



Experimental Comparison on Dental BioTribological Pairs Zirconia/Zirconia and Zirconia/Natural Tooth by Using a Reciprocating Tribometer

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Abstract

The application of tribology in dentistry is growing rapidly, intense research has been conducted to develop an understanding of dental tribology for better selection of artificial materials and dental implant design. Dental biotribology, has been one of the most important branches in biotribology in recent years. The aim of this research is to investigate the tribological performances in the tooth-to-tooth contact and material-to-natural tooth contact (zirconia vs. zirconia and natural tooth vs. zirconia). The presented research was carried out by testing the above mentioned tribological pairs with the use of a reciprocating tribometer under lubricated conditions (artificial saliva). The normal force used in the tests was 20 N the time for each test was of 60 min. The stroke length was 2 mm, according to the range of displacement used in scientific literature. The wear mass loss evaluation was evaluated by using a gravimetric method. In order to characterize the wear mechanisms, present in the worn surfaces after each of tribo-tests, a topographic analysis was carried with a 3D non-contact optical profiler. The results show that the minimum value of the COF is obtained in the case of Zirconia vs. Zirconia tribo-couple. The results on the wear mass loss show a very low wear rate when coupling in tribological condition natural tooth with a ceramic restoration (a mean value of 0.5 mg was found). This rate is even lower when the contact is between two artificial zirconia teeth.

Keywords Biotribology · Dental · Friction coefficient · Experimental

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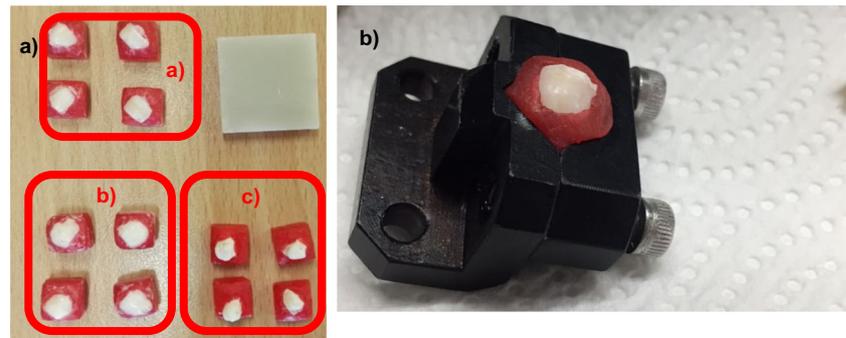
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Introduction

Human teeth are not only an important masticatory organ but also closely associated with both the pronunciation and facial aesthetics of humans. Teeth play an extremely significant role in our daily life. The wear of teeth, either natural or artificial, is unavoidable because they are continuously subject to mechanical and chemical stress [1]. However, excessive wear may lead to a lack of perfect contact between opposite teeth, a disturbance in the efficiency of the masticatory system, and a removal of chewing surfaces. In the human dentition, the tribological movements of tooth surfaces can result in physiologic wear [2]. Abrasion [3], attrition [4], erosion [5] and abfraction [6] are the main wear mechanisms which affect the functionality of the teeth during the masticatory process. In the case of the abrasive wear, the presence of the food particles can lead to three-body abrasion mechanism [7]. The attrition is characterized by two-body wear mechanism while the erosion is due to the actions of the food. The

Fig. 1 Natural enamel samples used in the tribo-test fixed in holders by acrylic resin: **a** Top view; **b** tooth holder for the tribotest



