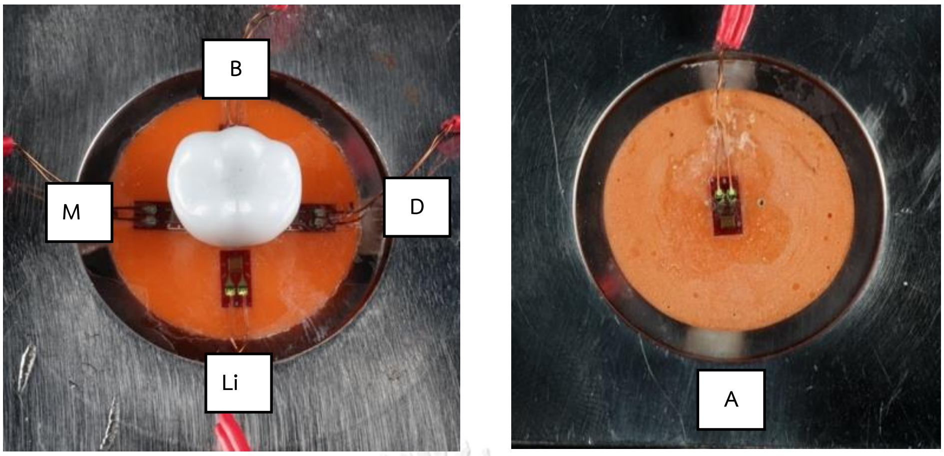


Figure 6 Strain gauges are attached to the specimen at the crestal and apical area

To determine the damping capacity of the tested specimens, the following data were collected from the previous experimental design: the curve of applied load against time (N/s), time required to reach the maximum load (s), and the curve of microstrains against time (/s) measured around crestal- and apical level of the specimen.

To remove the tested crown-abutment, a carbide bur was used in conjunction with an airotor to open access. Then the abutment was untorqued and unscrewed.

Part III: Statistical Analyses

The slopes of the applied load curves and microstrains curves at the buccal (B), lingual (Li), mesial (M), distal (D), and apical (A) areas were collected and calculated using a linear trendline with an R-squared value. The slopes obtained from the three loading cycles of each crown-abutment-implant complex were averaged using Microsoft Excel, Microsoft 365®. Similarly, time required to reach the maximum load (s) for each specimen was calculated by averaging the data obtained from the three loading cycles. In additional, the slopes of the microstrains curves at the four axes around the crestal level were calculated, and the average slope for the crestal (C) level was determined using the same software program.

Descriptive statistics for each group were primarily analyzed using the statistical software program (IBM SPSS Statistics, V.25.) The normality of the data was assessed using the Shapiro-Wilk test. Following the descriptive statistics and initial analysis, a two-way ANOVA was conducted. Tukey post hoc test was performed for the crown material group, and the independent t-test was conducted for the cement condition. (The level of significance will be set to α=.05)

Chapter 4
Results

The damping capacity of the implant-supported crown in each crown material with each cement condition was represented by the slope of load against time (N/s), the slope of microstrain against time (/s) (crestal and apical levels), and the time (s) to reach a maximum load, shown in Table 3 and 4. The results of two-way ANOVA of all slope curves and time indicated that there were no interactions between the crown materials and cement conditions, but there were significantly affected by each crown material and cement condition individually ($p < 0.05$).

All slopes of curve and time to reach the maximum load in Z and E group were not significantly different ($p>0.05$), except for the P group which had less steep slopes in all curves and required more time to reach the maximum load significantly ($p < 0.05$) (Table 2). The UN group had a significantly greater steep slope in crestal level microstrain curves against time and required less time to reach the maximum load than the AR group ($p < 0.05$) (Table 3).

Table 2 Mean and standard deviation of the slope of load against time (N/s), the slope of microstrain against time (/s), and time to reach the maximum load (s) in each crown material group. L: load against time; C: averaged microstrain at crestal level (buccal-, lingual-, mesial-, distal points) against time; A: microstrain at apical level against time; Within columns, different uppercase letters indicate significant differences between groups (p < 0.05).

