“The Wear Characteristics and Volume Loss of Different CAD/CAM Materials”

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LIST OF ABBREVIATIONS

CAD Computer aided design
CAD/CAM Computer aided design and computer aided manufacturing
e.max Brand name of lithium disilicate
e.max G Lithium disilicate glazed
e.max G+P Lithium disilicate glazed then polished
IPS Ivoclar porcelain system
SEM Scanning electron microscopy
Y-TZP Yttria-stabilized tetragonal zirconia polycrystal
Zr Zirconia
Zr G Zirconia glazed
Zr G+P Zirconia glazed then polished
A study of the wear characteristics between two CAD/CAM materials of different surface textures was carried out to evaluate the clinical implications of material selection and restoration finish. Utilizing a ball-on-disc tribometer and artificial saliva, glazed and glazed then polished samples of zirconia and lithium disilicate tested. Surface characterization was performed using white-light interferometry and scanning electron microscopy.

The volume loss, surface roughness and coefficient of friction of the samples were analyzed. All lithium disilicate samples exhibited increased wear compared to zirconia samples. In addition, lithium disilicate samples were rougher than zirconia samples after wear simulation. Similarly, the coefficient of friction of the lithium disilicate samples was greater than that of the zirconia samples.

The glazed then polished zirconia samples showed less volume loss than the glazed zirconia samples. In contrast, the glazed then polished lithium disilicate samples showed more volume loss than the glazed lithium disilicate samples. The differences seen between samples can be best explained by the introduction of three-body wear once previously worn material started to collect on the lithium disilicate samples. This is supported by the SEM imaging taken of the different samples.
1. INTRODUCTION

With the ever present need for dental rehabilitation of dental patients, there also has been the development of many different restorative options. Since the late 1950’s, porcelain has been layered on cast metal substructures to restore both esthetics and function to compromised teeth [1]. With changes in the understanding of dental ceramics, many new all-ceramic options have been utilized for dental rehabilitation. This includes predictable and repeatable computer-aided design and computer-aided manufacturing (CAD/CAM) of zirconia and lithium disilicate crowns, when occlusal and marginal accuracy are evaluated [2]. Thus far, these two all ceramic options have shown to have comparable, if not better, survival than traditional metal-ceramic restorations [3, 4]. In addition, all-ceramic restorations have become a more cost effective option due to the rising cost of gold alloys [5]. As a result, all-ceramic dental restorations have become an increasingly popular material choice for restorative clinicians.

Feldspathic and layered porcelains have already shown to have a significant wear potential on an opposing dentition. This wear observed is consistent whether the opposing dentition is enamel, or another porcelain fused to metal restoration [6]. Despite the high flexural strength of lithium disilicate and zirconia, initial studies have shown all ceramic materials exhibit less wear to enamel, when compared to porcelain fused to metal restorations [7]. This was also attributable to no noticeable wear of the zirconia samples, and less wear of the lithium disilicate samples compared to feldspathic porcelain. Instead, the amount of wear of the lithium disilicate surfaces was similar to enamel [8]. It also already has been documented that the surface finish and texture of a ceramic restoration will affect how much it will potentially wear, and how much it will cause wear to an opposing dentition [9, 10].
In the field of Prosthodontics, patients often require complex and extensive restorative care. Depending on the clinical situation, this often requires the use of various dental materials to restore both the maxillary and mandibular arch. Most current literature has evaluated the wear properties of different ceramics against enamel, but have not of dental ceramics opposing one another. With the increasing popularity and clinical use of CAD/CAM ceramic restorations, it is imperative to understand their behavior. Therefore, the goal of this study was to assess the wear potential and behavior of CAD/CAM zirconia and lithium disilicate against a similar material, and how the surface finish of these ceramics might affect their patterns of wear. Glazed and polished samples of zirconia and lithium disilicate were tested using a ball-on-block tribometer system, using a counter-body of the same material and surface texture as the all-ceramic block. It was hypothesized that lithium disilicate samples would experience more wear than all types of zirconia samples, and that the glazed samples would experience more wear than the polished samples of that same material.
2. LITERATURE REVIEW

Zirconia-

The form of zirconium (Zr) we use in medicine and dentistry, zirconium dioxide, was first extracted from the mineral zircon in 1787 by a German chemist [11]. For then almost two centuries, zirconia and zirconium dioxide were more considered a scientific curiosity than having any merit as a biomaterial. It wasn’t until 1969 that zirconia was considered to be a potential biomaterial by the medical field due to its very favorable biomedical properties [11].

Zirconia itself can potentially exist in three major different types of phases: tetragonal, cubic and monoclinical [12]. Above a temperature of 1170°C, a zirconia material will be transformed into a tetragonal phase. If the zirconia is then heated to a temperature of approximately 2370°C, the material will change into a cubic phase. If a cubic or tetragonal zirconia sample is then allowed to cool to room temperature, or back to a monoclinic phase, there will be a 5% expansion [12]. This will cause fracture and structural breakdown of the zirconia material. In order to overcome the potential phase changing of zirconia, biomedical scientists discovered to alloy zirconia with oxides such as calcia, magnesia, ceria and most commonly yttria [13]. This allowed a stabilization of the damaging phase transformation of tetragonal zirconia to monoclinic zirconia that would occur by maintaining a primarily tetragonal phase at room temperature. This yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) improves its thermal, physical and mechanical properties, and allows it to be potentially used as a biomaterial [14]. If a zirconia prosthesis is being used as a biomaterial as a load bearing force within the body, such as a joint or tooth replacement, significant forces can be applied to it. If the stress concentration is large enough, cracks can form from within the material. This could potentially cause the zirconia
material around the crack to be converted back to a monoclinic phase, and have a resulting volumetric expansion [15]. This phase transformation as a result will put the crack into compression, slowing its growth and potentially increasing the fracture toughness of the material. This property of the yttria-stabilized tetragonal zirconia is known as ‘transformation toughening,’ and potentially increases the reliability and survival of Y-TZP materials [15].

