# Evaluation of Surface Wear Resistance at Various Angles in 3-Dimensional Printing Occlusal Splints

Jarintip Suwanbutr, and Napat Nalamliang*

Department of Occlusion, Faculty of Dentistry, Chulalongkorn University, Bangkok, Thailand
*Corresponding author, E-mail: Napat.na@chula.ac.th

## Abstract

The current trend in dental materials focuses on incorporating digital workflows into practical applications. One of the key concerns in this development is wear resistance, which directly affects the longevity of occlusal splints. It has been suggested that printing angulation may significantly influence wear resistance properties. However, most previous studies on 3D printing in dentistry have primarily concentrated on other characteristics, such as as-built surface roughness or material composition, rather than on wear resistance. This study aims to evaluate the differences in maximum surface wear depth among occlusal splint specimens fabricated at various build angles when subjected to bruxing forces. A total of 30 specimens were fabricated and divided into five groups: a conventionally fabricated control group and four 3D-printed groups with build angles of 0°, 30°, 60°, and 90°, following adaptations of ISO 14569-2 guidelines (ISO, 2001). Each specimen underwent wear testing using a Universal Testing Machine, Fatigue Tester, applying a cyclic load of 225 N at 1 Hz for 840 cycles. Surface roughness was measured before and after testing using a contact profilometer. The results indicated that the 90° build angle exhibited the lowest maximum wear depth (2.8047 µm) among the 3D-printed groups, demonstrating the highest wear resistance. The maximum wear depth values increased progressively from 60° (4.2725 µm), 30° (4.6931 µm), to 0° (6.2137 µm), while the conventionally fabricated control group exhibited the lowest wear depth at 2.2131 µm. These findings can be implied that the increasing of build angle toward 90° enhances the wear resistance of 3D printed occlusal splints at a statistical significance level of 0.05.

***Keywords***: *occlusal splint, 3D printing, printing angle, surface wear resistance*

## 1. Introduction

Temporomandibular disorders (TMDs) encompass a wide range of orofacial conditions affecting the temporomandibular joint (TMJ), masticatory musculature, and associated structures (Grymak et al., 2022a). These disorders present with various clinical manifestations, including pain, joint dysfunction, and restricted jaw movement (Han et al., 2021; Benli et al., 2020). Bruxism is defined by the American Academy of Orofacial Pain (AAOP) as "a total parafunctional daily or nightly activity that includes grinding, gnashing, or clenching of teeth" (Taneva, & Uzunov, 2020). It is recognized as a major risk factor for abnormal tooth wear, mobility, fracture, intrusion, loss of occlusal contacts, drifting, erosion, pulpal pathologies, and TMD-related pain (Taneva, & Uzunov, 2020).

Occlusal splints represent a widely used conservative treatment approach for managing TMDs and bruxism (Grymak et al., 2022b). These devices act as a physical barrier between opposing teeth, mitigating the mechanical forces associated with parafunctional activities such as grinding and clenching (Checherita et al., 2013). Numerous studies have demonstrated the therapeutic benefits of occlusal splints in managing TMDs (Osiewicz et al., 2021; Yildiz, Aslan, & Ozkan, 2020; Schulte et al., 1987), bruxism (Osiewicz et al., 2021; Schmeiser, Baumert, & Stawarczyk, 2022), and other parafunctional habits (Schmeiser, et al., 2022; Taneva, & Uzunov, 2020).

The effectiveness of occlusal splints derives from their multifaceted functionality. Primarily, they protect against tooth wear resulting from bruxism (Han et al., 2021; Gibreel et al., 2021). Additionally, splints aid in muscle relaxation by influencing condylar positioning in centric relation (Gibreel et al., 2021) and reducing masticatory muscle hyperactivity (Han et al., 2021; Gibreel et al., 2021). Furthermore, they redistribute occlusal forces across the dentition (Han et al., 2021). The ultimate goal of splint therapy is to establish a stable occlusion and neuromuscular equilibrium (Han et al., 2021; Benli et al., 2020). Studies report high success rates (70%-90%) in alleviating TMD symptoms through occlusal splint therapy (Benli et al., 2020), particularly in cases where bruxism is a contributing factor (Taneva, & Uzunov, 2020; Gibreel et al., 2021). Occlusal contact disturbances have also been implicated in the exacerbation of bruxing events (Schmeiser et al., 2022). The durability of occlusal splints is critical, as their wear resistance directly influences their clinical longevity and therapeutic efficacy (Schmeiser et al., 2022). Given that splints must endure significant occlusal forces throughout extended treatment periods, their ability to withstand bruxing forces over time is crucial (Gibreel et al., 2021; Taneva, & Uzunov, 2020).