Crown materials	Mean ± SD			
	L (N/s)	C (/s)	A (/s)	Time (s)
Zirconia (Z)	11.13 ± 1.08 B	-6.38 ± 0.79 A	11.64 ± 1.21 B	19.70 ± 2.58 A
Lithium disilicate (E)	10.92 ± 1.37 B	-6.14 ± 0.94 A	11.49 ± 1.52 B	19.94 ± 3.54 A
Polymethyl methacrylate (P)	8.82 ± 0.98 A	-5.09 ± 0.56 B	9.25 ± 1.07 A	24.26 ± 3.25 B

Table 3 Mean and standard deviation of the slope of load against time (N/s), the slope of microstrain against time (/s), and time to reach the maximum load (s) in each cement condition. L: load against time; C: averaged microstrain at crestal level (buccal-, lingual-, mesial-, distal points) against time; A: microstrain at apical level against time; Within columns, different uppercase letters indicate significant differences between groups (p < 0.05).

Cement condition	Mean ± SD			
	L (N/s)	C (/s)	A (/s)	Time (s)
Uncement (UN)	10.72 ± 1.60 A	-6.25 ± 0.96 A	11.29 ± 1.69 A	19.84 ± 3.04 A
Adhesive resin cement (AR)	9.87 ± 1.40 A	-5.49 ± 0.78 B	10.29 ± 1.53 A	22.76 ± 3.84 B

Chapter 5
Discussion

According to the data obtained, the null hypotheses were rejected. There was a significant difference of the damping capacity among CAD/CAD crown materials with different cement condition.

In this study, some negative microstrain slopes were detected, but only their slope values were interpreted. This is because the normal strain is defined as the change in length of the specimen. Positive strain represents elongation, indicating that the area is undergoing tensile forces. Negative strain, on the other hand, represents a contraction of the specimen, indicating the presence of compressive forces (82).

There were several studies that demonstrated that implant prostheses should be improved their damping capacity to maintain the natural tooth behavior (42-45). Furthermore, these studies indicated that stress concentration tends to occur more in the crestal cortical bone (83-85). The critical area around dental implants, known as the crestal level, is prone to marginal bone loss and the development of peri-implantitis, a destructive inflammatory condition (86, 87). Based on the importance of this area in implant success and the potential impact of damping capacity on reducing strains, the present study specifically focused on measuring the energy levels around the crestal level.

The modulus of elasticity is a property that describes a material's stiffness (88). According to Hooke's law (82), materials with higher moduli of elasticity, such as metals and ceramics, are stiffer and more resistant to deformation, while materials with lower moduli of elasticity, such as polymers, are more flexible and easier to deform. Deformation within a material leads to energy loss in the system and is considered a form of damping effect (65, 66). This concept is supported by the present study, which investigated the CAD-CAM crown materials with different moduli of elasticity.

In the present study, the slope of the load and microstrain curves, as well as the time required to reach maximum force, varied among the CAD-CAM crown material groups. The P group, characterized by the lowest modulus of elasticity (2.98 GPa), exhibited less steep curve slopes and longer required time, indicating a higher damping capacity. In contrast, the Z and E groups showed similar curve slopes. These findings are consistent with other in vitro studies (16, 18, 19, 51, 81).

It is worth noting that the present study provided further evidence that the modulus of elasticity influences the damping capacity of crown materials. The lower modulus of elasticity exhibited by the P group contributes to its higher damping capacity. This information can be valuable in the selection of crown materials in the aspect of damping capacity. However, when considering the use of crown materials as permanent restorations, it is important to take into account other properties besides the modulus of elasticity. Factors such as flexural strength, compressive strength, and wear resistance should also be considered. These properties play crucial roles in the long-term durability and functionality of the crown material. Therefore, a comprehensive evaluation of various material properties is necessary to ensure the suitability of a crown material for clinical applications (89).

This study provided further evidence that the damping capacity of implant-supported crowns is influenced by cementation. The UN group exhibited steeper slopes in crestal level microstrain curves against time and shorter time required, indicating a lower damping capacity compared to the AR group. These findings align with previous studies that suggest the luting mode influences the damping effect in implant-supported crowns (19, 81). While the slopes of load and apical level microstrain against time may exhibit similarities, it is crucial to focus on the significant differences observed at the crestal level. This area holds particular importance in the system, as emphasized by the mentioned concept earlier. The reason why the condition of the cement had less influence on the damping capacity could be attributed to the narrow cement space in comparison to the larger volume of the crown material used in the system (19).