Many of the mechanical properties of yttria-stabilized tetragonal zirconia allows it to be used as an alternative at times for metal-ceramic systems [16]. In particular, the flexural strength and fracture toughness of zirconia is approximately 900 MPa and 5.5 MPa×m$^{1/2}$, respectively [17]. In contrast, a common feldspathic porcelain used for metal-ceramic restorations (VITA Mark II) has a flexural strength and fracture toughness of 154 MPa and 1.37 MPa×m$^{1/2}$, respectively (Ivoclar Vivadent). In addition to dentistry, yttria-stabilized tetragonal zirconia has been used as the ball heads in total hip prostheses since 1984 [18]. In the dental community, Y-TZP ceramics first was used for orthodontic brackets and endodontic posts in the early 1990s [19, 20]. It wasn’t until the late 1990s until the dental community utilized zirconia for fixed restorations as a result of the improvement of CAD/CAM technology [21].

There are different ways in CAD/CAM technology on how zirconia blocks can be prepared. To be specific, zirconia blocks can be milled in a green, pre-sintered or fully sintered stage [22]. If the blocks are milled in the green or pre-sintered stage, the zirconia structure is milled at an increased 20-25% in size to compensate for material shrinkage during the final sintering stage [22]. The advantage of milling in a green or pre-sintered stage is its less time consuming and causes less wear to the milling components. Although it would be expected that milling in a fully sintered stage would be the most accurate, some studies have shown that milling in the green or pre-sintered stage have the best marginal fit with crown and bridge applications.
Although the findings are mixed between the studies about milling accuracy in different stages, all have shown to produce clinically acceptable results.

In order to improve the esthetics of zirconia restorations, feldspathic porcelains are often added or the material is glazed [23]. Unlike metal-ceramic restorations, the chemo mechanical bond between zirconia and feldspatic porcelain is not entirely understood [23]. In addition, although the International Standards Organization has recognized a 25 MPa bond strength between ceramic and metal is adequate, there has been no such estimate for bond strength between all-ceramic materials. [23]. Although it is generally accepted that porcelain fused to zirconia restorations are a viable replacement for metal-ceramic restorations in certain situations, there is conflicting evidence of whether or not the layered zirconia restoration will have the same long term prognosis with veneer chipping [24, 25]. To achieve a strong bond between a framework material and layering porcelain, the coefficient of thermal expansion between the two entities should closely match [23]. In metal-ceramic systems, the layering porcelain selected typically has a slightly lower coefficient of thermal expansion than the framework material [26]. This slightly higher coefficient of thermal expansion of the framework puts desirable compressive forces into the layered porcelain. In order to potentially mimic this interaction that has worked predictably for metal-ceramic restorations for many years, manufacturers have developed specific products with a coefficient of thermal expansion close and slightly lower than that of the zirconia substructure [27]. In addition to layering porcelain, a pressing technique has been established to create the desired product without the firing shrinkage associated with any layering technique [28]. Although each technique has its advantages and disadvantages, both have shown similar shear strengths at the zirconia-veneering porcelain interface [29]. As the understanding of the chemo
mechanical properties of zirconia in its application to dentistry continues to improve, as does its prognosis as a long term restorative material.

Although high-strength core materials made of either a cast metal framework or oxide-based ceramic has shown clinical success, such as alumina or zirconia, there are certain disadvantages [30]. One of the major disadvantages is the high amount of opacity inherent with these substructure materials, which would not allow for a conservative preparation design to have optimum esthetics [31]. Another major disadvantage is the need for veneering material of the substructure to often improve esthetics. An issue with this is it creates a new interface between the substructure and layered porcelain, which has a higher degree of chipping and fracture due to its lower flexural strength and fracture toughness compared to a monolithic restoration [32]. This is partly due to the difficulty of creating an adequate bond at the interface of the dissimilar materials of silica-based glass ceramics and oxide-ceramic [27].

**Lithium Disilicate-**

There are other all-ceramic options that can provide both the strength and esthetics that is to be expected of a desirable dental restoration. This can be achieved by eliminating the bond interface between a substructure and a veneered porcelain by having a monolithic restoration [33]. In particular, this is possible with lithium disilicate as a restorative material [30, 31, 33]. Although lithium disilicate maintains approximately 70% of a crystalline phase, it still maintains the ability to refract light very naturally; it’s flexural strength being between 350 and 400 MPa (Ivoclar vivadent).

The actual mechanism of the crystallization of lithium disilicate is quite complex. Some x-ray diffraction studies have shown that both cristobalite (\(\text{SiO}_2\)) and lithium metasilicate
(Li₂SiO₃) are first formed in the process, prior to the growth and formation of actual lithium disilicate crystals (Li₂Si₂O₅) [34]. The final microstructure of the lithium disilicate crystals formed to be highly interlocked lithium disilicate crystals that are approximately 5 um in length and 1 um in diameter [35]. This high degree of interlocking of its microstructure and the coefficient of thermal expansion mismatch of the 70% lithium disilicate crystals embedded in the 30% glassy matrix both likely contribute to its unusually high strength as an all ceramic material [36].

The IPS e.max lithium disilicate is comprised mostly of lithium dioxide, phosphor oxide, alumina, potassium oxide and quartz (Ivoclar vivadent). All of these components are combined to produce a glass melt, which is then subsequently poured into a steel mold until fully set and no more dimensional changes occur (Ivoclar vivadent). These blocks, or otherwise known as ingots, are produced in a large batch based upon their respective shade and translucency. These glass ingots can then be processed via a CAD/CAM type of workflow, or pressed via a “lost-wax” technique (Ivoclar vivadent).