Additive manufacturing (AM), commonly known as 3D printing (Grymak et al., 2022a; Li, & Teng, 2024), has emerged as a rapidly advancing technology in the dental field (Taneva, & Uzunov, 2020). AM encompasses various fabrication techniques, including material jetting, powder bed fusion, and material extrusion (Li, & Teng, 2024). These techniques construct objects layer-by-layer based on digital models (Sajjadi et al., 2022; Li, & Teng, 2024). A key factor influencing the mechanical properties of 3D-printed components is the printing orientation (Li, & Teng, 2024), which refers to the angle between the internal layer structure and the print bed (Li, & Teng, 2024).

Regarding wear resistance, findings from broader engineering research indicate that the printing angle significantly affects surface roughness (Kumar, 2014; Leary et al., 2021; Li, & Teng, 2024; Grymak et al., 2022b). Studies have demonstrated that surface parameter values can vary substantially between components fabricated at parallel and perpendicular printing angles (Leary et al., 2021). However, the surface roughness described in these engineering studies pertains to inherent surface irregularities ("as-built surface notches") caused by the stair-step effect characteristic of additive manufacturing processes (Kumar, 2014; Leary et al., 2021; Li, & Teng, 2024). Research specifically addressing the effects of printing build angles and settings on the wear resistance of 3D-printed occlusal splint materials remains limited. Further investigation is necessary to enhance the durability of these devices and minimize the need for remanufacturing (Grymak et al., 2022b).

Therefore, this study aims to address the gaps identified in previous research (Grymak et al., 2022b) by evaluating the wear resistance of 3D-printed occlusal splint specimens fabricated at various printing angles. The specimens will undergo bruxism-simulated loading using a Universal Testing Machine, Fatigue Tester, to assess their wear resistance properties. This investigation will address the research question regarding the optimal angulation for printing occlusal splints, thereby providing clinicians with evidence-based guidance for 3D printing of these appliances in the future.

## 2. Objectives

To evaluate the differences in maximum surface wear depth among occlusal splint material specimens fabricated at various angulations when subjected to force using a Universal Testing Machine, Fatigue Tester.

## 3. Materials and Methods

Dental LT Clear (Formlabs) was selected as the material for this experiment, being compatible with the available Formlabs3 3D printing machine for occlusal splint fabrication. To access the wear resistance and mechanical properties, the ISO14569-2 (International Organization for Standardization [ISO], 2001) protocol is adapted for the specimen preparation steps. The round-shaped specimens, with a diameter of 8 mm. and 2 mm. depth were designed using commercial computer-aided design (CAD) software, specifically 3D Builder (version 20.0.4.0). During the CAD stage, the 3D-printed specimens were divided into four subgroups based on built angle orientations: 0°, 30°, 60°, and 90° (Figure 1). The designed specimens were then fabricated via the additive manufacturing technique of stereolithography (SLA) using a Formlabs printer (Formlabs Ohio Inc., Millbury, OH, USA). The sample size was determined using G*Power 3.1 software, based on ISO14569 guidelines. The priori power analysis was performed with the following parameters: effect size $f = 0.7$ (large effect), $\alpha$ error probability = 0.05, power ($1-\beta$) = 0.80, and the number of groups = 5. The analysis yielded a minimum required sample size of 30 specimens, which was evenly distributed equally among the five experimental groups (n = 6 specimens per group). For the control group, the heat-cured PMMA fabricated specimens by conventional flasking and packing were produced for 6 pieces. Following fabrication, the specimens were stored in 37 degrees Celsius distilled water for 7 days prior to testing. All specimens were undergoing multi-step polishing using abrasive silicon carbide paper until reaching the final grid P2400 (Grymak et al., 2022a). The polishing process was conducted on a polishing machine under wet conditions, utilizing water (Benli et al., 2020; Yildiz et al., 2020; Reyes et al., 2018; Issar-Grill et al., 2013) at room temperature (Minitech 233, Presi, France). Subsequently, the specimens were cleaned in an ultrasonic bath (VGT-1990QTD, China) operating at 40 kHz for a duration of 10 minutes at room temperature.