The role of cementation in the system for shock absorption can be explained by the introduction of interfaces, which contribute to the development of damping through electrostatic attractive forces (66). The luting cement aids in load dissipation within the system, as supported by studies demonstrating lower strain in cement-retained prostheses compared to screw-retained prostheses (90). In term of the cement selection, various factors such as retention and compressive strength may play a crucial role in clinical application (91). It is important to consider these factors holistically to ensure optimal performance of implant-supported crowns.

Limitations of this study included the use of an implant study model that simulated the human condition but did not replicate the masticatory cycle in an oral environment. Additional limitations of this study include the limited exploration of different cement material types and their potential influence on the damping capacity of implant-supported crowns. The study primarily focused on specific cement materials, and the findings may not fully reflect the variations and effects of different cement types available in clinical practice. Further investigation is needed to examine the impact of various cement materials on damping capacity and to assess their clinical implications.

Chapter 6
Conclusion

In conclusion, this study aimed to investigate the damping capacity of implant-supported crowns fabricated using different materials with and without cementation. The results obtained from the study indicated that both the crown material and cement condition had a significant impact on the damping capacity of the crowns.

The two-way ANOVA analysis revealed that there were no significant interactions between the crown materials and cement conditions, suggesting that their combined effect did not significantly influence the damping capacity. However, when examining each factor individually, both the crown material and cement condition were found to have a significant effect.

Among the different crown materials evaluated, the Zirconia (Z) and Lithium disilicate (E) groups exhibited similar damping capacity, while the PMMA (P) group demonstrated higher damping capacity with less steep slopes and longer time to reach the maximum load. This finding suggests that the crown material significantly affect the damping capacity of the implant-supported crown. Specifically, materials with lower modulus of elasticity were found to exhibit higher damping capacity.

Furthermore, the cement condition also played a significant role in the damping capacity. The uncemented (UN) group showed lower damping capacity with steeper slopes of microstrain at the crestal level and shorter time to reach the maximum load compared to the adhesive resin cement (AR) group. This indicates that the present of cement allows for better force transmission and dissipation in the implant-supported crown.

The findings of this study provide valuable insights for clinicians and researchers in choosing the appropriate crown materials for implant-supported restorations, ultimately contributing to improved clinical outcomes and long-term success of dental implant treatments. Further research in this area is warranted to explore additional factors and their effects on the damping capacity of implant-supported crowns.

REFERENCES

1. Misch CE. Rationale for Implants. 3rd ed: Mosby Elsevier; 2008. 3-19 p.
2. Howe MS, Keys W, Richards D. Long-term (10-year) dental implant survival: A systematic review and sensitivity meta-analysis. J Dent. 2019;84:9-21.
3. Esposito M, Hirsch J, Lekholm U, Thomsen P. Differential diagnosis and treatment strategies for biologic complications and failing oral implants: a review of the literature. Int J Oral Maxillofac Implants. 1999;14(4):473-90.
4. Esposito M, Hirsch JM, Lekholm U, Thomsen P. Biological factors contributing to failures of osseointegrated oral implants. (I). Success criteria and epidemiology. Eur J Oral Sci. 1998;106(1):527-51.
5. Esposito M, Hirsch JM, Lekholm U, Thomsen P. Biological factors contributing to failures of osseointegrated oral implants. (II). Etiopathogenesis. Eur J Oral Sci. 1998;106(3):721-64.
6. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: clinical guidelines with biomechanical rationale. Clin Oral Implants Res. 2005;16(1):26-35.
7. Koyano K, Esaki D. Occlusion on oral implants: current clinical guidelines. J Oral Rehabil. 2015;42(2):153-61.
8. Sadowsky SJ. Occlusal overload with dental implants: a review. Int J Implant Dent. 2019;5(1):29.
9. Albrektsson T, Johansson C. Osteoinduction, osteoconduction and osseointegration. Eur Spine J. 2001;10 Suppl 2(Suppl 2):S96-101.
10. Raghavendra S, Wood MC, Taylor TD. Early wound healing around endosseous implants: a review of the literature. Int J Oral Maxillofac Implants. 2005;20(3):425-31.
11. Skalak R. Biomechanical considerations in osseointegrated prostheses. J Prosthet Dent. 1983;49(6):843-8.
12. Kober C, Stübinger S, Hellmich C, Sader R, Zeilhofer HF. Finite element simulation of the human mandible: the role of (natural) teeth. Int J Comput Dent. 2008;11(3-4):169-74.