When utilizing the IPS e.max CAD technique, there is a two-stage crystallization process (Ivoclar vivadent). First, a double nucleation process where lithium meta-silicate crystals are precipitated out. The material is now known to be in its “blue block” state (Ivoclar vivadent). This intermediate meta-silicate crystal structure (Li₂SiO₃) allows the material to be easily milled at this stage without excessive bur wear. Afterwards, a second heat treating step (840-850°C) is performed where the meta-silicate phase is completely dissolved and the lithium disilicate crystallizes (Ivoclar vivadent). IPS e.max Press is produced similarly up until it is formed into a glass ingot. Afterwards, instead of having two stages, the glass ingots are both nucleated and crystallized in one heat treatment and then pressed at 920°C (Ivoclar vivadent).
Although IPS e.max CAD and IPS e.max Press are of the same composition, the difference in their production creates a difference in their mechanical properties. Both types of glass ceramic have a 70% volume of lithium disilicate crystals, but the e.max CAD ceramic has a crystal size of approximately 1.5μm in length, whereas e.max Press ceramic has a crystal size approximately 5μm in length (Ivoclar vivadent). Their material properties including coefficient of thermal expansion, modulus of elasticity, and chemical solubility are similar, whereas the flexural strength and fracture toughness of the e.max Press is slightly higher (Ivoclar vivadent). The flexural strength of e.max CAD and e.max Press are 360 MPa and 400 MPa, respectively.

Depending on the clinical situation and expectations of the final appearance of the restoration, there are many different opacities of lithium disilicate available. This is possible with different types of ingots that are available in the IPS e.max collection. These opacities include high opacity, medium opacity, low translucency and high translucency (Ivoclar vivadent). The difference in opacities is controlled by the nanostructure of the material. In particular, an increase in the amount of scattering of light at the interface between the crystals and glass matrix causes a higher opacity (Ivoclar vivadent). The manufacturing processes to control the opacity of the material does not have an effect on the materials’ mechanical properties.

**Wear Studies**-

Wear is a natural degradation process that occurs at the contact interface of two or more surfaces which are under relative motion and frictional forces [37]. This study of friction, wear and lubrication (solution to wear and friction) is known as tribology [38]. Tribological processes involve several degradation mechanisms which are acting together at the interfaces of the contacting bodies. With teeth, with or without dental restorations, are constantly in motion with one another, and wear on the opposing surfaces is inevitable [39]. This wear is a cumulative
process, which is an evolving and additive progression throughout the lifetime of a person [39]. The amount of progression of this wear depends primarily on the structure of the surfaces, the activity of any lubricating layer, the time the surfaces are contacting, the temperature of the medium the surfaces are contacting in, and the contact stress [39]. Oftentimes, the wear or abrasion of the tooth structure over the course of an individual’s lifetime or due to an isolated event requires the replacement of the missing tooth structure with a dental restoration. This tooth replacement should ideally have the same or greater wear resistance than the tooth it is replacing [40].

In the field of tribology, there are six major types of fundamental wear mechanisms: fretting wear, adhesive wear, wear caused by fatigue, corrosive wear, erosive wear, and abrasive wear [41]. These will occur in a various amount of combinations that will have the same end result of causing surface loss due to wear. Surface loss can also occur in static situations like rust, but this is not considered in the field of tribology, and instead must result from the movement of surfaces [37]. The likely most common type of wear is abrasive wear [38]. Abrasive wear can be subdivided into two separate types: two body wear and three body wear. Two body abrasive wear is when the cutting surfaces between the two objects are fixed to one or both surfaces. In contrast, three body abrasive wear is when there is loose, abrasive particles in between the two fixed objects that are in motion while in contact with one another [42, 43]. In general, the softer surface will be worn mostly by the abrasive particles present in the contact area. Two-body wear scenarios can also become three-body wear scenarios after particles or debris is created during the contact event [42]. In regards to the amount of abrasive wear experienced, this will be largely affected by the geometry of the abrasive materials, the sliding distance, the load, and the hardness of the materials in contact [42].
Fatigue wear can occur simultaneously with other mechanisms of wear, which is the result of the formation and growth of subsurface microcracks when two surfaces are in contact under a dynamic load [38]. When one surface is sliding over another surface while a force or load is applied, there is a zone of compression ahead of the motion on the surface, and a zone of tension on the surface behind the motion, causing an accumulation of plastic deformation energy under the subsurface [38]. This accumulation of plastic deformation can eventually cause cracks which will propagate with repeated cycles of sliding movement, the depth depending on the properties of the contacting materials [44]. Eventually these cracks can accumulate to form an interlinking network of cracks around a portion of the surface material, and this surface fragment will subsequently displaced. This displaced surface material could then potentially itself become wear debris and cause a three-body type of abrasion [38].

Adhesive wear is another type of wear that is observed when two surfaces slide past one another. In adhesive wear, the friction between the two moving surfaces in contact with one another can cause a cold-welding type of effect between different projections between their surfaces [39]. Additional movement between these two surfaces can then cause a fracture of this previously established cold-welding, but where the fracture occurs within the structure is not necessarily at the location or depth of where the cold welding occurred [44]. The overall result of this interaction is the transfer of material from one surface to the other [39]. This can cause layers of material to build up on one of the surfaces, which could potentially break away and contribute to a three-body abrasive slurry [39].

Corrosive wear will occur between two surfaces when there is a chemical degradation of one or both of the surfaces, and the surface(s) weakened by the chemical degradation will be removed after movement occurs while in contact with one another. [38]. Erosive wear is very
different, which instead is the result of the impact of particles or fluid under pressure [45]. Two examples of an erosive wear pattern is the wear of rocks under a stream of water, or a material that has surface loss due to sand-blasting. This is different than three-body abrasion where these particles are instead compressed between two surfaces, instead of being the actual wear medium as a second surface [45].

The last type of wear is fretting wear. Fretting wear is a result of prolonged, slow slipping between surfaces under load [39]. These conditions do not occur intra-orally, and therefore is not a normal feature seen with dental-related wear [39].

Intra-oral wear in general occurs from the direct contact and movement of teeth, and/or any abrasive particles or slurry that is between teeth during parafunctional movements or mastication [38]. There is also a non-mechanical type of wear processes with potential regurgitation or dietary chemical wear on teeth or restorative materials [38]. It has been long established that these many types of tooth wear occur usually in conjunction with one another, and likely is ever one type the sole cause of wear in any dental patient [38]. Abfraction is also a term used to describe non-carious tooth structure loss, but instead is a theoretical stress concentration at the cervical areas of teeth based on engineering analyses, that causes flexure and failure of enamel and dentin away from the site of loading [46].