abfraction could occur along the gingival margin and it is not caused by tooth decay. It is a pathologic loss of hard tissue substance caused by bio mechanical loading forces [6]. Thanks to the presence of saliva, which acts as a natural lubricant during mastication [8], the adhesion wear mechanism does not occur either in the tooth-to-tooth contact or in the restoration material contact with a natural tooth. All these wear mechanisms can occur simultaneously [9]. In recent years, the behaviour of the friction coefficient and the possibility of quantifying and analysing the wear of dental surfaces of the oral cavity represent one of the most important tribological issues in the human body [10, 11]. In fact, all this is necessary in order to avoid a reduction in the efficiency of the masticatory system and to reduce the inevitable wear of both natural and artificial teeth. It is well known that, besides the environmental factors present in the oral cavity [12], the tribological behaviours between dental restorations and enamel are influenced by the mechanical properties, by the superficial microstructure and by the topography of the used materials [11]. Eisenburger et al. in 2002, in order to determine the influence of load and time on friction enamel wear, in neutral and in vitro acids, have tested two different specimens, including a cusp and a polished flat, obtained from recently extracted third molars. The specimens were tested in a wear simulator under neutral (saline) and acidic (citric acid pH 3.2) conditions [13, 14]. Zheng et al. in 2007 studied the wear of the enamel against a titanium alloy in salivary lubrication by using an alternative ball-on-flat tribometer with saliva as lubricant. The results showed that a delamination mechanism occurred on the surface of enamel at the early stage of wear. The wear rapidly increased in depth with the number of cycles [15]. Mayworm et al. in 2008, compared the wear resistance and hardness of two dental nano-hybrid composites in order to evaluate the influence of artificial saliva storage on these properties. The results showed that after storage in artificial saliva, the wear resistance increases for both materials. After storage in artificial saliva, the micro hardness of both materials decreases [16]. Jung et al. in 2010 conducted a study in order to evaluate the clinical validity of a zirconia full-coverage crown by comparing zirconia's wear capacity over antagonistic teeth with that of feldspathic dental porcelain. The tests were

conducted with 240,000 cycles with a double axis chewing simulator. The results were that zirconia may be more beneficial in terms of antagonistic tooth wear [17]. In dentistry, the choice of material depends on: corrosion behaviour, cost, availability, biocompatibility and aesthetic values. The materials used to replace the missing teeth or the fabric of the teeth of patients who have suffered lesions to the teeth due to trauma or disease are divided into three macro groups: metals and their alloys, ceramics, polymers and composites [18–21]. In recent years, ceramic materials have been widely used in dentistry thanks to factors such as aesthetics, chemical stability and biocompatibility. Initially these types of dental implants consisted of a zirconium core and a shell veneered formed by several layers of fused porcelain (bi-layer restorations). Recently, the production of these dental crowns has been replaced by ceramic restorations. The use of this material allows to completely avoid the problem of chipping porcelain, present in the bi-layer dental implants [22]. In fact, a monolithic zirconia restorations have presented a better wear performance than porcelain [23, 24].

For all these reasons, the objective of this study is to investigate tribological performances [25] in terms of friction coefficient and wear in zirconia tooth-to-zirconia tooth contact, material-to-natural tooth contact. The tests were carried out by using a reciprocating pin-on-plate tribometer. Two different tribo-couples were examined: zirconia vs. zirconia and natural

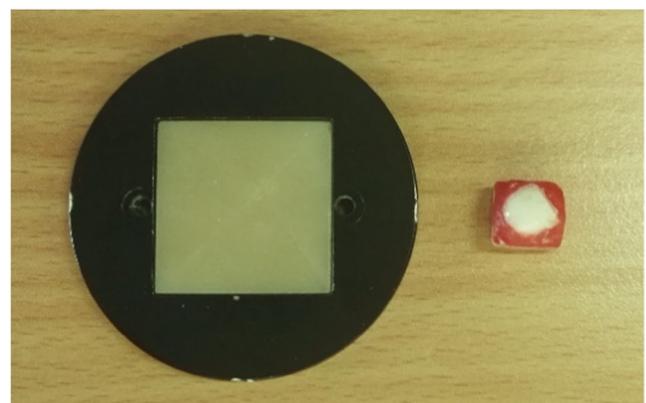
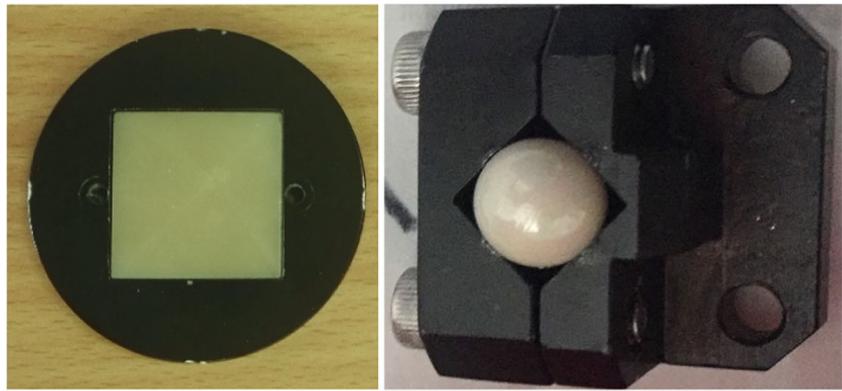


