Retention force of differently fabricated telescopic PEEK crowns with different tapers

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To assess the retention force between primary and secondary PEEK crowns made by different fabrication methods. Primary crowns with different tapers (0°, 1°, and 2°) were fabricated and secondary crowns that were either milled from breCam BioHPP blanks, pressed from pellets (BioHPP Pellet) or granules (BioHPP Granulat) were produced. Each specimen was measured 20 times in a pull-off-test and results were analyzed using 2-/1-way ANOVA and linear regression analyses ($p<0.05$). Within 0° tapered crowns milled secondary crowns showed lower retention forces compared to pressed pellet crowns. Crowns with a 1° taper, however, showed no impact of the fabrication method on retention force. At a 2° taper, granular pressed crowns displayed lower values than their milled counterparts. Within the milled group, a 0° taper showed lower retention values than the higher tapers, whereas in the pressed groups, no impact of taper angle on retention force was found.

Keywords: PEEK, Tapered crowns, Retention force, CAD/CAM, Double crowns

INTRODUCTION

Polyetheretherketone (PEEK) represents a modification of the main thermoplastic high-performance polymer group polyetheraryl ketone (PEAK). It is a high-temperature thermoplastic polymer, consisting of an aromatic backbone molecular chain, interconnected by ketone and ether functional groups[1)]. The melting point is at roughly 343°C, the density accounts for 1.3–1.5 g/cm[1)]. Besides its high thermal stability, PEEK is characterized by a high hardness[2)] and a lower water absorption and solubility[2)]. Therefore, PEEK is an interesting alternative to traditional alloy and ceramic dental materials.

There are two ways of processing PEEK: Milling from computer aided design/computer aided manufacturing (CAD/CAM) out of blanks or vacuum pressing. With regard to the latter, the market provides either industrially pre-pressed pellets or a granular form. The procedure is similar to the alloy cast process, which includes a preheated muffle with melted PEEK that is then placed in a vacuum-pressing device. In this context, a recent *in vitro* study already found that the fabrication method may influence the fracture load of three-unit fixed dental prostheses (FDPs) and that CAD/CAM milled FDPs presented higher fracture load results compared to pressed FDPs from granular. CAD/CAM milled FDPs and FDPs pressed from pellets showed spontaneous and brittle fractures near the pontic area without deformation. On the other hand, FDPs pressed from granular material showed some plastic deformation without fracture. CAD/CAM fabricated FDPs and those pressed from pellets showed higher Weibull moduli than FDPs pressed from granular. Furthermore, this study showed that industrial pre-pressing of blanks, such as CAD/CAM or pellet blanks increased the mechanical properties and reliability of PEEK restorations[3)]. Thus, there already is evidence that the fabrication method may significantly influence the mechanical properties of PEEK.

Another study suggested that biofilm formation on the surface of PEEK is equal to or even lower than on prosthodontic materials such as zirconia and titanium[4)]. Nevertheless, the low surface energy generates a resistance to surface modifications by different chemical treatments[5,6)]. Many studies showed that a pre-treatment using sulfuric acid increases the surface energy and thus improves the bonding properties to dimethacrylate-based resin composites[7-10)]. However, highly concentrated sulfuric acid is hazardous for clinical chair-side applications and therefore not recommended. One recent publication investigated the retention force of differently pre-treated PEEK crowns, which were adhesively bonded on dentin abutments. The authors reported reliable results when a combination of air-abrasion with a MMA-based adhesive system such as visio.link or Signum PEEK Bond was used[8)]. Therefore, after the major problems of bonding to other resin materials were solved, many clinical indications of this material have become the focus of development, research and clinics.