Following the polishing process, the surface roughness of a designated area on each specimen was evaluated using a three-dimensional contact surface profilometer (Talyscan 150, England). The instrument was set to measure a field of 3 x 3 mm². The machine equipped with a 0.06 µm stylus tip will run until the whole selected area is reached. The profilometer software recorded the maximum surface depth parameter (µm), a vertical resolution of 40 µm and a horizontal resolution of 0.5 µm. Subsequently, the maximum depth of the area will be told by the profilometer machine manufactured program.

All 30 specimens underwent load-applied simulation using a Universal Testing Machine, Fatigue Tester (E1000, Instron, United Kingdom). The tester was configured to deliver a vertical contact load of 225 N, approximating the average bruxing force exerted during sleep. The selected force magnitude was derived from prior studies that documented a mean bruxing force of 22.5 kgf (approximately 220.65 N). This value was applied to evaluate whether the specimens could withstand the simulated bruxism force during mechanical property testing (Figure 2) (Nishigawa et al., 2001).

To mimic the application force from the realistic amount of bruxing force, the specimens will be directly pressed under a hydraulic machine at a frequency of 1 Hz (Reyes et al., 2018; Lutz et al., 2019; Issar-Grill et al., 2013; Murali et al., 2015; Farah et al., 2019) for a total of 840 times per specimen. This chosen frequency aligns with the reported approximation of 1 Hz for rhythmic masticatory muscle activity (RMMA) associated with sleep bruxism (Murali et al., 2015; Farah et al., 2019).

Following the force pressing step, the specimens were subjected to a second surface characterization using the same three-dimensional contact surface profilometer (Talyscan 150, England). Material loss was quantified by analyzing the measured profile for maximum surface wear depth. It is important to note that the measured profile represents the actual surface topography, filtered by the probe tip radius and the inherent skid of the probe system. Wear depth measurements were re-performed in the same area as the pretest measurement, under the same conditions of the contact profilometer machine.

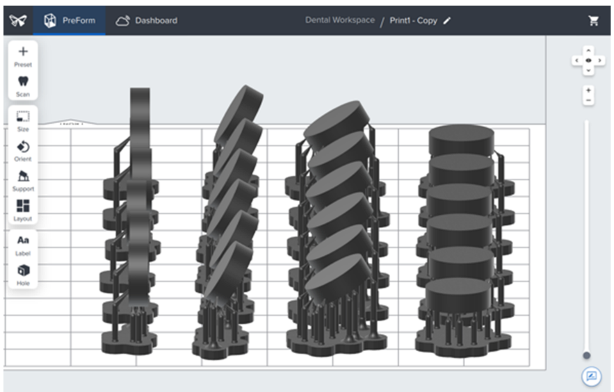


**Figure 1** CAD design into four subgroups
(From left to right: 90°, 60°, 30°, 0°)

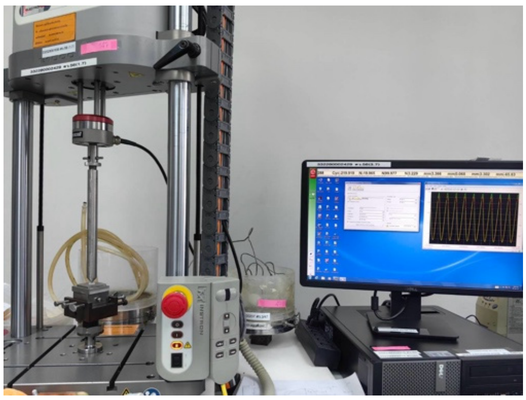

**Figure 2** Universal Testing Machine, Fatigue Tester

Data analysis was conducted using IBM SPSS Statistics Version 28.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were reported as mean, standard deviation (SD) and 95% confidence intervals (95% CI). The level of significance was set at $\alpha = 0.05$. Since all of the material groups showed normal distribution from the normality test evaluated with the Shapiro-Wilk test, the differences between the pre-test and post-test vertical maximum depth loss were analyzed using one-way analysis of variance (ANOVA) with Tukey HSD post hoc tests.