Fig. 2 Tribo-couples used in the test: natural tooth vs. zirconia

Fig. 3 Tribo-couples used in the test: zirconia vs. zirconia



tooth vs. zirconia. All the tests were carried out in lubricated conditions with the interposition of artificial saliva between the sliding surfaces [26]. For the wear mass loss evaluation was carried out by using a precision balance. A topographic analysis followed each reciprocating tribotest, it was carried with a 3D non-contact optical profiler in order to characterize the wear mechanisms present in the worn surfaces. This analysis consists of three fundamental phases: preparation of samples; wear test at the alternative tribometer in order to evaluate the friction coefficient; surface investigations about the roughness and wear of teeth with the aim of quantify the wear mechanisms acting in the tribological pair.

Materials and methods

Samples preparation

Natural enamel samples

Three wisdom teeth without caries were used, placed in a solution of chlorhexidine 0,2%, and separated in four parts by using a diamond saw. The teeth were cut perpendicularly in four parts resulting in 15 pins and fixed in holders by acrylic resin (PATTERN RESIN™ LS© GC America Inc.) (Fig. 1).

In order to characterise surface roughness of the natural teeth a 3D surface profilometer (SENSOFAR Plu Neox) was used. The roughness measurements were made according to ISO 4287:1997. The Gaussian filter was applied to evaluate

the roughness parameters [27]; this filter uses appropriate mathematical algorithms or electronic conditioning, removes or reduces unwanted data in order to analyse only the wavelengths of interest [28, 29]. The cut-off used in this investigation is in accordance with the ISO 4288-1997 recommendations. For this reason, the used cut-off has been of 0.08 mm which correspond to an evaluation length of 0.4 mm (equivalent to five times the cut-off). The roughness (Ra [μm]) has been detected along the two mutually orthogonal directions (x and y), in three different areas of the acquired zone in order to obtain a statistically acceptable value.

Dental materials samples

Four specimens of composite zirconia were realized. The four specimens were obtained through sintering at 1500 °C using 3 M™ Lava™ Esthetic Zirconia discs. These discs are composed of high purity zirconium dioxide stabilized with 5% mole of yttrium. They comply with ISO 6872: 2015, type II, class 4 CTE (25–500 °C): $10 \pm 0.5 \cdot 10^{-6} \text{ K}^{-1}$ [30].

The restorations were obtained with the use of dental CAD software Rhinoceros® and then turned into milling paths by the CAM software hyperDENT®. The raw blocks were machined with milling machines, CORiTEC 350i, suitable for processing pre-sintered zirconium oxide. Once milled, the restorations were synthesized in an oven (Dekema - AUSTROMAT μSiC), suitable for zirconium oxide with the proper thermal cycle [31]. This type of material possesses a strength of 800 MPa and a high translucency optimized for

Fig. 4 a Schematic representation of the assembly of the tribological pairs in reciprocating tribometer; b Orientation of the tooth in the holder during the test

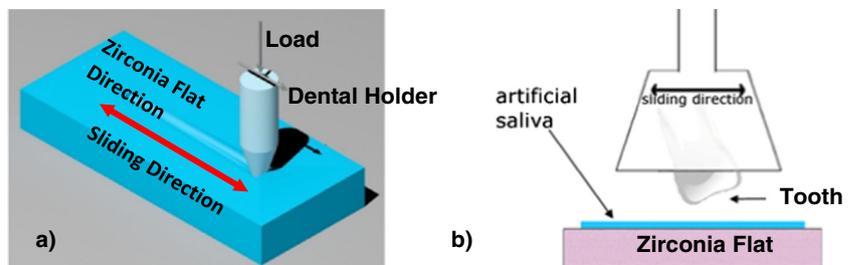


Table 1 Chemical composition of the used artificial saliva according to Mayworm et al., 2008