In prosthetic dentistry, PEEK has been used as implant, provisional abutment, implant supported bar, clamp material in the field of removable dental

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prostheses (RDP) and for FDPs such as bridges or crowns[11-14]. In general, the literature describes good long-term survival rates and a high degree of patient comfort concerning telescopic crowns[15]. These double crowns are effective for retaining removable partial dentures due to the fact that they more effectively transmit the occlusal forces along the direction of the long axis of abutments. Furthermore, they provide guidance, support and protection from movements that might dislodge the removable partial dentures[16]. Former studies already investigated the influence of taper angle and a number of pull-offs with regard to the retention force of double crowns from noble metal alloys[15,17]. But the respective behavior of a relatively soft material like PEEK with a low elasticity modulus of 3 GPa remains to be examined. Many dentists in private practice are, however, already using PEEK material successfully in daily clinical practice for these indications. Despite this, according to the authors' knowledge there are currently no studies on either this topic or the retention force of PEEK double crown systems. In this context it is also unknown whether the fabrication method of PEEK double crowns and the taper have an influence on the retention force.

Therefore, the aim of this study was to assess the retention forces of secondary PEEK crowns, which were made by different fabrication methods with three different tapers. The tested null hypotheses were that

i. The number of pull-off cycles shows no impact on the retention force values
ii. The fabrication method of secondary crowns from PEEK shows no impact on the retention force values
iii. Different tapers also display no impact on the retention force values.

MATERIALS AND METHODS

The telescopic crowns used in the present investigation differed with regard to the following two characteristics:

A. Materials and fabrication methods

i. breCam BioHPP blank (bredent, Senden, Germany, LOT 394172) for CAD/CAM milling
ii. BioHPP Pellet (bredent, LOT 393554) for pressing of PEEK pellet
iii. BioHPP Granulat (bredent, LOT 379806) for pressing of PEEK granular

B. Degree of taper

The taper of the primary crowns was set at 0°, 1°, 2°. The experimental design therefore resulted —based on A and B— in 9 different test groups with 10 specimens each. To avoid any operator influence all specimens were made by one qualified person. The random division of the secondary crowns is illustrated in Fig. 1.

Fabrication of the primary crowns

For the fabrication of the crowns, a standardized anatomically supported base metal alloy model (Remanium GM800+, Dentaurum, Ispringen, Germany, LOT 936) with an elasticity modulus of 230 GPa was used. The abutment tooth was modeled according to a mandibular molar crown with a height of 6.9 mm and a mesio-distal dimension until the preparation margin of 8.2 mm and oro-vestibular of 7.8 mm (Fig. 2). In total, 30 abutment models were fabricated using a casting method. Afterwards, each abutment model was scanned and three master STL-files of the primary crowns with a taper of 0°, 1° and 2° were designed (Fig. 3; Ceramill Mind 2.3.0, AmannGirrbach, Koblach, Austria) and in each case, *i.e.* 0°, 1° and 2°, 10 primary crowns were milled (ZENO Tec System, ZENO 4030 M1, Wieland+Dental, Pforzheim, Germany). The 30 primary crowns were designed using the same parameters with a cement spacer thickness of 0.05 mm starting at 1 mm. The wall thickness was set at 1.8 mm. In order to ensure good comparability between the different groups, all primary crowns had a

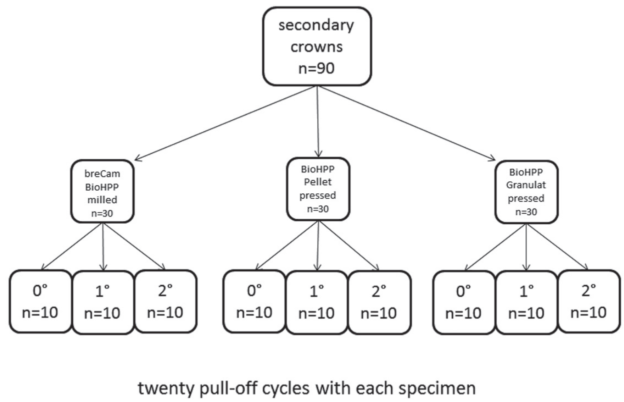

Fig. 1 Division of the secondary crowns.

Fig. 2 Abutment tooth, cast, made of base metal alloy.

comparable friction area of 175 mm^2.