13. Watanabe F. IMZ (Intramobile Zylinder) Implants. J Jpn Gnathol. 1989;10(1):15-25.

14. Cibirka RM, Razzoog ME, Lang BR, Stohler CS. Determining the force absorption quotient for restorative materials used in implant occlusal surfaces. J Prosthet Dent. 1992;67(3):361-4.

15. Datte CE, Tribst JP, Dal Piva AO, Nishioka RS, Bottino MA, Evangelhista AM, et al. Influence of different restorative materials on the stress distribution in dental implants. J Clin Exp Dent. 2018;10(5):e439-e44.

16. Gracis SE, Nicholls JI, Chalupnik JD, Yuodelis RA. Shock-absorbing behavior of five restorative materials used on implants. Int J Prosthodont. 1991;4(3):282-91.

17. Magne P, Silva M, Oderich E, Boff LL, Enciso R. Damping behavior of implant-supported restorations. Clin Oral Implants Res. 2013;24(2):143-8.

18. Menini M, Conserva E, Tealdo T, Bevilacqua M, Pera F, Signori A, et al. Shock absorption capacity of restorative materials for dental implant prostheses: an in vitro study. Int J Prosthodont. 2013;26(6):549-56.

19. Rosentritt M, Schneider-Feyrer S, Behr M, Preis V. In Vitro Shock Absorption Tests on Implant-Supported Crowns: Influence of Crown Materials and Luting Agents. Int J Oral Maxillofac Implants. 2018;33(1):116-22.

20. Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JY. Clinical complications with implants and implant prostheses. J Prosthet Dent. 2003;90(2):121-32.

21. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. Int J Dent. 2014;2014:783948-.

22. Joda T, Ferrari M, Gallucci GO, Wittneben J-G, Brägger U. Digital technology in fixed implant prosthodontics. Periodontol 2000. 2017;73(1):178-92.

23. Joda T, Brägger U. Digital vs. conventional implant prosthetic workflows: a cost/time analysis. Clin Oral Implants Res. 2015;26(12):1430-5.

24. Rekow ED, Erdman AG, Riley DR, Klamecki B. CAD/CAM for dental restorations--some of the curious challenges. IEEE Trans Biomed Eng. 1991;38(4):314-8.

25. Kapos T, Evans C. CAD/CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants. 2014;29 Suppl:117-36.

26. Mombelli A, van Oosten MA, Schurch E, Jr., Land NP. The microbiota associated with successful or failing osseointegrated titanium implants. Oral Microbiol Immunol. 1987;2(4):145-51.

27. Dhir S. Biofilm and dental implant: The microbial link. J Indian Soc Periodontol. 2013;17(1):5-11.

28. Mombelli A, Décaillet F. The characteristics of biofilms in peri-implant disease. J Clin Periodontol. 2011;38 Suppl 11:203-13.

29. Mombelli A, Marxer M, Gaberthüel T, Grunder U, Lang NP. The microbiota of osseointegrated implants in patients with a history of periodontal disease. J Clin Periodontol. 1995;22(2):124-30.

30. Romanos GE, Delgado-Ruiz R, Sculean A. Concepts for prevention of complications in implant therapy. Periodontol 2000. 2019;81(1):7-17.

31. Isidor F. Histological evaluation of peri-implant bone at implants subjected to occlusal overload or plaque accumulation. Clin Oral Implants Res. 1997;8(1):1-9.

32. Carter DR, Giori NJ. Bone-Bio Material Interface. 33 Effect of Mechanical Stress on Tissue Differentiation in the Bony Implant Bed: University of Toronto Press; 2016. p. 367-79.

33. Delgado-Ruiz RA, Calvo-Guirado JL, Romanos GE. Effects of occlusal forces on the peri-implant-bone interface stability. Periodontol 2000. 2019;81(1):179-93.

34. Frost HM. A 2003 Update of Bone Physiology and Wolff's Law for Clinicians. The Angle Orthodontist. 2004;74(1):3-15.

35. Miyata T, Kobayashi Y, Araki H, Ohto T, Shin K. The influence of controlled occlusal overload on peri-implant tissue. Part 3: A histologic study in monkeys. Int J Oral Maxillofac Implants. 2000;15(3):425-31.