Chemical composition	
NaCl (g)	0,4
KCl (g)	0,4
CaCl ₂ ·2H ₂ O (g)	0,795
NaH ₂ PO ₄ ·2H ₂ O (g)	0,78
Na ₂ S·9H ₂ O (g)	0,005
Urea (g)	1
Distilled (ml)	1000

crowns and aesthetic bridges with full profile. The specimens were milled with dimensions of 25 mm × 25 mm × 5 mm to fit in the lower holder. The specimens were polished sequentially with a three step system for zirconium oxide (Isodiamant): green coarse, blue refining polisher and yellow high shine polisher.

Friction and wear tests

Tribological tests were performed using a Reciprocatory Friction Monitor TR-BIO 282 (Ducom Instruments, Bangalore, India), following a well-established procedure [32–34]. This test works fine on many materials and is a very good simulation of a reciprocating motion, such as the relative sliding that occurs during chewing. The testing apparatus constantly monitors and records the frictional force through a load cell positioned below the flat specimen holder.

The normal force in these tests was 20 N, and they last 60 min. The stroke length was 2 mm, according to the range of displacement used in the works of [35, 36] and frequency oscillation 5 Hz (harmonic alternative motion). With this setup, the total sliding distance was equal to 72 m. Every test was realized at room temperature (20 ± 1 °C), in laboratory air at controlled levels of relative humidity (55 ± 5%). Two different tribo-couples were examined: natural tooth vs. zirconia (Fig. 2) and zirconia vs. zirconia (Fig. 3), to analyse the tribological behaviour of prosthesis and natural teeth.

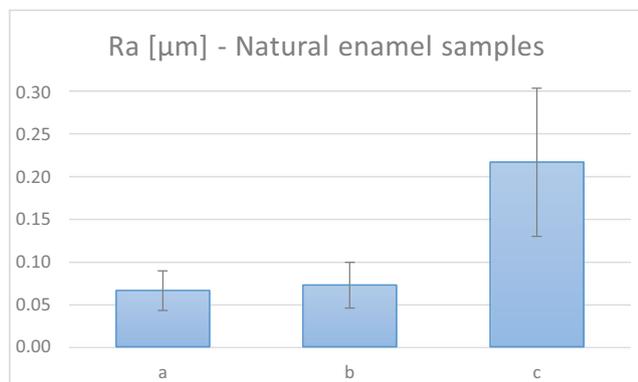


Fig. 5 The results of the measured surface roughness of the natural enamel samples

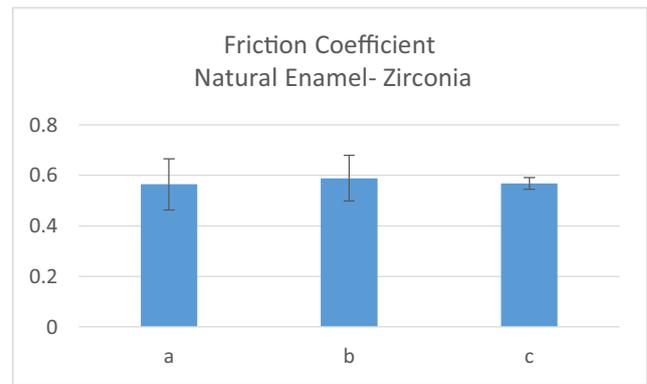


Fig. 6 Friction coefficient of natural enamel vs. Zirconia

In the second tribo-couple a zirconia ball of 10 mm diameter, clamped on the holder, was alternatively moved by a linear actuator, rubbing against a flat specimen of zirconia. The test was carried out three times for the repeatability. In this case of the tribo-couple, natural tooth and a zirconia flat specimen, the tooth was clamped to the moving holder, the orientation of the tooth was chosen to obtain a concentrated contact (Fig. 4b).