After fitting of the crowns with occlusion spray (Arti-Spray, white, BK 285, Dr. Jean Bausch, Cologne, Germany), the crowns were adhesively cemented on the base metal alloy abutments using a self-adhesive resin cement according to the manufacturer's instruction (RelyX Unicem 2, 3M ESPE, Seefeld, Germany, LOT 509981). Afterwards, the primary crowns were embedded in a stone model in order to maintain the same path of insertion for all primary crowns (Hera Octastone CN, Heraeus Holding, Hanau, Germany, LOT 3252822). The primary crowns got their precise taper of 0°, 1° and 2° by grounding and milling (Profile bur tungsten carbide with relief, bredent, REF F1372H15 (0°), REF F2002K29 (1°), REF F2002H23 (2°)), using an electric, high-speed hand-piece (W&H Perfecta 900, W&H Dentalwerk Bürmoos, Bürmoos, Austria), mounted in a surveyor device (parallelometer F4 basic, DeguDent, Hanau, Germany). Afterwards, all primary crowns were polished with silicone polisher (Komet Dental, Lemgo, Germany, LOT 307723), brushes (Komet Dental, LOT 226983) and a polishing paste (Abraso-Starglanz asg, bredent, REF 52000163,) using a handpiece.

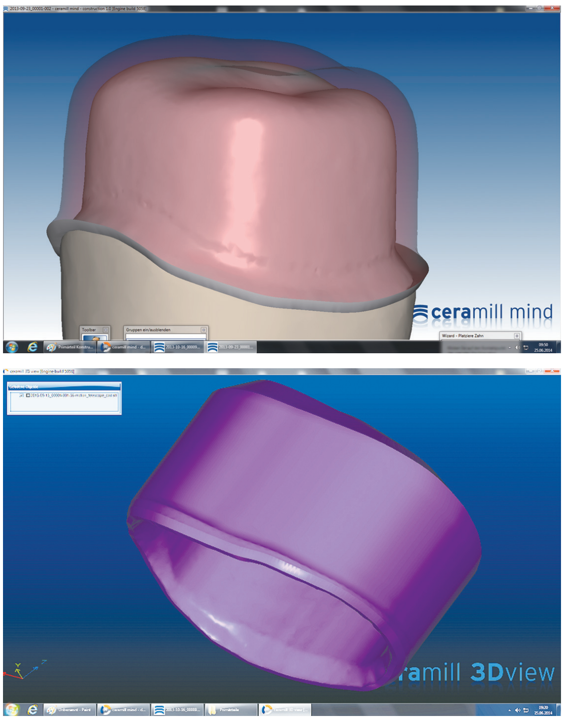

Fig. 3 Screenshot: primary crown construction designed with Ceramill mind.

Fabrication of the secondary crowns

Each primary crown was individually scanned (Arti-Spray, white, BK 285, Dr. Jean Bausch; Ceramill map 300, AmannGirrbach) and the secondary crowns were designed and adapted in the horizontal and vertical dimension with a minimal thickness of 1.0 mm. For this purpose, the software parameters "Add. distance occl." were adjusted on 0.5 mm and "Add. distance x/y" on −0.02 mm (taper 1° and 2°) and 0.03 mm (taper 0°), respectively. For an optimal fit "Add. distance x/y" was tested in 0.01 mm increments. Since no common value could be identified for all tapers, different values of "Add. distance x/y" had to be used in order to get a perfect fitting between each primary and secondary crown as determined preliminary tests. On the occlusal surface of the secondary crown a hole was generated mimicking a roof ridge for later retention force tests (Fig. 4).

In this way, 30 secondary PEEK crowns (breCAM BioHPP, bredent) and sixty wax crowns (Add. distance x/y 0.02–0.05 mm) (breCAM.wax, bredent, LOT 382697) were fabricated (ZENO 4030 M1, Wieland+Dental). The secondary crowns in wax were then randomly divided into two groups (n=30 per group) and pressed using either PEEK pellets (BioHPP Pellet, diameter: 25 mm,