## 4. Results and Discussion

### *4.1 Results*

For the comparison of maximum depth differences between groups with varying printing orientations, a statistically significant difference was observed in the vertical maximum wear depth ($p < 0.001$). Wear depth values decreased significantly as the printing angle increased from 0°, 30°, 60°, to 90° (Mean (SD) = 4.04 (1.59)). All data collected from laboratory tests are presented in Figure 3.

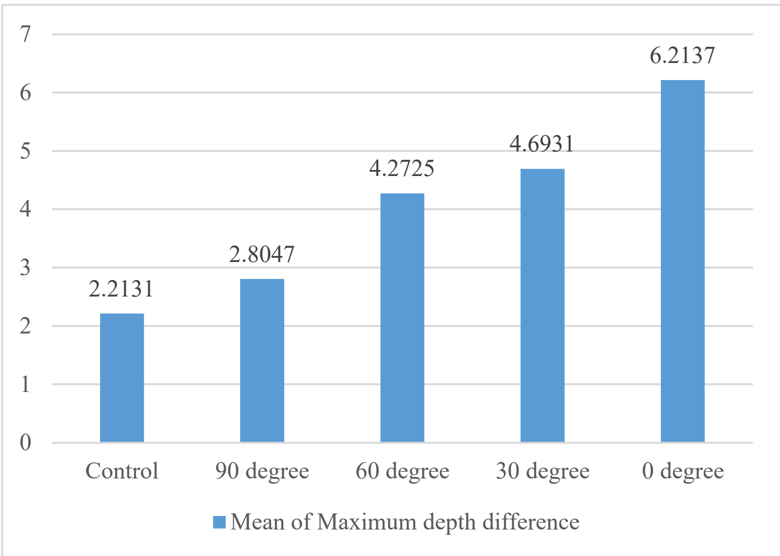


**Figure 3** Maximum wear depth (Micrometer)

The results from the wear testing indicated that the vertical maximum wear depth had a mean value of 4.04, with a corresponding standard deviation (SD) of 1.59 obtained from the descriptive statistics (Table 1).

**Table 1** Descriptive statistics

| Groups | | Statistics |
|---|---|---|
| Between groups difference | Mean | 4.04 |
| | Median | 4.27 |
| | Variance | 2.52 |
| | Std.deviation | 1.5 |
| | Minimum | 2.21 |
| | Maximum | 6.21 |

When examining the difference between each angle maximum depth difference groups, a one-way ANOVA has been used to test, and it shows significance ($p > 0.05$). After that, the post hoc test, Tukey HSD, has been performed. The results indicate that the maximum depth difference in the control group is significantly different from the 0° angle ($p < 0.001$), 30° angle ($p < 0.001$), and 60° angle ($p < 0.001$) groups.

The 0° angle group is significantly different from the 30° angle ($p = 0.012$), 60° angle ($p = 0.001$), and 90° angle ($p < 0.001$) groups. The 30° angle group is also significantly different from the 90° angle group ($p = 0.001$). The groups that seem not to significantly different from each other are the 30° angle group to the 60° angle group ($p = 0.01$), and the conventional group to the 90° angle group ($p = 0.01$). All of the results are shown in Table 2.

To examine differences between the maximum wear depth values for each group, a one-way analysis of variance (ANOVA) was performed, revealing statistical significance ($p < 0.05$). Post hoc testing using Tukey's HSD test indicated the following significant differences: the control group exhibited significant differences from the 0° ($p < 0.001$), 30° ($p < 0.001$), and 60° ($p < 0.001$) groups. In addition, the 0° group showed significant differences from the 30° ($p = 0.012$), 60° ($p = 0.001$), and 90° ($p < 0.001$) groups. Furthermore, the 30° group displayed significant differences compared to the 90° group ($p = 0.001$). The groups that did not show significant differences were the 30° and 60° ($p = 0.860$), and the conventional group versus the 90° group ($p = 0.642$). All of these results are summarized in Table 3.