All the tests were carried out with the interposition of artificial saliva between the sliding surfaces. The chemical composition of the used artificial saliva is in accordance with the study of Mayworm et al., 2008, and it is shown in Table 1 [16].

Wear mass loss and characterization of the worn surfaces

A gravimetric analysis was executed to evaluate the wear, in term of mass loss [35]. Before each test the two counterparts were cleaned using ethanol and let dry in ambient air, then weighted on a precision scale (resolution of 0.01 mg). A topographic analysis followed each reciprocating tribotest, it

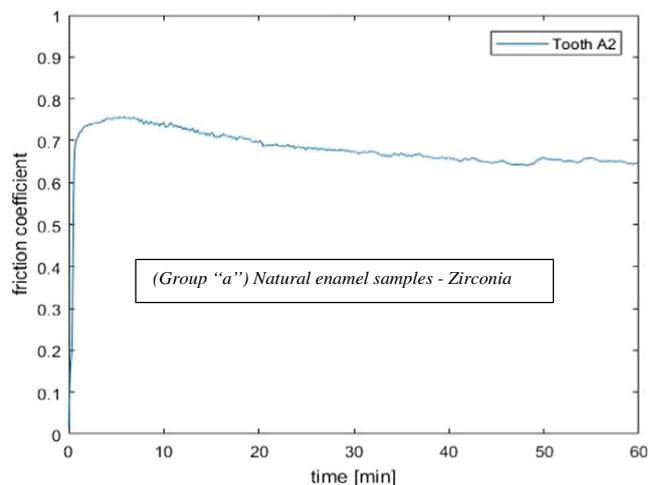


Fig. 7 Evolution of the COF of the natural tooth belonging to the group “a” that correspond to higher mean value of the COF

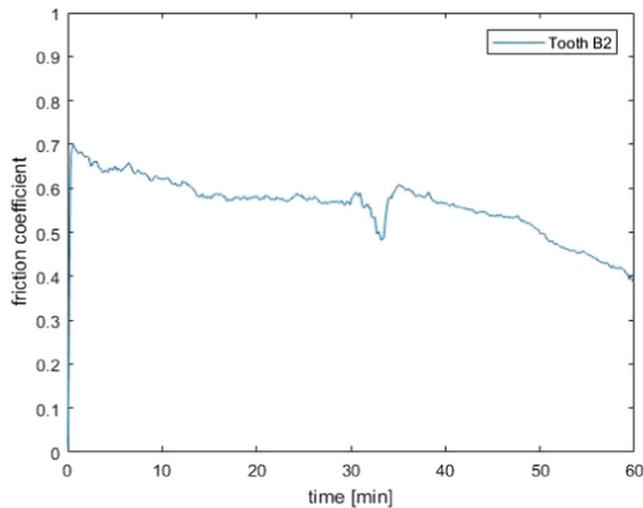


Fig. 8 Evolution of the COF of the natural tooth belonging to the group “b”

was carried on a 3D non-contact optical profiler, PLuS neox (Sensofar, Terrassa, Spain), which can act as interferometric or confocal microscope [37]. The worn surfaces, cleaned from debris, were scanned using a magnification of 20 X. The scans returned isometric and contour images, which provided rapidly qualitative information on the worn area [38], whereas quantitative information, such as the maximum wear depth, were extracted from the topographies analyzed through Spip™ (Scanning Probe Image Processor) Image Software.

