TO COMPARE THE SURFACE WEAR OF ALIGNER ATTACHMENTS FABRICATED USING DIFFERENT COMPOSITE RESINS

By

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Abstract

Aims: To evaluate the difference in surface wear between various composite materials when utilised as clear aligner attachments.

Materials and Method: A custom-made experimental apparatus was utilised, in combination with an MTS Criterion Model 42 machine (Model 42, MTS Criterion® Series 40 Electromechanical universal test systems, MTS systems corporation, Minnesota, USA), to replicate the clinical technique of aligner removal. Rectangular composite attachments were placed onto a first permanent molar within a typodont. Four commercially available nanohybrid composite resins were evaluated. These included two conventional composites, Venus Pearl (Heraeus-Kulzer, GmbH) and Tetric EvoCeram (Ivoclar Vivadent, Liechtenstein), one flowable composite Wave (SDI Limited, Bayswater, Victoria, Australia) and BracePaste an orthodontic adhesive (American Orthodontics, Sheboygan, CA, USA). A baseline 3D surface scan was taken and a second scan re-taken after a 250 and 500 aligner insertion and removal cycle. Following scan superimposition the median surface wear was assessed for each composite.

Results: Using the current model, wear occurs only on the gingival aspect of composite attachments, with the greatest wear being found on the distal corner of the gingival aspect. The median value of wear in the distal corner of the gingival aspect after 500 cycles was 0.06mm for Tetric EvoCeram (ranging from 0.05mm-0.06mm), 0.04mm for Venus Pearl (ranging from 0.03-0.05mm), 0.08mm for Wave (ranging from 0.05-0.08mm) and 0.06mm for BracePaste (ranging from 0.05-0.06mm). The amount of wear found was progressive from 250 to 500 cycles. There was a statistically significant difference in wear at the distal corner of the gingival aspect of the attachments, across the four composite resins tested (p-value = 0.013 and p = 0.024 for 250 and 500 cycles respectively). Post-hoc pairwise comparisons of the four composite resins showed that there was statistically significantly more wear of Wave composite compared to Venus Pearl (p-value = 0.006 and $p = 0.016$ for 250 and 500 cycles respectively after Bonferroni correction).

Conclusion: Based on the current *in vitro* model of aligner insertion and removal the distal gingival surface of the attachments showed the greatest wear. The wear of Wave was statistically significantly ($p < 0.05$) greater than Venus Pearl. Clinically, the amount of wear would probably not be significant.

Dedication

I would like to dedicate this research project
to my late Father, who would have taken great joy in reading this.

Acknowledgements

I would like to thank my research supervisors, Professor Khambay and Emile Habib for their ongoing support with this thesis. I would like to acknowledge the funding received from DB Orthodontics, by way of experimental materials.

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LITERATURE REVIEW

1.1 Introduction

In recent years there has been a dramatic increase in the number of adults seeking orthodontic treatment and an increase in requests for aesthetic orthodontic appliances. There are a wide range of aesthetic appliances available on the market, including lingual appliances, tooth-coloured fixed appliances and clear aligners (Kundal and Shokeen, 2020). Each of these appliances have their perceived benefits and limitations, but by offering a transparent and removable option clear aligners have grown in popularity with patients. In addition, dentists and orthodontists also appreciate the ease of use and patient acceptability of clear aligners (Meade *et al.*, 2024).

Clear aligners are active, removable orthodontic appliances made from clear, thermoplastic materials. There are a range of materials used for clear aligners, including polypropylene, polycarbonate and thermoplastic polyurethanes. The material currently used is the 3rd generation multi-layered polyurethane material, with hard and soft layers (Kundal and Shokeen, 2020). The outer hard layer provides strength and durability during function within the mouth, whilst the softer inner layer elastically deforms during placement. This arrangement provides the ideal biomechanical forces required for optimal tooth movement whilst allowing insertion and removal of the appliance and increasing patient comfort (Shontell, 2020).