Although abrasion, attrition, and erosion have been used to describe these intra-oral wear processes, the dental and tribology interpretation and meanings are quite different [38]. The likelihood of this confusion between the practices of tribology and dentistry is because in dentistry these mechanisms of wear are describing the etiology of the wear, instead of the actual wear mechanisms like in tribology [39].
In dentistry, attrition is understood as the wear caused by direct contact between teeth or dental restorations [47, 48]. This characteristic wear is often seen by flattened incisal edges or cusp tips, in association with wear facets present on occlusal surfaces [38]. These facets will eventually be worn away to have a ‘cupping’ characteristic of the tooth structure, and potentially will also cause a ‘grooving’ of worn incisal edges [49].

With dental erosion, it is instead describing the tooth surface loss due to usually an acidic solution that is not of bacterial origin [47]. Although this now weakened tooth surface is subsequently rubbed off, this type of wear etiology is more chemical in nature. The clinic manifestations of this type of dental wear is a glazing of the enamel surface, shallow concavities on the cervical region of the smooth surfaces of teeth, and protruding amalgam restorations [50]. The type of erosion can also be divided into regurgitation erosion, dietary erosion and industrial erosion, depending on the source of the erosive factor [49].

Abrasion is used most diversely when describing wear in dentistry, and essentially is used to explain any wear of restorations that occur on a non-contacting surface [39]. Usually this type of wear is caused by habits of the particular individual, and is seen in examples such as pipe smoking and improper selection of material or use when tooth brushing [39].

Clinical studies on dental wear are very limited due to the difficulties of accurate measurement of intra-oral wear, and due to a lack of control of an oral environment [51]. Therefore, laboratory simulation methods have been developed to best mimic wear conditions in the mouth, which should include both masticatory and oral environment conditions [51]. Since in vitro testing does allow researchers much more control over many different experimental variables and to make more accurate measurements than in vivo testing, in vitro testing has been widely accepted for its advantages in evaluating both the wear mechanisms of natural teeth and
replacement dental materials [52]. Given that the oral environment is impossible to re-create and calculate, it is important to note that in vitro wear studies can only tell us about trends and indications as to what extent true intra-oral wear occurs [53]. Some of the aspects of clinical wear that are difficult to replicate include the complicated shapes of teeth and dental restorations, where most of the tribology testing machines are designed to incorporate test pieces with flat surfaces [54]. In addition, most wear simulators must be tested with a constant load, and cannot incorporate a progressive load like what might be experienced during a normal masticatory cycle [54]. Although a two-body wear contact of back and forth sliding movements on a flat surface does not replicate true masticatory movement in vivo, it is an essential component in the intra-oral wear process and better evaluates potential complications due to microfatigue [55]. In contrast, wear stimulators where the stylus, or counter body, is lifted during function there is more uncontrolled impulse forces that are introduced to the system [56].

The amount and type of wear observed is based upon the physical and mechanical properties of the materials in contact with one another. The brittle nature of ceramic material affects the type of wear that is experienced [57]. Due to this nature, it has been shown that the formation of cracks in a flat ceramic surface will be 10 times more likely with a sliding type of motion, compared to the same amount of force with a static compression of the surface [57]. In addition, the presence of a surface medium will variously affect the wear of different materials in moving contact with one another. For example, zirconia has shown to have a 10-fold increase in the amount of wear when in a wet condition than in a dry condition [58]. In general, ceramics experience mild wear or severe wear [38]. In mild wear, there are smooth surfaces, constant friction and the type of wear is caused primarily by surface reaction and slow plastic flow [38]. In
contrast, severe wear is seen due to the brittleness of ceramics when there are rougher surfaces, friction is a changing variable and the major mechanism of wear is due to fracturing [38].

There has been a very diverse report within the literature about the wear of different restorative materials and their relative wear in opposition of enamel [59]. This is likely due to many different variances between many of the studies, which include: the type of machine or wear simulator used for testing, the thickness of the enamel used as an antagonist, the geometry or shape of the dental materials or enamel that is being tested, the loading force that is applied to the two surfaces in motion, the type of lubrication or surface liquid used in conjunction with tribologic testing if any, the number of cycles of rotating or sliding movements the materials are placed under, the surface texture and polishing methods for the samples being tested, and the total sliding movement for each cycle [59]. Although this made it difficult to compare the results among different authors using various methodologies, it was important to see the behavior of the dental materials compared to one another in each individual study [59].

There has been a consistent scientific improvement to develop dental materials that not only resemble the esthetics of a natural tooth, but also to have improved physical and mechanical properties to not cause inadvertent damage to an opposing tooth [60]. In an ideal situation, a replacement restorative material should show a similar amount of wear and aging that would be expected in a normal physiologic situation [55]. This amount of wear for tooth enamel can be measured to be between 15 to 38 um, annually [61]. Based upon the type of ceramic material chosen as a dental restoration, there is varying damage and wear that will occur to the opposing tooth [10]. Although material choice affected the potential wear, variations in the microstructure, ceramic composition and fusing temperatures did not correlate well with enamel wear [62].
There are some varied scientific findings for the performance of lithium disilicate and zirconia restorations, in relation to their wear performance against enamel [55]. For lithium disilicate restorations, they have shown to be at least as wear friendly and wear resistant when opposing enamel, in comparison to feldspatic porcelains that would traditionally be layered or veneered on metal or ceramic substructures [63]. In regards to glazed, heat pressed lithium disilicate crowns, it has been shown that there is significantly less volume loss of the restorative material when compared to the mean volume loss enamel would normally experience after one year of function [64]. It also was found that there was no significant relationship between maximum clenching force and the wear rate of the enamel or ceramic crowns [64]. Although some of the earlier studies showed that zirconia restorations were comparable to metal ceramic restorations, a recent study has shown that zirconia is superior in regards to a superior wear behavior and lower antagonistic wear [63]. In fact, zirconia has been shown to exhibit less wear on enamel than enamel itself, and has also shown to have a smaller increase in surface roughness compared to enamel after masticatory simulation [65]. In addition, zirconia has also been shown to have superior wear behavior and lower antagonistic wear when compared to lithium disilicate, composite resin and veneering porcelain [66]. It also has been previously shown that polished monolithic zirconia also exhibits less significantly lower wear on enamel when compared to glazed monolithic zirconia [67, 68]. If the zirconia ceramic is not carefully polished prior to glazing, there will likely be an increase in amount of wear to the opposing tooth structure after the glazed layer is worn through and the zirconia layer is reached [67]. In general, it has been concluded that current zirconia and lithium disilicate restorations do not have statistically significant differences in volumetric or linear reduction of natural enamel tooth surfaces when compared to the physiologic wear that would be experienced when opposing another natural enamel tooth structure.
Further, it has been shown the surface roughness of lithium disilicate and zirconia is less than porcelain fused to metal restorations, after functioning against enamel over a period of time [69].
3. MATERIALS AND METHODS