Results and discussions

Natural enamel samples

The results of the measured surface roughness of the natural enamel samples are showed in Fig. 5. The results are

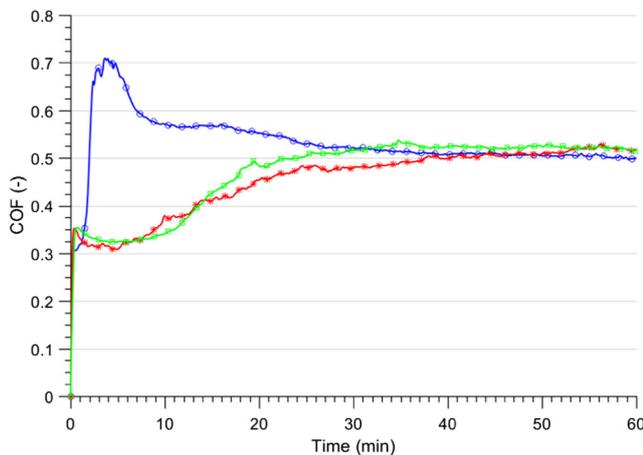


Fig. 9 Friction coefficient evolution for zirconia vs. zirconia

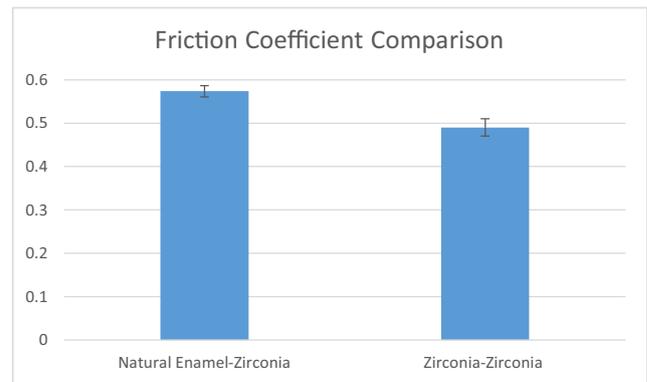


Fig. 10 Friction coefficient comparison

presented for the three enamel samples used for the tribological test (Fig. 1a).

From the roughness analysis, we can verify that the roughness values of teeth belong to group “c” have and higher value than sample “a” and “b”. This tendency may be indicative of higher wear of teeth belong to group “c” and will be confirmed by the 2D topographies.

Friction and wear tests

Natural enamel vs zirconia

Figure 6 shows the results for the friction coefficient (COF) value in the case of the tribo-couple Natural Enamel vs. Zirconia for the three groups of natural teeth tested (Fig. 1a). The high mean value corresponds to the group “b” and it is equal to $0,589 \pm 0,09$. It is important to indicate that the higher value for the COF has been found for a portion of the natural tooth belonging to the group “a” (Fig. 1a) and the Fig. 7 shows the evolution of the COF in this case.

In this case the friction coefficient presents higher values in the beginning of the tests, afterward it goes rapidly to a stable value, which ranges from 0.6 to 0.7. In one (group “b”) test it

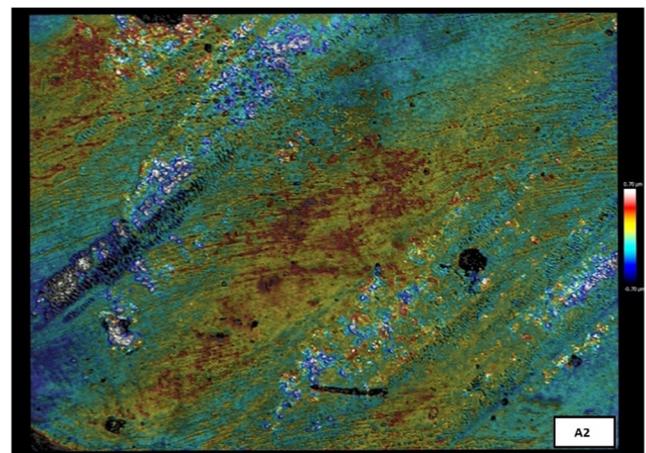


Fig. 11 2D topographies of wear surface related to tooth of group “a”