Initially clear aligner systems were introduced to correct minor malalignments of teeth, by utilising a sequence of clear plastic aligners and three-dimensional computer modelling as an alternative to conventional fixed appliances. The first aligner systems produced tooth movement exclusively from the aligner, with each aligner produced with the teeth gradually repositioned to their desired position. These appliances systems were suitable for mild malocclusions but without the incorporation of any auxiliaries, they were inferior to fixed appliance treatment for moderate to severe malocclusions (Djeu *et al*., 2005).

Advancements in 3D technology, thermoplastic materials and clinical studies have meant the CAT appliance systems have evolved to incorporate composite attachments, buttons for inter-maxillary elastics and inter-proximal reduction (IPR). These third-generation appliance systems have been shown to produce clinical results that are an alternative to fixed appliances (AlMogbel *et al.,* 2024). The use of composite attachments, as a fixed component, have produced the biomechanical advantages required for orthodontic tooth movement (Gopffarth, 2022).

1.2 History of Clear Aligner Therapy (CAT)

Although only recently popularised, the concept of using an aligner to straighten teeth was first hypothesised in the 1940s by Kesling (Kesling, 1946). Kesling used a tooth positioning appliance for refinement in the final stages of orthodontic treatment. This appliance was created by using a laboratory wax up of the teeth in a Class I occlusion and facilitated minor tipping of teeth whilst maintaining the alignment of the remaining teeth within the arch. Kesling predicted that more complex tooth movements could be created with a series of aligners, however the technology was not available. Initially clear aligners were produced by Kesling using a manual set-up. This is a labour-intensive process that involved manually repositioning teeth that require alignment on models, followed by securing the teeth in wax and the production of vacuum-formed retainers, which were then worn for 10-15 days. Aligner fabrication involved new impressions and a new working cast at each visit. For this reason, aligners produced by manual set-up were not commercially viable.

In 1999, Align technology released the Invisalign™ system, which was the first digital aligner system and utilised computer aided design (CAD) and computer aided manufacturing (CAM). The advent of this digital system revolutionised aligner technology, it allowed a sequence of custom aligners to be made from a single impression (Hajeer *et al.*, 2004). Since then, numerous companies have created CAD-CAM produced aligner systems. The most well-known and commonly used being Invisalign®. A literature review in 2015 found 27 different clear aligner systems and this number is still rapidly increasing (Tamer *et al.,* 2019).

1.3 Principles of aligners

The process for producing aligners by CAD-CAM technology has become relatively standardised. For each patient, the clinician submits a set of polyvinyl siloxane impressions and a centric occlusion bite registration, or equivalent three-dimensional scan, the later has recently gained popularity with clinicians. After the impressions are uploaded to the computer, a 3D construction of the models is produced. The orthodontist's prescription is then followed to position the teeth in proper alignment and to correct the occlusion (Tamer *et al*., 2019). The tooth movements required to achieve this proper alignment are then staged. The number of stages is dependent on the complexity of the initial malignment, and difficulty of the tooth movements required. Each aligner by default can move a tooth approximately 0.25mm, which is the width of the periodontal ligament and around 2 degrees of rotation, numerous teeth can be moved simultaneously (Mitchell, 2013; Feinberg, 2015). Therefore, the total number of aligners depends on the extent of the tooth movements required and the complexity of the malocclusion. The combined total of the individual tooth movements should not exceed 5mm per set of aligners (Kim and Ozturk-Ortan, 2009).

The treatment plan is then sent to the clinician for approval. Once the treatment plan has been approved, the computer images are converted to models by stereolithography (Wong, 2002). This model is then used to create the sequence of clear plastic aligners by pressure moulding. The clinician can then deliver these aligners to the patient and perform any other procedures required, for instance the bonding of composite attachments. Patients are instructed to wear each aligner for a minimum of 22 hours a day, as per Align Technology clinical guidelines, for between 7-14 days (Feinberg, 2015; Invisalign, 2024). Throughout this treatment tooth movement is monitored by the clinician to ensure the teeth are moving as planned and as required. At the end of the sequence of aligners the clinician can then decide if treatment is completed or if further refinements are required.