A. Specimens and solution

A total of 20 all-ceramic blocks approximately 16.0 mm in length and 2.0 mm-thick were used. Of those blocks, ten were Zenostar Zirconia and ten were IPS e.max CAD (Ivoclar Vivadent). The lithium disilicate blocks were sectioned from the C14 – IPS e.max CAD blocks (8×8×2 mm) using a slow-speed diamond saw under water lubrication (Isomet, Buehler, Lake Bluff, IL, USA). All lithium disilicate blocks were crystallized, and glazed (IPS e.max CAD Crystall Glaze, Liquid/Paste) following the manufacturer’s recommendation (Program 1 - 850°C, Programat CS2, Ivoclar Vivadent). In addition, 10 zirconia blocks were sectioned from the Zenostar Zr Translucent block (98×25 mm) using a diamond wafering blade (Buehler-Series 15LC Diamond) at a slow speed under water lubrication (Isomet, Buehler, Lake Bluff, IL, USA). All zirconia blocks were sintered and glazed (IPS e.max Ceram Glaze FLUO, Paste) according to manufacturer’s recommendation (403°C low temp, full vacuum starting at 450°C, 850°C high temp with a 1-minute hold, Ivoclar Vivadent). All ten of the zirconia samples and ten of the lithium disilicate samples were then sintered, crystallized and glazed, following the manufacturer’s recommendations. Afterwards, five of the glazed zirconia samples and five of the glazed lithium disilicate samples were adjusted at 15,000 RPM under water irrigation, utilizing an electric high speed hand piece to control the torque and a fine grit/red striped chamfer diamond bur (Brasseler, USA). After a controlled number of 12 adjustment strokes, the samples were polished with the OptraFine kit, a three step polishing system (Ivoclar Vivadent). This polishing system includes two stages of adjustments with synthetic rubber tips containing diamond granulate and titanium oxide, followed by utilization of a diamond polishing paste that contains diamond dust from 2-4 um in an emersion of glycerine, sodium lauryl sulphate and propylene glycol (Ivoclar Vivadent). After the polishing
was completed, all 10 polished samples were sonicated in 70% isopropanol for 15 minutes. To function as a counter body, two Zenostar Zirconia spheres and two IPS e.max CAD spheres were fabricated with a radius of 5mm. Similar to the all-ceramic blocks, all of ceramic spheres were initially sintered and glazed following the manufacturer recommendations. Afterwards, one zirconia sphere and one lithium disilicate sphere were mounted on a 1x20mm wood stick and carefully adjusted and polished following the protocol just described for the all-ceramic blocks. Prior to removing the mounted wooden sticks, the area potentially affected by the adhesive was marked to be avoided during the tribology testing. See Figure 1 for schematic design of setup.

Artificial saliva with a pH of 6.5 and temperature of 37ºC was used as a lubricant in a well surrounding the block mounting, which would leave the block slightly submerged (~10ml). A water bath and water pump was utilized to maintain the temperature of this artificial saliva, as it was exposed to an open air environment for the 14-hour duration of a cycle. In addition, an IV bag with solution was equipped to the well of the mount to maintain the volume of artificial saliva when evaporation occurred. The composition of the lubricant was based on Fusayama and Meyer’s solution listed in Table 1.

B. Tribology Test Protocol

All trials were performed using a linear reciprocating tribometer (DUCOM-Material Characterization Systems, Evanston, IL, USA) Figure 2 shows the schematic setup of the tribometer apparatus. The total number of reciprocating cycles was fixed at 100,800 cycles, with a frequency of 2Hz, a stroke size of 2mm and a constant load of 8.5N. The block and counter-body sphere tested against each other during a trial was always of the same material and same surface texture. For example, a zirconia block that was roughened and polished would have a sphere counter body that was similarly roughened and polished. Each ceramic block was replaced
after each trial, which was sonicated for 15 minute in 70% isopropanol prior to storage. In contrast, each sphere was marked where a previous test had occurred, and was subsequently rotated to an ‘untested’ surface.

During the sliding process, the tangential load experienced by the tribometer was measured and by which the coefficient of friction was estimated and recorded. This coefficient of friction evolution was recorded with a 1 second save dwell/interval.

C. Surface Characterization

To evaluate the volume loss of each ceramic block after the experimental trials were completed, a white light interferometry microscopy (Zygo New View 6300, Middlefield, CT) was used. In addition, white light interferometry was used to record the surface roughness of the ceramic materials inside and outside of the worn surfaces. Afterwards, surface characterization was performed using Scanning Electron Microscopy to analyze the wear patterns and method of wear of the ceramic blocks (SEM, Joel JSM-6490 LV, Japan). Due to the reflective nature of the zirconia material, the zirconia blocks were first coated with gold particles in order to be analyzed by the machine.

Utilizing SPSS, a one-way between-groups analysis of variance was conducted to statistically analyze the impact of material on coefficient of friction, wear volume loss and surface roughness. Post-hoc comparisons Bonferroni test was performed to evaluate the significant differences among groups. A mean difference significance at the 0.05 level was used for all comparisons.
4. RESULTS

A. Coefficient of Friction

The coefficient of friction was recorded for each trial of each sample, using a one second save dwell during the duration of the 14 hour cycle. These results were tabulated and analyzed by plotting the different sample groups in comparison of one another. The results can be visualized as a coefficient of friction evolution in Figure 3, or as an average in Figure 4.