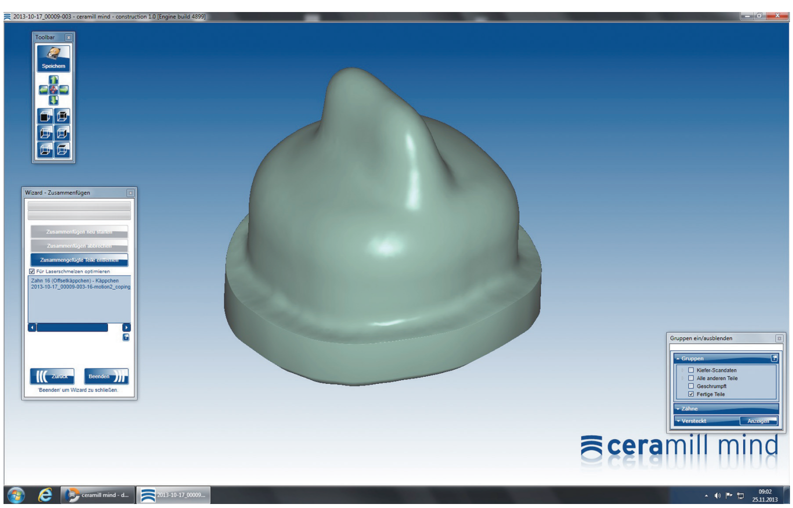

Fig. 4 Screenshot: secondary crown construction with generated clamp.

15 g) or PEEK granular material (BioHPP Granulat). The wax crowns were embedded (Brevest for 2 press investment material, bredent, LOT 1) in a muffle according to the manufacturer's instruction. After 25 min, the muffle was heated up to 850°C for 60 min, then cooled to 400°C at a cooling rate of 8°C/min and kept for 60 min. Subsequently, the pre-heated muffle was filled with PEEK granular/pellets, and kept in the preheating oven for 20 min at 400°C. As the next step, crowns were pressed at a pressure of 4.5 bar in a special vacuum-pressing device (Vacuum pressing device for 2 press, bredent). For this pressing process, one plunger (for 2 press filler, 20 mm/26 mm, bredent, LOT 397014) for each muffle was used and the pressing process lasted for 25 min. After cooling, the investment material was removed in a blasting unit (Fine-blaster type FG 3, Sandmaster, Zofingen, Switzerland) using 50 µm Al_2O_3 (Hasenfratz, Sandstrahltechnik, Aßling, Germany) at a pressure of 2 bar. The secondary crowns were finished using a silicone polisher (Ceragum Wheel, bredent, REF PRKM22000) and polishing paste (Abraso-Starglanz asg, bredent, REF 52000163) for 3 min. Then, the secondary crowns were ultrasonically cleaned in distilled water for 5 min (Ultrasonic T 14, L&R manufacturing, Kearny, NJ, USA). The adaptation process was carried out with cross cut burs (Komet Dental, LOT 277889). Finally, each secondary crown got the same final processing by polishing 3 min with silicone polishers (Ceragum Wheel, bredent, REF PRKM22000), polishing brushes (Komet Dental, LOT 226983) and polishing paste (Abraso-Starglanz asg, bredent, REF 52000163). One calibrated operator (VS) fabricated all primary crowns and performed the construction as well as the adaption of the secondary crowns in order to standardize the technical baseline situation, which might influence the retention force.

Retention force measurements

The specimens were placed in a universal testing machine (Zwick 1445, Zwick, Ulm, Germany) and loaded with a crosshead speed of 50 mm/min. Before each measurement, all secondary crowns were set on their respective primary crown for 20 s applying a load of 5 kg weight on top[17,18]. Then, the secondary crown was held by a hook, allowing the whole system to self-align. Specimens were positioned in the jig with the occlusal surface perpendicular to the loading direction (Fig. 5). The jig was then attached to the load cell and pulled apart by an upper chain. Twenty pull-off cycles of each specimen were carried out in each case using artificial saliva (Glandosane, cell pharm, No. 9235461109) and mean retention force were computed.

Statistical analyses

Linear regression in each test group was applied to disclose the association with pull-off cycles and retention force. For the data analysis of mean retention force, Kolmogorov-Smirnov and Shapiro-Wilk tests were used to verify the normality of data distribution of all data measured. Descriptive statistics (mean, standard deviation (SD), 95% confidence intervals (CI), minimum, median and maximum) were computed. Significant differences between the groups were tested with 2-way (taper type with three levels and fabrication method with three levels) and 1-way (test group with nine levels) ANOVA, followed by the Tukey-HSD post-hoc test. All statistical tests were performed with IBM SPSS (Version 20; IBM). Differences were considered statistically significant when p was <0.05.