36. Lindquist LW, Rockler B, Carlsson GE. Bone resorption around fixtures in edentulous patients treated with mandibular fixed tissue-integrated prostheses. J Prosthet Dent. 1988;59(1):59-63.

37. Heitz-Mayfield LJ, Schmid B, Weigel C, Gerber S, Bosshardt DD, Jönsson J, et al. Does excessive occlusal load affect osseointegration? An experimental study in the dog. Clin Oral Implants Res. 2004;15(3):259-68.

38. Naert I, Quirynen M, van Steenberghe D, Darius P. A study of 589 consecutive implants supporting complete fixed prostheses. Part II: Prosthetic aspects. J Prosthet Dent. 1992;68(6):949-56.

39. Quirynen M, Naert I, van Steenberghe D. Fixture design and overload influence marginal bone loss and fixture success in the Brånemark system. Clin Oral Implants Res. 1992;3(3):104-11.

40. Naert I, Duyck J, Vandamme K. Occlusal overload and bone/implant loss. Clin Oral Implants Res. 2012;23 Suppl 6:95-107.

41. Brånemark PI. Osseointegration and its experimental background. J Prosthet Dent. 1983;50(3):399-410.

42. Robinson D, Aguilar L, Gatti A, Abduo J, Lee PVS, Ackland D. Load response of the natural tooth and dental implant: A comparative biomechanics study. J Adv Prosthodont. 2019;11(3):169-78.

43. Pei D, Hu X, Jin C, Lu Y, Liu S. Energy Storage and Dissipation of Human Periodontal Ligament during Mastication Movement. ACS Biomater Sci Eng. 2018;4(12):4028-35.

44. Wang C, Fu G, Deng F. Difference of natural teeth and implant-supported restoration: A comparison of bone remodeling simulations. J Dent Sci. 2015;10(2):190-200.

45. Karimi Dastgerdi A, Rouhi G, Dehghan MM, Farzad-Mohajeri S, Barikani HR. Linear Momenta Transferred to the Dental Implant-Bone and Natural Tooth-PDL-Bone Constructs Under Impact Loading: A Comparative in-vitro and in-silico Study. Front Bioeng Biotechnol. 2020;8:544.

46. Kirsch A. The two-phase implantation method using IMZ intramobile cylinder implants. J Oral Implantol. 1983;11(2):197-210.

47. Manea A, Baciut G, Baciut M, Pop D, Comsa DS, Buiga O, et al. New Dental Implant with 3D Shock Absorbers and Tooth-Like Mobility-Prototype Development, Finite Element Analysis (FEA), and Mechanical Testing. Materials (Basel). 2019;12(20):3444.

48. Mehdi G, Belarbi A, Mansouri B, Azari Z. Numerical study of effect of elastomeric stress absorbers on stress reduction in bone-dental implant interface. J Appl Oral Sci. 2015;23(1):87-93.
49. van Rossen IP, Braak LH, de Putter C, de Groot K. Stress-absorbing elements in dental implants. J Prosthet Dent. 1990;64(2):198-205.
50. Adell R, Lekholm U, Rockler B, Brånemark PI. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. Int J Oral Surg. 1981;10(6):387-416.
51. Taha D, Cesar PF, Sabet A. Influence of different combinations of CAD-CAM crown and customized abutment materials on the force absorption capacity in implant supported restorations – In vitro study. Dent Mater J. 2022;38(1):e10-e8.
52. Omaish HHM, Abdelhamid AM, Neena AF. Comparison of the strain developed around implants with angled abutments with two reinforced polymeric CAD-CAM superstructure materials: An in vitro comparative study. J Prosthet Dent. 2022;127(4):634.e1-.e8.
53. Zhang Y, Kelly JR. Dental Ceramics for Restoration and Metal Veneering. Dent Clin North Am. 2017;61(4):797-819.
54. Rosentritt M, Raab P, Hahnel S, Stöckle M, Preis V. In-vitro performance of CAD/CAM-fabricated implant-supported temporary crowns. Clin Oral Investig. 2017;21(8):2581-7.
55. Hassan M, Asghar M, Din SU, Zafar MS. Chapter 8 - Thermoset polymethacrylate-based materials for dental applications. In: Grumezescu V, Grumezescu AM, editors. Materials for Biomedical Engineering: Elsevier; 2019. p. 273-308.
56. Zafar MS. Prosthodontic Applications of Polymethyl Methacrylate (PMMA): An Update. Polymers. 2020;12(10):2299.
57. Al-Dwairi ZN, Tahboub KY, Baba NZ, Goodacre CJ. A Comparison of the Flexural and Impact Strengths and Flexural Modulus of CAD/CAM and Conventional Heat-Cured Polymethyl Methacrylate (PMMA). J Prosthodont. 2020;29(4):341-9.
58. Leite FJ, Martins W, Rosin HR, Pires CR, Lopes F, Ribeiro RF. A completely digital workflow for an interim implant-supported crown: A clinical report. J Prosthet Dent. 2021;125(3):377-82.