In addition, a one-way between-groups analysis of variance was conducted to explore the impact of material on coefficient of friction. There was a statistically significant difference at the P<0.05 level for 4 material groups: F (3, 14)=5.146, p=0.013. Post-hoc comparisons using the Bonferroni test indicated the mean scores for lithium disilicate Glazed (Mean=1.14, SD=0.29) was significantly different from group Zr Glazed + Polished (Mean=0.664, SD=0.14) (p=0.022).

The glazed lithium disilicate samples (e.max G) showed a slightly higher coefficient of friction than the lithium disilicate samples that were polished after glazing (e.max G+P). In general, both surface finishes of lithium disilicate had a very similar coefficient of friction during the duration of the trials, which can be best visualized by the evolution of their coefficient of friction. The coefficient of friction for both lithium disilicate samples also remained relatively constant over the duration of the trials.

In regards to the zirconia samples, both surface finishes of the zirconia samples had a smaller coefficient of friction than the lithium disilicate samples. The zirconia samples that were polished after glazing (Zr G+P) had a very consistent coefficient of friction during the duration of the trial. In contrast, the glazed zirconia samples (Zr G) initially had a very similar coefficient of friction compared to the lithium disilicate samples, which decreased over time. During the study
period, the zirconia glazed samples had a coefficient of friction that gradually approached and eventually became similar to that of the zirconia glazed and polished samples.

**B. Surface Roughness**

The surface roughness of each sample was measured using white light interferometry (WLI). The surface roughness was measured on two locations on each block; one location on the wear scar itself where the opposing ceramic ball was contacting, and the other being just outside of the wear scar. This allowed an evaluation of the surface roughness of the material before and after tribologic testing. The surface roughness values of the sample blocks can be visualized in Figure 5.

Both groups of glazed materials had a similar surface roughness prior to wear testing. Similarly, both groups of the glazed then polished materials had a similar surface roughness prior to testing. In contrast, both groups of the glazed then polished materials had a higher surface roughness prior to testing when compared to glazed only samples of the same material. Further, both zirconia samples were significantly less rough than the lithium disilicate samples after testing. Only the Zr G+P surface finish became less rough after wear testing.

To evaluate the statistical significance, a one-way between-groups analysis of variance was conducted to explore the impact of material on surface roughness. There was a statistically significant difference at the p<0.05 level for 4 material groups: F (3, 8)=59.642, p<0.001. To be specific, lithium disilicate Glazed was statistically different from all of the groups (lithium disilicate Glazed + Polished, Zr Glazed, Zr Glazed + Polished) (p=0.015, p<0.001, p=0.002 respectively). In addition, lithium disilicate polished was statistically different from the zirconia samples (Zr Glazed, Zr Glazed + Polished) (p<0.001, p<0.001 respectively).
C. Wear Volume Loss

In order to measure the wear volume loss of the samples, WLI was again utilized. This was possible by measuring the depth and area of the wear scar, knowing the block initially started with a flat surface. The amount of volume loss for each sample can be visualized with Figure 6.

Both lithium disilicate samples experienced more volume loss than the zirconia samples. The lithium disilicate G+P samples exhibited the most volume loss, whereas the Zr G+P samples exhibited the least amount of volume loss. A one-way between-groups analysis of variance was conducted to explore the impact of material on volume loss. There was a statistically significant difference at the p<0.05 level for 4 material groups: F (3, 14)=29.263, p<0.001. Post-hoc comparisons using the Bonferroni test indicated the mean scores for lithium disilicate Polished (Mean=7400000, SD=16069380) was significantly different from the rest of the groups (e.g., max Glazed, Zr Glazed, Zr Glazed + Polished) (p=0.003, p<0.001, p<0.001 respectively). Also, the lithium disilicate Glazed samples showed a statistically significant difference in volume loss when compared to Zr Polished samples (p=0.002).

D. Surface Characterization

The wear scar obtained in each specimen was evaluated using both scanning electron microscopy (SEM) and WLI.

The applicable SEM images of the wear scars after tribology testing can be visualized in Fig. 7. The ball-on-block fretting motion was from left to right in all depicted images. Lines were made with a marker to best find the location of the wear scar while scanning the image. These lines can be seen in the 30x images. Different patterns are noted between all four types of surface finishes, and all 300x and 3,000x magnifications were taken within the wear scar. The lithium disilicate glazed samples had a much smoother wear pattern than the lithium disilicated glazed and
polished samples (Fig 7A-F). The lithium disilicate glazed and polished samples instead exhibited a grooving pattern in the direction of the ball-on-block tribometer. The zirconia samples exhibited a much smaller wear scar than the lithium disilicate samples (Fig 7A-L). The glazed zirconia samples exhibited a whiter material in the center of the wear scar, with striations running in the opposite direction of the movement of the ball-on-block tribometer (Fig 7G-H). In contrast, the glazed and polished zirconia sample had barely any noticeable wear scar present (Fig 7J-L). The only noticeable change was a slight difference in surface texture approximating the wear scar location which was marked on the block prior to removing it from the tribometer (Fig 7J).

The most representative WLI images for each all-ceramic block type and surface texture can be visualized in Figure 8. It can be seen that the lithium disilicate glazed and polished samples exhibited a wear scar that was similar in depth compared to the lithium disilicate glazed sample, but had a larger overall surface area (Fig. 8A-B). In addition, it is obvious the lithium disilicate samples had much larger wear scars than the zirconia samples (Fig. 8A-D). The zirconia glazed sample had a wear scar that was much more columnar than the spherical shaped wear scars of both lithium disilicate samples (Fig. 8A-C). Similar to the SEM images, a wear scar was also barely noticeable with WLI (Fig. 8D).
5. DISCUSSION