**Table 2** Post Hoc Test (Tukey HSD)

| (I) Group | (J) Group | Mean Difference (I-J) | Sig. |
|---|---|---|---|
| Control | 0 | -4.0006* | <.001 |
| | 30 | -2.4800* | <.001 |
| | 60 | -2.0694* | <.001 |
| | 90 | -0.5916 | .642 |
| 0 degree building angle | Control | 4.0006*- | <.001 |
| | 30 | 1.5206* | .012 |
| | 60 | 1.9412* | .001 |
| | 90 | 3.4090* | <.001 |
| 30 degree building angle | Control | 2.4800* | <.001 |
| | 0 | -1.5206* | .012 |
| | 60 | 0.4206 | .860 |
| | 90 | 1.8884* | .001 |
| 60 degree building angle | Control | 2.0694* | <.001 |
| | 0 | -1.9412* | .001 |
| | 30 | -0.4206 | .860 |
| | 90 | 1.4678* | .016 |
| 90 degree building angle | Control | 0.5916 | .642 |
| | 0 | -3.4090* | <.001 |
| | 30 | -1.8884* | .001 |
| | 60 | -1.4678* | .016 |

*. The mean difference is significant at the 0.05 level

### *4.2 Discussion*

Based on the experimental results, it was concluded that when considering the force applied perpendicularly to the surface of the tested material, the more the built angle orientation leaned towards 90°, the greater its ability to withstand forces. This indicated a higher wear resistance at a perpendicular building angle.

When compared with previous studies, various conclusions have been drawn. For instance, in 3D printing, it has been reported that a 0° orientation exhibited higher wear resistance than 45° and 90° orientations, respectively (Grymak et al., 2022a). Conversely, there was one study (Grymak et al., 2021) that suggested that 3D printing at a 45° orientation provided the highest wear resistance. Additionally, some investigations in detail examined multiple material brands and found that some exhibited maximum resistance at 0°, while others did so at 45°. However, the authors attributed this phenomenon not directly to the inherent properties of the material but rather to the variations in post-processing capabilities, particularly polishing effectiveness. They concluded that once the polished outer layer was worn away, the internal structure of 3D-printed samples became more prone to wear due to the nature of the material, which typically consisted of a hard outer shell and a softer internal structure, as well as lattice layering and a porous structure (Grymak et al., 2022a). This issue had also been discussed in another study, which confirmed that surface finishing and polishing influenced material strength (Taneva, & Uzunov, 2020).

Based on the experimental results of this study, it was observed that at a 0-degree build angle, the wear rate was the highest and progressively decreased as the build angle approached 90 degrees, where it equaled that of conventional manufacturing. This phenomenon can be explained based on the principles of mechanical engineering. In the context of additive manufacturing, two key terms are relevant: build angle and force resolution. The term "build angle" is defined as the angle between the build direction and a specified reference axis or feature of the part.

Regarding the significance of build angle, when a force is applied perpendicularly to the surface of a printed material at a 0-degree angle, the force is primarily distributed into the interlayer region (Gibson, Rosen, & Stucker, 2010).

The term "force resolution" involves decomposing a force vector into compressive force (perpendicular to the surface) and shear force (parallel to the surface, causing sliding or shearing deformation) (Hibbeler, 2016; Gibson et al., 2010). This concept can be effectively illustrated using a free body diagram (Figure 4). When a force vector is applied vertically to an object's surface, the compressive force is expressed as $F\cos\theta$, while the shear force is $F\sin\theta$ (Hibbeler, 2016). Consequently, as the build angle approaches vertical, the compressive force component increases, whereas the shear force component increases as the build angle approaches a horizontal orientation (Hibbeler, 2016). This concept was validated by experimental results showing that the greatest wear depth occurred at a 0° printing angle, with the 90° orientation demonstrating the highest wear resistance, comparable to conventional fabrication methods ($p = 0.999$).