Fig. 5 Specimen positioned in a Universal Testing Machine, chain clipped on secondary crown clamp.

RESULTS

The number of pull-off cycles led to a significant decrease in retention force values only in the group with secondary crowns made of pressed granular material with a 0° (p=0.02) and 1° taper (p=0.042) as well as when pressed pellets were used at a 0° taper (p=0.004) (Table 1).

According to the Kolmogorov-Smirnov and Shapiro-Wilk tests all mean retention force value groups were normally distributed, therefore the data were analyzed using parametric tests. The global results of the descriptive statistics are presented in Table 1. Data are shown in Fig. 6. The 2-way ANOVA interaction between the taper type and PEEK fabrication method for the secondary crowns was highly significant (p<0.001). The main reason for interaction was found to be the milled group with a 0° taper (breCam BioHPP milled) which showed a different behavior with respect to the retention force than the other 0° taper angles of the pressed material groups. Due to this interaction, the fixed effects could not be directly compared. Consequently, a 1-way ANOVA with a factor test group with nine levels was computed.

The milled group with 0° taper showed the lowest retention force (p<0.042) compared to all other test

Table 1 Descriptive statistics of mean retention force measurements (N), results of the one-way ANOVA for the test group factor together with estimates of slopes and corresponding *p*-values provided by the linear regression for all tested groups

	Mean±SD	95% CI	Min/Med/Max	Slope	*p*
taper of 0°					
breCam BioHPP milled	4.29±1.48 $^{a/A}$	(3.1;5.4)	2.1/4.5/6.8	−0.026	0.157
BioHPP Pellet pressed	14.9±7.62 $^{a/B}$	(9.3;20.5)	4.1/15.6/25.1	−0.270	0.004
BioHPP Granulat pressed	11.64±5.74 $^{a/AB}$	(7.4;15.8)	2.7/9.9/21.3	−0.162	0.02
taper of 1°					
breCam BioHPP milled	21.12±9.17 $^{b/A}$	(14.4;27.7)	9.2/21.2/34.8	−0.093	0.415
BioHPP Pellet pressed	17.46±7.13 $^{a/A}$	(12.2;22.6)	5.8/17.8/28.1	−0.100	0.262
BioHPP Granulat pressed	15.11±8.05 $^{a/A}$	(9.2;20.9)	7.1/11.3/30.9	−0.204	0.042
taper of 2°					
breCam BioHPP milled	29.06±9.37 $^{b/B}$	(22.2;35.8)	6.8/32.5/37.8	−0.150	0.211
BioHPP Pellet pressed	19.73±4.21 $^{a/AB}$	(16.6;22.8)	13.6/19.8/26.2	−0.106	0.071
BioHPP Granulat pressed	17.08±9.29 $^{a/A}$	(10.3;23.8)	6.0/12.9/31.8	0.147	0.199

^{a,b} differences between different tapered crowns within one fabrication method group
^{A,B} differences between the fabrication method groups within one taper type

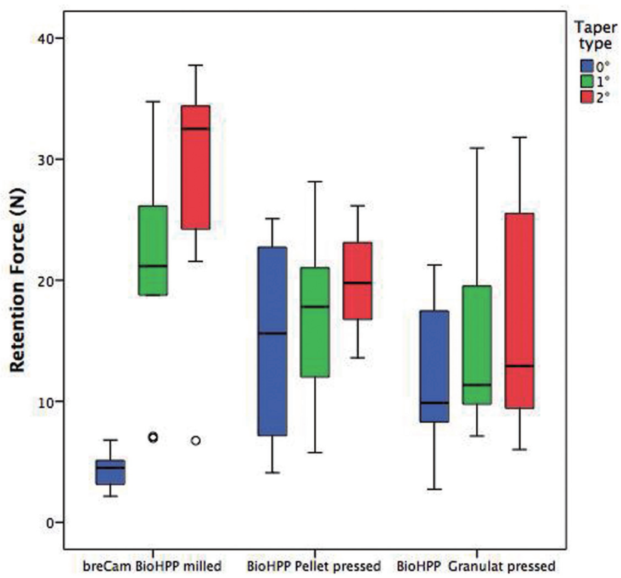

Fig. 6 Boxplot of all tested retention force groups.

groups except for the pressed granular material group with a 0° taper. In contrast, the milled group with a 2° taper showed the highest retention force ($p<0.019$) when compared to all other test groups except for the pressed pellet group with a 2° taper.