5.1 Coefficient of friction evaluation

As expected, there was a different friction evolution between the different materials, and between the different surface finishes [70]. This overall friction being experienced in the system could potentially be affected by any or all of these factors: the surface and material properties of the ball and/or block, the potential build of ceramic material after wear simulation has begun and the viscosity of the saliva and the ability of the ceramic ball to move through it [71]. Based upon the results, it appears that both glazed ceramic materials experienced a similar coefficient of friction early on in wear simulation. As wear occurred and the glazed layer on the ceramic material changed, noticeable differences were observed. The glazed lithium disilicate samples continued to behave very similarly to the lithium disilicate glazed and polished samples after wear simulation began. In contrast, the glazed zirconia samples slowly began to behave very similar to the zirconia glazed and polished sample. The difference observed is likely due to the very different material properties of lithium disilicate and zirconia (Ivoclar vivadent). Since zirconia is a much harder and has previously been shown to be a minimally abrasive material, the glazed layer was simply being slowly removed from the surface as wear simulation occurred [55]. As this glazed layer was slowly removed, more of the zirconia surface itself was exposed to the wear simulation. Due to the much higher hardness of zirconia material (Ivoclar vivadent), the glazing material might have minimally or never became embedded into the zirconia sample itself to function as a third body, and was instead removed from the wear system. In contrast, since lithium disilicate is not as hard of a material as zirconia (Ivoclar vivadent), wear of the glazed layer potentially also changed the surface of the lithium disilicate material itself. This potentially could have also occurred to both the glazed and the glazed and polished lithium disilicate samples. This could have been to a greater
extent with the glazed and polished lithium disilicate samples because these samples were at first adjusted and polished under only a water spray, and not worn under complete immersion like the glazed samples.

5.2 Wear volume loss evaluation

There was a statistically significant difference between the volume loss observed between many of the groups. A three-dimensional representation of the volume loss can be visualized in Figure 8, with the white light interferometry images. As expected, due to the increased hardness of the zirconia material, more wear was observed for the lithium disilicate material [65]. The only comparison between lithium disilicate and zirconia samples that did not have a statistically significant difference in volume loss is between the lithium disilicate glazed and zirconia glazed samples. This is likely due to the presence of the glazed layer on the zirconia and lithium disilicate samples, which would likely wear at a similar rate even though it is covering two different materials. After the glazed layer of the glazed zirconia samples was worn through, the volume loss per stroke then likely began to decrease. This has been previously described, where the surface finish of the underlying ceramic is the ultimate factor in affecting the wear rate, and not the superficial glazed layer [72].

Since the glazed layer was primarily removed when adjusting and polishing the zirconia glazed and polished blocks, very little volume loss was observed for the glazed and polished zirconia samples. This again can be explained by the innate hardness of the zirconia material, and how most of the contacting wear surface was primarily the zirconia material itself.

A very surprising result was the volume loss of the lithium disilicate glazed and polished samples, especially in comparison to the lithium disilicate glazed samples. It has been previously
shown in earlier studies that a polished ceramic surface would typically wear less than a glazed surface [67]. What likely explains this phenomenon that was observed is the likely presence of three-body wear [38]. The presence of this three body wear could potentially cause more of a grooving or ploughed effect on the block [38]. This ploughed appearance has been described previously in wear studies involving lithium disilicate, whereas the SEM imaging of a surface worn by zirconia is a smoother surface [73]. This grooving can be seen in the striations present in the SEM images in Figure 7, particular images D and E. The particles that could be contributing to this wear could be from the glaze material, the materials used to polish the samples, and/or lithium disilicate particles that have been previously worn or polished off the surface and now are functioning as abrasive materials. These particles can be visualized in Figure 7, with particular attention to image F.

5.3 Surface roughness

The surface roughness of the samples was evaluated with the use of white light interferometry. There were two spots on each block where surface roughness was evaluated: inside the wear scar, and outside of the wear scar. The surface roughness outside of the wear scar represents the surface roughness of the material prior to wear simulation. In contrast, the surface roughness on the inside of the wear scar represents the outcome roughness of the block, after wear simulation was completed.

As expected, the glazed samples had a much lower surface roughness than the polished samples [74]. This is due to the glossy and smooth nature of a dental material that has been properly glazed [74]. After wear simulation of the glazed samples, this glazed layer was damaged and partially removed, resulting in a rougher surface. Although one would expect all samples to become rougher after wear simulation, the zirconia glazed and polished samples instead became
smoother. This could potentially be that since zirconia is such a hard material, the polishing system could only smooth the surface so much after the surface was adjusted with a diamond bur. When this adjusted and polished zirconia surface was placed in contact with a similar surface and was allowed to wear against it, this likely caused an overall smoothing event to a point where the polishing system was not a rigid enough of a material to complete this. This is unlike what was seen with the lithium disilicate glazed and polished samples, because as discussed earlier, this group likely experienced a larger amount of three-body wear from particles that were previously abraded.

5.4 SEM Images and possible wear mechanisms

The SEM images were taken at multiple magnifications (30x, 300x, and 3,000x) allows there to be an evaluation of the potential wear mechanisms that occurred, which could potentially explain the volume loss that was observed. For the lithium disilicate glazed sample, it is evident that this surface wore very evenly, and had minor to very little grooving that occurred. This could potentially indicate that there was minimal three body wear that occurred with this sample [42]. There was a small amount of particles present on the surface, which could potentially be glaze or lithium disilicate particles that had been worn from the surface previously [37].

The imaging for the lithium disilicate glazed and polished samples behaved very differently. This is evident from the multiple grooves that can be seen on the surface, in the direction of the sliding movement [42]. In addition, at higher magnifications, it is clear that there are particles of some sort that are in and around these grooved channels that are on the surface of the material. As stated earlier, it is likely these particles that caused the extra abrasion and volume loss of the lithium disilicate glazed and polished samples, when compared to the glazed samples. A potential explanation for these particles being present on the glazed and polished samples, but
not the glazed samples is the fact all wear and potentially damaging movement to the lithium disilicate glazed samples occurred while the block was submerged in the artificial saliva. In contrast, the lithium disilicate glazed and polished samples were adjusted with a diamond bur only under water irrigation at a point before wear simulation. This damaging event to the surface of the material with a coarse object could have potentially embedded some of these abrasive particles in the block or counter body, leading to increased abrasive wear [42]. This could only have been exacerbated when compared to the lithium disilicate glazed samples because an adjustment under water irrigation would likely not have the same removal of worn particles affect as a sample that was only worn away at when completely submerged in a liquid material. This finding also cannot be explained by the polisher being ineffective in polishing the lithium disilicate material after adjustments, as the surface texture immediately outside of the wear scar is smooth and does not share the very characteristic grooving seen within the scar.