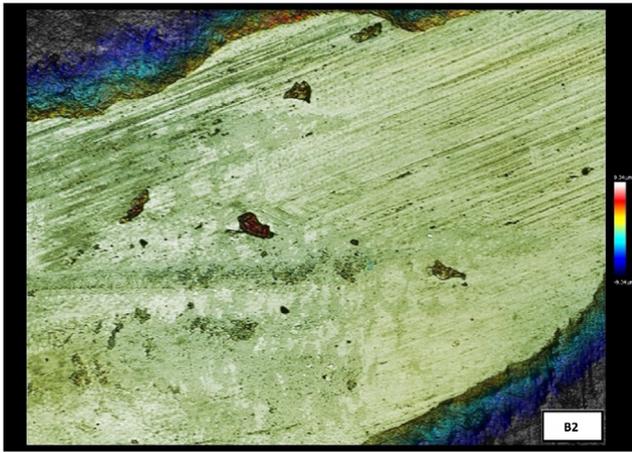


Fig. 12 2D topographies of wear surface related to tooth of group “b”

was found a decreasing trend during the final part, this can be ascribed to the smoothing of the tooth and the consumption of the enamel layer (Fig. 8).

Zirconia vs zirconia

In Fig. 9 it is shown the evolution of the COF during the tests realized with zirconia vs. zirconia. In these tests, the variation of the initial-transient phase is more evident than in the formers. By the way, after 20 min of running, the COF reach a steady stable value, which is settle around 0.5. Furthermore, it was possible to obtain the evolution of the friction coefficient during the roundtrip of the upper part on the zirconia specimen.

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In Fig. 10, the summary of the investigation on the COF is shown. It is clear that, the minimum value of the COF is obtained in the case of Zirconia vs. Zirconia tribo-couple, corresponding to 0.49 ± 0.03 . Whereas, for the natural enamel-Zirconia tribocouple this value is 0.57 ± 0.02 . However, both COF are similar.

Wear mass loss and characterization of the worn surfaces

Regarding the gravimetric analysis, performed to acquire the wear rate, it was only possible to find a weight variation of Zirconia in the tests with teeth as counter bodies. In the other cases, i.e. using the ball of zirconia, the high-resolution scale did not weight any variations. However, a mean value of 0.5 mg was found as mass loss on the teeth counter body. Therefore, it is possible to assess a very low wear rate of Zirconia when coupling together a natural tooth with an artificial one, which is even lower when the contact is between two artificial zirconia teeth.

Figure 11 show the worn surface of tooth of the “a” group (Fig. 1a) subjected to tribo test. In this the case the wear damage of the enamel is dominated by abrasive wear. It is possible to note that the higher surface damage is of the tooth A2 that corresponds the higher COF (Fig. 7) with formation of rough parallel furrows according to the higher friction coefficient.

Figure 12 show the worn surface of tooth of the “b” group (Fig. 1a) subjected to tribo test. In this case the main wear mechanism is abrasive wear, with formation of parallel