Within the group of crowns with a 0° taper, milled secondary crowns showed significantly lower retention forces compared to those of the pressed pellet group ($p=0.042$). Crowns with a 1° taper showed no impact of the fabrication method on retention force results ($p>0.662$). Among crowns with a 2° taper, secondary crowns made from pressed granular material displayed significantly lower values than milled ones ($p=0.013$).

Within the milled crown group, a taper of 0° showed significantly lower retention forces than tapers of 1° and 2° ($p<0.001$). Within both pressed groups, however, no impact of the taper angle on retention force was observed ($p>0.769$).

DISCUSSION

This study examined the effects of different fabrication methods of PEEK subjected to different kinds of taper on retention force values. The obtained results showed that taper as well as fabrication method have a significant impact on retention force values.

The influence of pull-off cycles investigated by the linear regression showed a decrease of retention force in three groups, the pressed granular material with 0° and 1° taper and the pressed pellet group with 0° taper. For these three, the retention force decreased already during twenty pull-off tests. Therefore, the first null hypothesis has to be rejected. A possible explanation for this observation, especially in the pressed groups, could be a lower elasticity modulus of the pressed PEEK material compared to milled PEEK material. Pressed PEEK materials are softer, especially when fabricated from granular forms[3]. Due to this fact, a slight plastic deformation of the pressed PEEK material may lead to the bending of the secondary crown and thus to a decrease of the retention force values during the first twenty pull-off cycles already. Before measuring the twenty pull-off cycles the authors aimed to produce more or less the same initial situation for each pair of primary and secondary crown by polishing every secondary crown the same way for 3 min. However, this standardized initial situation ensured not necessarily the same initial values of retention force. Due to these potentially different initial values, already at this stage the effect of the different fabrication methods on retention force may emerge. The period of twenty pull-off cycles corresponds to approximately ten clinical days with insertion and removal two times a day. This laboratory study tried to elaborate whether the material can withstand such an initial phase and may therefore be suitable for double crown technique and thus be able to achieve robust retention force values. But the induced simulated stress does not mimic the long-term exposure to thermal and mechanical stress, which occurs under daily wear. This is, of course, a shortcoming of this investigation. However, this was not the primary goal of this screening study. A recent study, which tested PEEK and cobalt chromium (CoCr) frameworks of RPDs, showed that PEEK achieved good results under clinical conditions in prosthetic dentistry[19]. After a wearing time of four weeks the patients' periodontal status, preferences and the number of adjustments were examined. Although seven of twelve patients preferred CoCr, PEEK obtained less BOP, Plaque Index and pocket depths. Unfortunately, no data on stability and mechanical behavior were recorded.

The second hypothesis has to be rejected as well, because the results showed statistically significant differences between the differently fabricated types with regard to retention forces. Especially the pressed groups with comparable retention force values differed from the milled group. This difference can be the result of a different processing chain. It can be assumed that the pressing process included a more difficult sequence with a higher number of potential sources for errors. Especially the rather unpredictable expansion coefficient of the investment material caused incalculable dimensional changes hence interacting with the telescopic fitting. The pre-heating process depends on the individual heating properties of the oven. The contraction of the material during the cooling time changes the fitting values as well, even at the inner surface. The inner surface which was roughened by airborne particles to remove the investment material also might have changed the retention forces[15] and even the calculated fitting. Besides that, the heating process potentially influenced the special chemical structure of the PEEK material itself. The ratio of the amorphous and crystalline fractions in PEEK is modified by several heating processes that occur especially in the PEEK pellet converting process. Generally, the PEEK granular material is the raw material being extruded into PEEK blanks and PEEK pellets. After the industrial manufacturing of PEEK, the pellets, in contrast to PEEK blanks, are heated in an oven to be pressed into their final form. Due to the modified amorphous and crystalline ratio, material properties as well as telescopic fitting can be influenced.