Understanding the biomechanics of tooth movement when using aligners is an important aspect of clear aligner therapy. A good understanding of the mechanics can lead to better patient selection, more accurate treatment staging which then leads to better patient results (Drake *et al.,* 2012). Orthodontic tooth movement is caused by the action of a sustained external force placed upon teeth. With clear aligners, the mechanism of tooth movement is achieved by two different systems, the displacement driven system and the force driven system.

The displacement driven system allows for simple tooth movements, such as tipping and minor rotations. Each set of aligners is formed by moving the position of the teeth to the desired position for the next stage. The anatomical crown shape of the teeth is maintained. When the aligner is seated, a force is applied to the teeth to produce tooth movement until it lines up with the aligner position, and the aligner becomes passive (Drake *et al.,* 2012).

The force driven system utilises biomechanical principles to achieve more complex tooth movements, such as root movements, torque, intrusion, uprighting and extrusion. The force driven system is more effective at controlling tooth movement (Tamer *et al.*, 2019) and produces root movement. The shape of the aligners is not necessarily identical to the shape of the teeth and is altered depending on the tooth movements required to apply the desired forces to the teeth.

Computer software is utilised to determine the specific movements required for each tooth, which then determines the aligner shape. In the earlier stages of clear aligner therapy more complex tooth movements were achieved by altering the shape of the aligner with pressure points for uprighting or intrusion power ridges for root movements and torque (Weir, 2017), or by contracting/expanding the aligner when manufactured (Drake *et al.,* 2012; Malik *et al.*, 2013).

Although the force driven system improved the range of possible tooth movements with clear aligners, the lack of anchorage resulted in difficulty in achieving certain, more complex tooth movements such as extrusion, root paralleling and more significant rotations. The development of smart force attachments (Invisalign, 2015) by Align Tech

(Align Technology, Santa Clara, CA, USA), expanded the range of tooth movements achievable with clear aligners. The generic name for these being composite attachments.

Composite attachments are small projections of composite of varying shapes placed in specific locations on specific teeth, in order to produce a force system favourable for the desired movements (Tamer *et al*., 2019). These composite attachments have been shown to increase the efficiency of orthodontic tooth movement (Dasy *et al*., 2015; Hennessy and Al-Awadhi, 2016) and the accuracy of the final treatment outcome (Rossini *et al.,* 2015). Auxiliary components such as elastics, buttons and temporary anchorage devices can also now be used in combination with clear aligners to increase the range of treatments possible.

1.4 Manufacturing process for aligners

Although most CAD-CAM manufactured aligner systems follow these same generic principles, not every system is equal. They vary in terms of clinical protocol and the thickness and material the aligners are constructed in. The material chosen should have certain properties to be an effective aligner material.

The first-generation aligner materials were made from single layered or monophasic plastic, the second generation were made from a single layer rigid polyurethane and the third-generation made from polyurethane-like material. This polyurethane-like material comprises hard and soft layers, the soft layer allows elastic deformation for aligner seating and the hard layer provides strength and durability (Kundal and Shokeen, 2020). Most manufacturers now use polyethylene terephthalate glycol-modified (PET-G) but polypropylene, polycarbonate, thermoplastic polyurethanes are also used. Since 2013, when polyurethane material was introduced, it has been widely regarded as the best material for aligner therapy, due to its high strength and toughness (Gold *et al*., 2021).

From a mechanical perspective, thermoplastics with higher yield strength, ultimate tensile strength and toughness are desirable to produce clear aligners. This is because aligners must withstand both short term forces when the aligner is first loaded on insertion and long-term forces due to the displacement caused by programmed tooth movement (Gold *et al*., 2021; Ho *et al.,* 2021). Aligners should be durable and resistant to wear from masticatory forces. Studies have shown polyurethane and polycarbonate exhibit higher resistance to surface cracking. For aesthetic reasons, aligner materials should exhibit good light transmittance; polyurethane, polyester and polycarbonate all exhibit good optical properties. For retention and efficiency of tooth movement, it is important that the aligner material can adapt to the models during the thermoforming process. It has been shown polyurethane performs superiorly in comparison to other aligner materials (Gold *et al.,* 2021). In addition to the above properties, it is important aligner materials are biocompatible and resistant to chemical degradation (Gold *et al*., 2021).