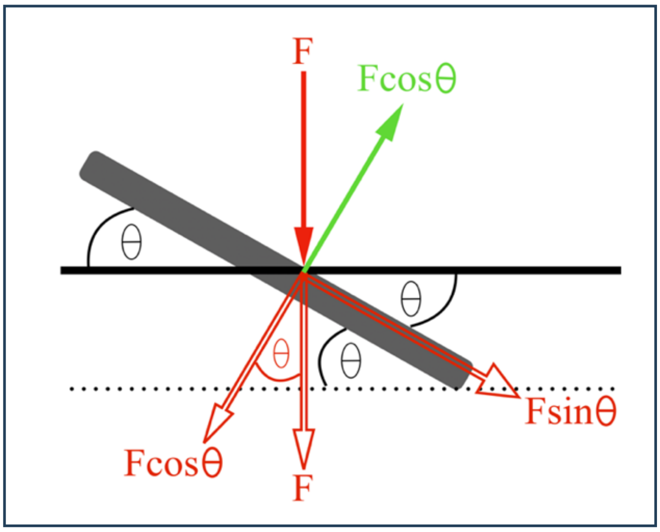


**Figure 4** Free body diagram

In additive manufacturing, materials are deposited layer by layer. After forming the initial layer, the subsequent layer adheres to it through a process known as polymer chain diffusion. At the molecular level, polymer chains diffuse into regions with elevated temperature or liquid phase and require time for entanglement to occur. Two critical terms related to this process are intralayer and interlayer adhesion. Intralayer adhesion occurs under continuous deposition conditions, ensuring uniform material properties and high strength. Conversely, interlayer adhesion is affected by diffusion time constraints, leading to incomplete polymer chain entanglement (Gibson et al., 2010). This results in anisotropic mechanical properties, where interlayer adhesion is weaker than intralayer adhesion (Gibson et al., 2010; Ahn et al., 2002)

Due to this characteristic, when an external force is applied to the surface of a printed object at various build angles, the force is transmitted differently across the layers. The fundamental distinction between a 0-degree build angle and other orientations lies in the macrostructural and microstructural perspectives.

At the macrostructural level, when the top surface is covered by only a single uppermost layer, the applied force is directly transferred to that layer. However, at the microstructural level, due to incomplete molecular bonding, the force is transmitted into weak interlayer adhesion regions. This results in localized stress accumulation, which, upon reaching a critical threshold, leads to shear-induced micro-sliding. This phenomenon, known as microdelamination, propagates to the upper layers, eventually causing microcracking. The cumulative effect is observed at the macrostructural level as a decrease in surface integrity, accelerating wear (Gibson et al., 2010).

For a 90-degree build angle, the dominant force acting on each layer is the compressive force, which is applied directly along the material's principal direction. At the molecular level, this force is distributed within the intralayer region, which has better structural continuity. The interlayer regions experience increased compaction, improving adhesion and reducing shear-induced stress accumulation. As a result, the overall bonding strength is enhanced, leading to improved load-bearing capacity and reduced wear susceptibility (Gibson et al., 2010).

Previous research (Patzelt et al., 2022) indicated that the wear resistance of CAD-CAM-milled materials was comparable to that of conventionally fabricated materials. However, their findings suggested that during the initial 5,000 wear cycles, milling demonstrated superior wear resistance compared to conventional methods. However, at 20,000 and 120,000 cycles, milling exhibited increased wear, and by 200,000 cycles, the wear levels between milling and conventional methods were nearly identical. This trend was corroborated by other studies (Schmeiser et al., 2022; Grymak et al., 2022a), which also reported alternating wear patterns that ultimately converged.

The findings from this study suggested that 3D printing at a 90° orientation, or a perpendicular built angle, resulted in wear resistance comparable to that of conventionally fabricated materials. Given the lack of statistically significant differences ($p=0.999$), this suggests that the 90° printing angle might be the most appropriate, offering wear resistance similar to both conventional and milling methods.

Nevertheless, these results could not be directly extrapolated to clinical applications, as several additional factors had to be considered, including mechanical properties and individual biological variations (Yildiz et al., 2020). Further studies are required to comprehensively assess these influences.

In this experiment, a vertical force was selected to eliminate shear forces that could complicate the interpretation of the forces acting on each layer. Consequently, human-like wear simulation was not feasible, as the study aimed solely to evaluate the mechanical properties of the materials. The primary factors of interest were the magnitude of force, printing angle, and differences in maximum wear depth.

A review of previous experimental studies indicated that the number of loading cycles varied widely. Additionally, there were standardized recommendations in ISO guidelines. However, in this study, 840 loading cycles were selected based on clinical force calculations. This was determined considering that patients were typically recalled for check-ups and occlusal adjustments every one to two weeks. A systematic review (Cid-Verdejo et al., 2024) reported that individuals with bruxism exhibited an average of seven clenching episodes per hour. Assuming an eight-hour sleep duration per night, this equated to approximately 56 episodes per night. To ensure comprehensive coverage and simplify calculations, this was rounded to approximately 60 cycles per night. Given nightly use over two weeks, the material was subjected to approximately 840 cycles before the splint underwent re-polishing.