59. Oh KC, Jeon C, Park J-M, Shim J-S. Digital workflow to provide an immediate interim restoration after single-implant placement by using a surgical guide and a matrix-positioning device. J Prosthet Dent. 2019;121(1):17-21.

60. Willard A, Gabriel Chu TM. The science and application of IPS e.Max dental ceramic. Kaohsiung J Med Sci. 2018;34(4):238-42.

61. Brignardello-Petersen R. Implant-supported and tooth-supported single crowns fabricated with lithium-disilicate seem to have a high 10-year survival rate. JADA. 2017;148(5):e48.

62. Gracis S, Thompson VP, Ferencz JL, Silva NR, Bonfante EA. A new classification system for all-ceramic and ceramic-like restorative materials. Int J Prosthodont. 2015;28(3):227-35.

63. Silva LHD, Lima E, Miranda RBP, Favero SS, Lohbauer U, Cesar PF. Dental ceramics: a review of new materials and processing methods. Braz Oral Res. 2017;31(suppl 1):e58.

64. Larsson C, Wennerberg A. The clinical success of zirconia-based crowns: a systematic review. Int J Prosthodont. 2014;27(1):33-43.

65. Alciatore DG, Histand MB. System response. Introduction to Mechatronics and Measurement Systems. 4th ed. New York, USA: McGraw-Hill; 2007. p. 139-45.

66. Géradin M, Rixen DJ. Damped Vibrations of n-Degree-of-Freedom Systems. Mechanical vibrations theory and application to structural dynamics. 3rd ed. United Kingdom: John Wiley & Sons Ltd; 2015. p. 149-208.

67. Ahsanizadeh S, Li L. Visco-hyperelastic constitutive modeling of soft tissues based on short and long-term internal variables. BioMed Eng Online. 2015;14(1):29.

68. Khan AS, Phillips MJ, Elizabeth Tanner K, Wong FS. Comparison of the visco-elastic behavior of a pre-impregnated reinforced glass fiber composite with resin-based composite. Dent Mater. 2008;24(11):1534-8.

69. Lukas D, Schulte W. Periotest--a dynamic procedure for the diagnosis of the human periodontium. Clin Phys Physiol Meas. 1990;11(1):65-75.

70. Anastassopoulos G, Panteliou S, Christopoulou G, Stavropoulou A, Panagiotopoulos E, Lyritis G, et al. Vibrational bone characteristics versus bone density

for the assessment of osteoporosis in ovariectomized rats. J Med Eng Technol. 2010;34(1):35-42.

71. Ho KN, Lee SY, Huang HM. Damping ratio analysis of tooth stability under various simulated degrees of vertical alveolar bone loss and different root types. Biomed Eng Online. 2017;16(1):97.

72. Feng SW, Ho KN, Chan YH, Chang KJ, Lai WY, Huang HM. Damping Factor as a Diagnostic Parameter for Assessment of Osseointegration during the Dental Implant Healing Process: An Experimental Study in Rabbits. Ann Biomed Eng. 2016;44(12):3668-78.

73. Pesqueira AA, Goiato MC, Filho HG, Monteiro DR, Santos DM, Haddad MF, et al. Use of stress analysis methods to evaluate the biomechanics of oral rehabilitation with implants. J Oral Implantol. 2014;40(2):217-28.

74. Cozzolino F, Apicella D, Wang G, Apicella A, Sorrentino R. Implant-to-bone force transmission: a pilot study for in vivo strain gauge measurement technique. J Mech Behav Biomed Mater. 2019;90:173-81.

75. Atsumi M, Park S-H, Wang H-L. Methods used to assess implant stability: Current status. Int J Oral Maxillofac Implants. 2007;22:743-54.