On the other hand, the milling process may be influenced by the software program, which provides small path differences of the milling machine. Small path differences offer a smooth inner surface area resulting in less postprocessing, but they are difficult to achieve. As a matter of fact, the software program had to be revised in order to support the right milling angle on the inner surface. To prevent manual postprocessing the development of adapted parameters like cement gap, horizontal and vertical dimension is indispensable. Even the adaption of parameters can be seen as an indicator regarding the influence of the fabrication method.

The third null hypothesis relating to the taper angle must also be rejected because the data showed that the taper influences the retention force of the milled group. This study defined the taper angles of 0°, 1° and a maximum taper of 2°. The reason for the latter maximum value was that Ohkawa and co-workers suggested this range because retention was rapidly lost when the taper angle exceeded 2°[17]. Previous studies have shown that a decrease in taper angle resulted in an increase of the retention forces of double crowns[15,18]. In contrast to these findings, the results of this study showed a lower retention force in the milled group with 0° taper compared to the milled ones with 1° and 2°. Potential explanations may be differences regarding the manufacturing process within the machine and the milling process. Especially for the milling approach, parallel surface area and the insertion direction play a decisive role. This means that the milling strategy including tool changes also impacts the inner surface of the secondary crown. Furthermore, PEEK with its low elasticity modulus of 3 GPa is not comparable to the 110 GPa of noble metal alloys that are conventionally used in such studies and clinical applications. This seems to be the reason for the divergent behavior with regard to taper. On the other hand, the PEEK pressed groups were hardly influenced by the taper angle. Again, the softer material properties of pressed PEEK material could play a role. Pressed secondary crowns could slightly bend up and could tolerate small inaccuracies.

Summarizing, the physical properties of the three PEEK materials show a few differences. This study found that retention force values of crowns pressed from granular PEEK (taper 0° and 1°) decreased after twenty pull-off cycles while values of the other groups remained almost unchanged. Furthermore, the study worked out that pressed PEEK material was hardly influenced by the taper angle. This might be explained by softer material characteristics as compared to the milled PEEK. A previous study mentioned above also found that pressed PEEK, especially when pressed from granular form, was softer than milled PEEK[3].

In general —in contrast to metal double crowns— PEEK was easier to process, which facilitated especially the adaption process. In addition, PEEK was more flexible than metal but more difficult to polish. However, the polish was necessary for an optimal running surface and subsequent measurement.

In this study the measurement of retention force was performed with a crosshead speed of 50 mm/min. In literature different crosshead speed values ranging between 20 mm/min[20] and 100 cm/min[15,17] have been described. Ohkawa *et al.* tested the speeds of 0.05, 2.5, 5, 10, 25, 50 and 100 cm/min with the important finding that there was no significant difference among retention forces at each speed[17]. Therefore, we decided to use a crosshead speed with 50 mm/min, which represented a mean value of clinical relevance, which can be commonly used under most technical settings.

Because an increase in the size of friction area increases the retention force, a relatively large contact surface of 175 mm^2 was used to ensure increased retention forces to get comparable values. Thus it is probable that the retention forces of PEEK were a result of the large surface dimension and would decrease with lower surface dimensions. Therefore, if this contact surface is brought down to average size, retention force values will be optimized for using PEEK double crown as a retainer of fixed and removable dental prostheses (Table 1).

Altogether, the milled group with 2° taper obtained the highest retention force values in total. However, the milled group with 0° taper achieved the lowest retention force values, not least because of the demanding 0° taper milling process. Both pressed groups achieved comparably high retention forces, which were unrelated to the taper angle. However, it should be noted that processing PEEK from pellets or granular is obviously more laborious than processing from CAD/CAM blanks. Construction and milling are followed by embedding, heating up and the pressing process itself. So if the milling process operates properly, milling PEEK from CAD/CAM blanks might be more used and show more predictable results for clinical usage.

CONCLUSION

According to this laboratory study, milled PEEK crowns with a 0° taper showed the lowest retention force values, whereas milled PEEK crowns with a 2° taper showed the highest retention force values. For pressed PEEK crowns the taper angle had no impact on retention force. However, insights based on long-term studies are still necessary.

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