The limitations of this study arose from the fact that, for a clinically relevant assessment of material wear, numerous additional factors had to be considered. In vitro wear simulations could not fully replicate the complex wear behaviors occurring in the human oral environment. However, laboratory-based experiments were beneficial for evaluating basic wear mechanisms (Yildiz et al., 2020). Nonetheless, as this study specifically aimed to investigate mechanical properties related to different 3D printing angles, introducing additional variables to simulate intraoral conditions would have introduced confounding factors. For example, previous studies have indicated that the use of lubricants during wear simulations could significantly increase wear rates compared to dry conditions, particularly when water is used as a lubricant (Grymak et al., 2022a).

Future studies should focus on investigating additional mechanical properties to further inform the selection of the most appropriate printing angle. Moreover, if future research aims to build upon the foundational mechanical property data obtained in this study, experimental approaches that closely replicate real-world human masticatory conditions would be essential. In this regard, human trials would provide more accurate and clinically relevant insights than attempting to simulate intraoral conditions in a laboratory setting.

## 5. Conclusion

When considering the printing angle of materials used in occlusal splints as an isolated factor, a 90° printing orientation provides the highest wear resistance against forces generated by bruxism. Furthermore, its wear resistance closely resembles that of conventionally fabricated materials.

Future research should explore additional mechanical properties and extend to investigating actual wear outcomes in human subjects, which would provide valuable insights for further study.

## 6. Acknowledgements

First and foremost, I would like to express my deepest gratitude to Professor Viritpon Srimaneepong, Thai Board of Prosthodontics at the Department of Prosthodontics, Chulalongkorn University, for the invaluable guidance, insightful advice, and continuous support throughout this research. The unwavering encouragement and constructive feedback have been instrumental in shaping this study and bringing it to fruition. I am truly and sincerely grateful for the mentorship and dedication.

Furthermore, I would like to extend my sincere gratitude to the Faculty of Dentistry, Chulalongkorn University, for their facilitation in conducting this research, including the provision of facilities, the Dental Material Research and Development Center, the dental laboratory, and other essential resources that contributed to the seamless execution of the project.

## 7. References

Ahn, S., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling abs. *Rapid Prototyping Journal*, *8*(4), 248–257.

Benli, M., Eker Gümüş, B., Kahraman, Y., Gökçen-Rohlig, B., Evlioğlu, G., Huck, O., & Özcan, M. (2020). Surface roughness and wear behavior of occlusal splint materials made of contemporary and high-performance polymers. *Odontology*, *108*(2), 240–250.

Checherita, L., Beldiman, M.-A., Stamatin, O., Foia, U., & Forna, N. (2013). Aspects on structure of materials used for different types of occlusal splints. *Revista de Chimie*, *64*, 864-867.

Cid-Verdejo, R., Chávez Farías, C., Martínez-Pozas, O., Meléndez Oliva, E., Cuenca-Zaldívar, J. N., Ardizone García, I., Martínez Orozco, F. J., & Sánchez Romero, E. A. (2024). Instrumental assessment of sleep bruxism: A systematic review and meta-analysis. *Sleep Medicine Reviews, 74*, 101906.

Farah, C. S., Balasubramaniam, R., & McCullough, M. J. (2019). *Contemporary oral medicine: A comprehensive approach to clinical practice* (1st ed.). Springer.

Gibreel, M., Perea-Lowery, L., Vallittu, P. K., & Lassila, L. (2021). Characterization of occlusal splint materials: CAD-CAM versus conventional resins. *Journal of Mechanical Behavior of Biomedical Materials*, *124*, 104813.

Gibson, I., Rosen, D., & Stucker, B. (2010). *Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing*. Springer.

Grymak, A., Aarts, J. M., Ma, S., Waddell, J. N., & Choi, J. J. E. (2021). Comparison of hardness and polishability of various occlusal splint materials. *Journal of the Mechanical Behavior of Biomedical Materials*, *115*, 104270.

Grymak, A., Aarts, J. M., Ma, S., Waddell, J. N., & Choi, J. J. E. (2022b). Wear behavior of occlusal splint materials manufactured by various methods: A systematic review. *Journal of Prosthodontics*, *31*(6), 472-487.

Grymak, A., Waddell, J. N., Aarts, J. M., Ma, S., & Choi, J. J. E. (2022a). Evaluation of wear behavior of various occlusal splint materials and manufacturing processes. *Journal of Mechanical Behavior of Biomedical Materials*, *126*, 105053.