76. Olivé J, Aparicio C. The periotest method as a measure of osseointegrated oral implant stability. Int J Oral Maxillofac Implants 5:390-400. Int J Oral Maxillofac Implants. 1990;5:390-400.

77. Hearn EJ. Chapter 6 - Experimental Stress Analysis. In: Hearn EJ, editor. Mechanics of Materials 2 (Third Edition). Oxford: Butterworth-Heinemann; 1997. p. 166-92.

78. Bhavikatti S. Finite Element Analysis. 4th ed. Delhi, India: New Age International (P) Ltd., Publishers; 2021. 334 p.

79. Hussaini S, Vaidyanathan TK, Wadkar AP, Quran FA, Ehrenberg D, Weiner S. Peri-Implant Strain in an In Vitro Model. J Oral Implantol. 2015;41(5):532-7.

80. Cousland GP, Cui XY, Smith AE, Stampfl APJ, Stampfl CM. Mechanical properties of zirconia, doped and undoped yttria-stabilized cubic zirconia from first-principles. J Phys Chem Solids. 2018;122:51-71.

81. Taha D, Sabet A. In vitro evaluation of material dependent force damping behavior of implant-supported restorations using different CAD-CAM materials and luting conditions. J Prosthet Dent. 2021;126(1):93.e1-.e9.

82. Beer PF JE, DeWolf TJ, Mazurek FD. Mechanicals of materials. 7th ed. New York: Mcgraw-Hill Education; 2015. 831 p.

83. Kaleli N, Sarac D, Külünk S, Öztürk Ö. Effect of different restorative crown and customized abutment materials on stress distribution in single implants and peripheral bone: A three-dimensional finite element analysis study. J Prosthet Dent. 2018;119(3):437-45.

84. Lee JH, Jang HY, Lee SY. Finite Element Analysis of Dental Implants with Zirconia Crown Restorations: Conventional Cement-Retained vs. Cementless Screw-Retained. Materials. 2021;14(10).

85. Mohanty AK, Varghese T, Bhushan P, Mahapatro RK, Kashi AB, Kariyatty P. Influence of Occlusal Stress on Implant Abutment Junction and Implant Bone Interface: A Finite Element Analysis Study. J Contemp Dent Pract. 2022;23(12):1190-4.

86. Castellanos-Cosano L, Carrasco-García A, Corcuera-Flores J-R, Silvestre-Rangil J, Torres-Lagares D, Machuca-Portillo G. An evaluation of peri-implant marginal bone loss according to implant type, surgical technique and prosthetic rehabilitation: a retrospective multicentre and cross-sectional cohort study. Odontology. 2021;109(3):649-60.

87. Galindo-Moreno P, Catena A, Pérez-Sayáns M, Fernández-Barbero JE, O'Valle F, Padial-Molina M. Early marginal bone loss around dental implants to define success in implant dentistry: A retrospective study. Clin Implant Dent Relat Res. 2022;24(5):630-42.

88. Furtado de Mendonca A, Shahmoradi M, Gouvêa CVD, De Souza GM, Ellakwa A. Microstructural and Mechanical Characterization of CAD/CAM Materials for Monolithic Dental Restorations. J Prosthodont. 2019;28(2):e587-e94.

89. de Kok P, Kleverlaan CJ, de Jager N, Kuijs R, Feilzer AJ. Mechanical performance of implant-supported posterior crowns. J Prosthet Dent. 2015;114(1):59-66.

90. Pimentel AC, Manzi MR, Polo CI, Sendyk CL, da Graça Naclério-Homem M, Sendyk WR. Photoelastic Analysis on Different Retention Methods of Implant-Supported Prosthesis. J Oral Implantol. 2015;41(3):258-63.

91. Powers JM, Farah JW, Craig RG. Modulus of elasticity and strength properties of dental cements. J Am Dent Assoc. 1976;92(3):588-91.

VITA

NAME	Charnikan Sukkasam
DATE OF BIRTH	24 January 1993
PLACE OF BIRTH	Chonburi, Thailand
INSTITUTIONS ATTENDED	Doctor of Dental Surgery, Chulalongkorn University Master of Science in Prosthodontics, Chulalongkorn University
HOME ADDRESS	39/160 M.4 Phattra Cozy Sattahip Chonburi