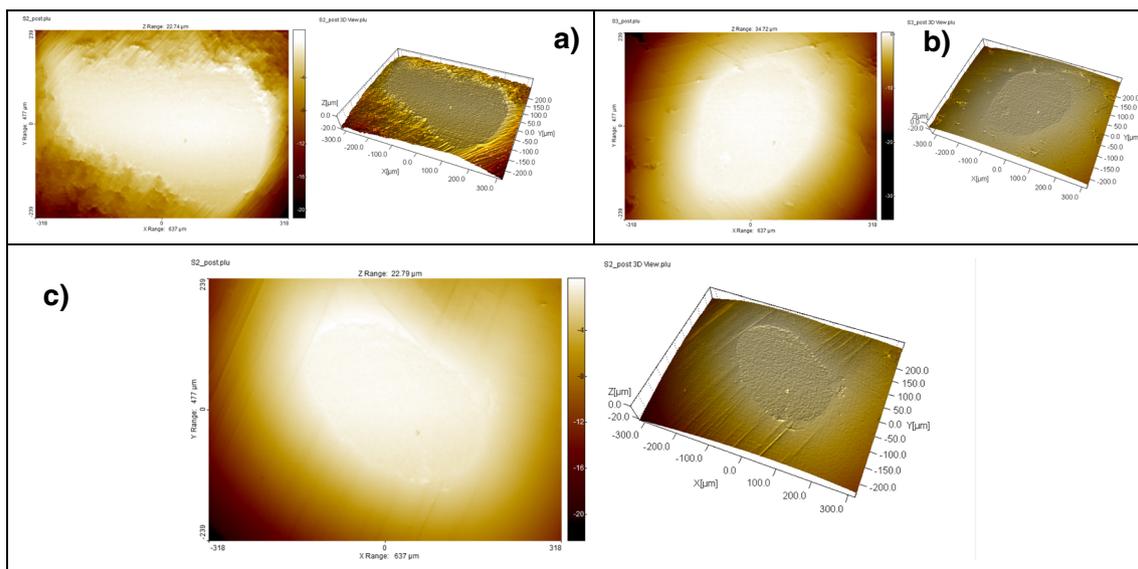


Fig. 13 2D and 3D topographies of the worn surfaces acquired by confocal instrumentation for the Zirconia-Zirconia tribo contact/SimplePara>

furrows that present small depth because of the lower friction coefficient.

Moreover, in all natural enamel worn surface, the surface is also characterized by small cracks and reticular cracks that confirm the presence of fatigue wear too. The presence of this cracks is in agreement with what seen in SEM analysis related to polished Zirconia in the study of Wang et al. [35]. Abrasive wear results as the main wear mechanism acting on tooth enamel in this condition. For this reason, through further investigations, a wear model could be developed by taking into account the penetration of the micro asperities of the harder material (zirconia) into the softer (enamel).

In Fig. 13 there are represented the 2D and 3D topographies of the worn surfaces acquired by confocal instrumentation.

The worn areas present typical signs of adhesive/abrasive wear in all the different cases analysed by 3D topography, being these surfaces characterized by scars parallel to the sliding direction. On the surface of the worn zone there are different signs of pitting, two of them clearly visible in the upper part of the image. These pitting features reveal the presence of high localized Hertzian pressure.

Figure 13 A shows the worn area of the first test coupling zirconia ball and zirconia counter face, in this case the equivalent diameter is 405 μm . Whereas Fig. 13 B and C show the wear scars on the second and the third ball, having respectively 295 μm and 305 μm diameter.

Conclusions

Wear of the teeth and of the restorative materials are clinical problems in dentistry. In fact, the tribological behavior and therefore the wear of the teeth is an important consequence of the occlusal interaction. Dental wear if not controlled could cause a low masticatory function with a concomitant reduction in quality of patient life. For these reasons the tribology of the dental materials is of fundamental importance in order to understand the mechanism and the factors that affect the friction and wear mechanisms. For these reasons, in this study the tribological performances in the tooth-to-tooth contact and material-to-natural tooth contact (zirconia vs. zirconia and natural tooth vs. zirconia) were investigated by using a reciprocating tribometer under lubricated conditions. In order to simulate the real conditions of the mouth the chosen lubricant was artificial saliva. The wear mass loss evaluation was evaluated by using a gravimetric method but with the used test parameters no significant results were obtained on Zirconia. The results on the wear mass loss show a very low wear rate of Zirconia both coupled with Zirconia, both with natural tooth; while a mean value of 0.5 mg was found on natural tooth coupled with Zirconia. The results, in terms of COF, are similar in the case of Zirconia vs. Zirconia tribo-couple,

corresponding to 0.49 ± 0.03 and in the case of natural Tooth-Zirconia couple this value is 0.57 ± 0.02 . This rate is even lower when the contact is between two artificial zirconia crowns. This study represents a first step toward an extensive tribological characterization of new artificial dental materials in order to fully understand differences in tribological behavior principally against natural teeth. This allows to choose restorative materials with the objective to minimize wear phenomena on dental tribosystems natural tooth/artificial material useful for all patients but in particular for who suffers from bruxism.

Compliance with ethical standards

Conflict of interest Alessandro Ruggiero declares that he has no conflict of interest. Roberto D'Amato declares that he has no conflict of interest. Ludovico Sbordone declares that he has no conflict of interest. Fernando Blaya Haro declares that he has no conflict of interest. Antonio Lanza declares that he has no conflict of interest.

This article does not contain any studies with human participants performed by any of the authors.

This article does not contain any studies with animals performed by any of the authors.

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