The zirconia glazed group had a much smaller wear scar when compared to the lithium disilicate samples. This is due to the smaller amount of volume loss present for zirconia glazed samples, and therefore a much smaller resulting contacting area as wear simulation progressed. There is what appears to be a chalky layer in the center of wear scar. This could potentially be glaze material that remained on the surface after wear simulation. What is difficult to explain is the vertical striations present within this chalky layer, which are occurring in a direction perpendicular to the actual sliding motion of the counter-body onto the block. It is possible that due to the higher contact pressure present with the zirconia sample compared to the lithium disilicate samples, there was some vertical component to the movement of the ball during the sliding strokes. The starting hertzian contact pressure of the zirconia sample is about double that
of lithium disilicate sample due to the much higher elastic modulus of the zirconia material, and likely only increased in disparity as the surface area of the lithium disilicate samples increased.

The zirconia polished samples barely had any noticeable wear in the SEM imaging. In the 30x image (Figure 7F), there is a slightly noticeable border of where the wear scar is. In the magnified images, the surface appears relatively smooth. In the 3,000x image, some small irregularities can be seen on the surface, which could have been caused by the initial damage of the diamond burs and polishing system, or by the wear simulation in opposition of the zirconia ball.
6. CLINICAL SIGNIFICANCE

It is clear that different CAD/CAM materials behave very differently when placed in function opposing one another. Despite the material properties of zirconia, this is another study demonstrating its low abrasive and wear potential, even when placed in function against a like material just as hard with identical material properties. In addition, it has been demonstrated that a glazed zirconia restoration will potentially behave like the surface finish of the underlying zirconia material after the glaze layer has been worn through during function. Therefore, zirconia restorations should be very carefully polished prior to being glazed. Otherwise, the restoration will potentially be a much more abrasive surface, and the dental provider will have the false security of a polished restoration due to the glossy nature of a polished ceramic restoration.

It has also been demonstrated in this study that lithium disilicate restorations experienced a moderate amount three-body wear after adjustments were made, especially compared to zirconia restorations. Since less three-body wear occurred to the glazed restorations that only experienced a traumatic event to its surface while completely submerged in a solution, this might affect how we decide to adjust lithium disilicate restorations prior to delivery. Perhaps it is beneficial to make any adjustments to the surface of lithium disilicate when the restoration is completely submerged in a solution, when compared to what is typically done with the normal water spray from a dental hand piece. This could potentially lead to a less abrasive surface finish for the restoration long term.

It is important to note that although zirconia potentially performed better than lithium disilicate, some wear is not necessarily an undesirable observation in vivo because even natural teeth in a healthy situation will experience some volume loss in function. It is important in future
studies to evaluate how much a ‘healthy’ amount of wear might be between natural teeth. In addition, it is necessary to evaluate different restorative materials with similar surface finishes, in an identical in vitro testing environment, to best compare and predict the behavior of these dental materials that are used to rehabilitate patients in a clinical setting.
7. CONCLUSIONS

Using a ball-on-block tribometer, different all-ceramic CAD/CAM materials were evaluated in terms of surface roughness, coefficient of friction and volume loss. The following conclusions can be drawn based upon the outcomes of this study:

- All lithium disilicate samples exhibited increased wear compared to zirconia samples.
- Even though there was a similar initial roughness prior to testing, lithium disilicate samples were rougher than zirconia samples after wear simulation.
- Glazed zirconia samples showed more wear than glazed and polished zirconia, whereas glazed lithium disilicate samples showed less wear than glazed and polished lithium disilicate samples.
- The volume loss differences that were visualized can be best explained by the introduction of three-body wear once previously worn material started to collect on the lithium disilicate samples. This is supported by the SEM imaging taken of the different samples.
- Further studies are required to verify these results, and to expand on material selection, material surface finish and inter-material wear comparisons.
FIGURES:

Figure 1. Schematic design of experimental setup

IPS e.max CAD

Crystalize and glazed

Crystalized, glazed & polished

n=5

2mm

100,800 cycles

Zenostar Zirconia

Sintered and glazed

Sintered, glazed and polished

n=5

2mm

100,800 cycles
Figure 2. Schematic design of the tribometer setup
Figure 3. Coefficient of friction evolution

Figure 4. Coefficient of friction average
**Figure 5.** Surface roughness of the ceramic blocks

**Figure 6.** Volume loss
**Figure 7:** SEM images of the worn areas of the all-ceramic blocks after tribology experimentation

A. Lithium disilicate glazed with 30x magnification  
B. Lithium disilicate glazed with 300x magnification  
C. Lithium disilicate glazed with 300x magnification  
D. Lithium disilicate glazed and polished with 30x magnification  
E. Lithium disilicate glazed and polished with 300x magnification  
F. Lithium disilicate glazed and polished with 3000x magnification  
G. Zirconia glazed with 30x magnification  
H. Zirconia glazed with 300x magnification  
I. Zirconia glazed with 300x magnification  
J. Zirconia glazed and polished with 30x magnification  
K. Zirconia glazed and polished with 300x magnification  
L. Zirconia glazed and polished with 3000x magnification
Figure 8. White light interferometry 3D images of all-ceramic blocks after tribology experimentation. X and Y axes are in mm, and Z axis is in µm. A. Surface of lithium disilicate glazed  B. Surface of lithium disilicate glazed and polished  C. Surface of zirconia glazed  D. Surface of zirconia glazed and polished
TABLES:

**TABLE I**
FUSAYAMA AND MEYER’S ARTIFICIAL SALIVA COMPOSITION

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<thead>
<tr>
<th>Component</th>
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<tr>
<td>NaCl</td>
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<tr>
<td>CaCl. 2H₂O</td>
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<tr>
<td>NaH₂PO₄. 2H₂O</td>
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<td>Na₂S. 9H₂O</td>
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</table>

Lactic acid is added to adjust the pH to 6.5
REFERENCES


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