Han, Y., Bai, Y., Bian, J., Guo, X., Liu, B., & Wang, Z. (2021). Polydimethylsiloxane-based mechanoluminescent occlusal splint with the visualization of occlusal force. *ACS Applied Polymer Materials*, *3*(10), 5180-5187.

Hibbeler, R.C.. (2016). *Engineering Mechanics: Statics & Dynamics* (14th ed.). New Jersey: Pearson.

Issar-Grill, N., Roberts, H. W., Wright, E. F., Dixon, S. A., & Vandewalle, K. S. (2013). Volumetric wear of various orthotic appliance materials. *Cranio*, *31*(4), 270-275.

International Organization for Standardization. (2001). *Dental materials - Guidance on testing of wear - Part 2: Wear by two- and/or three-body contact* (ISO 14569-2:2001).

Kumar, T. S. P. (2014). Testing of polymeric materials. In S. Hashmi (Ed.), *Comprehensive materials processing* (Vol. 9, pp. 1–20). Elsevier.

Leary, M., Khorasani, M., Sarker, A., Tran, J., Fox, K., Downing, D., & Du Plessis, A. (2021). Surface roughness. In Yadroitsev, I., Yadroitsava, I., du Plessis, A., & MacDonald, E. (Eds.), *Fundamentals of Laser Powder Bed Fusion of Metals* (pp. 179-213). Elsevier.

Li, Y., & Teng, Z. (2024). Effect of printing orientation on mechanical properties of SLA 3D-printed photopolymer. *Fatigue & Fracture of Engineering Materials & Structures*, *47*(5), 1531-1545.

Lutz, A. M., Hampe, R., Roos, M., Lumkemann, N., Eichberger, M., & Stawarczyk, B. (2019). Fracture resistance and 2-body wear of 3-dimensional-printed occlusal devices. *Journal of Prosthetic Dentistry*, *121*(1), 166-172.

Murali, R. V., Rangarajan, P., & Mounissamy, A. (2015). Bruxism: Conceptual discussion and review. *Journal of Pharmacy & Bioallied Sciences*, *7*(1), S265-S270.

Nishigawa, K., Bando, E., & Nakano, M. (2001). Quantitative study of bite force during sleep-associated bruxism. *Journal of Oral Rehabilitation*, *28*(5), 485-491.

Osiewicz, M. A., Werner, A., Roeters, F. J. M., & Kleverlaan, C. J. (2021). Effects of occlusal splint therapy on opposing tooth tissues, filling materials, and restorations. *Journal of Oral Rehabilitation*, *48*(10), 1129-1134.

Patzelt, S. B. M., Krügel, M., Wesemann, C., Pieralli, S., Nold, J., Spies, B. C., Vach, K., & Kohal, R.-J. (2022). In vitro time efficiency, fit, and wear of conventionally- versus digitally-fabricated occlusal splints. *Materials*, *15*(3), 1085.

Reyes-Sevilla, M., Kuijs, R. H., Werner, A., Kleverlaan, C. J., & Lobbezoo, F. (2018). Comparison of wear between occlusal splint materials and resin composite materials. *Journal of Oral Rehabilitation*, *45*(7), 539-544.

Sajjadi, S. A., Ashenai Ghasemi, F., Rajaee, P., & Fasihi, M. (2022). Evaluation of fracture properties of 3D-printed high-impact polystyrene according to essential work of fracture: Effect of raster angle. *Additive Manufacturing*, *59*, 103191.

Schmeiser, F., Baumert, U., & Stawarczyk, B. (2022). Two-body wear of occlusal splint materials from subtractive computer-aided manufacturing and three-dimensional printing. *Clinical Oral Investigations*, *26*(9), 5857-5866.

Schulte, J. K., Anderson, G. C., Sakaguchi, R. L., & DeLong, R. (1987). Wear resistance of isosit and polymethyl methacrylate occlusal splint material. *Dental Materials*, *3*(2), 82-84.

Taneva, I., & Uzunov, T. (2020). Influence of post-polymerization processing on the mechanical characteristics of 3D-printed occlusal splints. *Journal of Physics: Conference Series*, *1492*(1), 012018.

Yildiz Domanic, K., Aslan, Y. U., & Ozkan, Y. (2020). Two-body wear of occlusal splint materials against different antagonists. *BMC Oral Health*, *20*(1), 174.