In addition to the material used, the thickness of the material has the potential to affect the mechanical properties and performance of clear aligners. Clear aligners are manufactured in a variety of thicknesses, which can range from 0.5mm to 1.5mm. A systematic review and meta-analysis has shown that aligner thickness does not play a significant role in force application (Illiadi *et al*., 2019).

1.5 Aligner material and the effect on attachments

Clear aligners are worn for a minimum of 22 hours a day but are taken out for eating, drinking and oral hygiene. It is estimated most patients insert and remove their aligners at least five times a day (Feinberg, 2015; Invisalign, 2024). On average each clear aligner is worn for a minimum of 10 days so over this time inserted and removed approximately 50 times. If a patients clear aligner treatment lasts for 20 aligners, it is estimated in total aligners are inserted and removed 1000 times. The repeated insertion and removal of the rigid plastic aligner against the teeth and composite attachments has the potential to wear both the composite attachments and the aligners.

The amount of wear of the composite attachments depends on many different factors, including the mechanical properties of the composite chosen, the number of times the aligners are inserted or removed, and the type of material chosen for aligner production and the surface properties of the aligner. Although a more rigid aligner material will ensure strength and durability, a material with a higher elastic deformation will allow smoother aligner seating and reduced friction, properties that will reduce the wear of the teeth and composite attachments (Kundal and Shokeen, 2020). Third generation multi-layered polyurethane-like materials comprised of hard and soft layers, combine the benefits of strength and durability with elastic deformation for aligner seating and reduced capability for composite wear.

1.6 Attachments

1.6.1 Development of attachments

Historically, clear plastic aligners could only be used for simple tooth movements, such as the alignment of mild crowding, anterior space closure and a minimal amount of expansion. Clear aligner therapy had faced scepticism, mainly related to its inability to produce certain orthodontic movements. More recently, the range of tooth movements that can be achieved with aligners has increased due to the introduction of composite attachments by Align Technology (Paquette *et al.,* 2017). Attachments used as part of clear aligner therapy are composite geometries bonded to the crowns of teeth, to achieve predictable, more complex tooth movements and improve the clinical efficacy of aligners (Dasy *et al*., 2015; Hennessy and Al-Awadhi, 2016; Yaosen *et al*., 2021). Attachments are created with use of composite resin, which can be either conventional or flowable composite which is then bonded to the tooth with the use of adhesives (Mantovani *et al*., 2019).

Orthodontic tooth movement in clear aligner therapy is a result of the interaction between the aligner, the tooth and the composite attachments placed (Simon *et al*., 2014; Garino *et al*., 2016). In each treatment stage the aligner corresponds to the new tooth position to be achieved, so when the aligner is fitted, there is a discrepancy between the aligner and the teeth. This discrepancy produces a force, applied to the tooth, which gradually results in tooth movement. The attachments act as pressure points for the interaction between the aligner and the tooth, increasing the possible range of tooth movements. Initially after placement, composite attachments are not always fully engaged within the clear aligners. As the patient progresses through the sequence of clear aligners the attachments continue to engage within the aligner and become more active (Hennessy and Al-Awadhi, 2016).

The shape, size and position of the composite attachments are determined during the treatment planning stages of aligner treatment. A template is produced by the aligner manufacturer and sent to the clinician. The attachment template has wells that correspond to the attachment geometries required. The wells are then be filled with composite resin and bonded to the teeth, curing the composite through the template. Once the template is removed, the required composite attachments remain bonded to the tooth in the desired position for the duration of treatment, or for as long as required to achieve the desired movement. This template can then be retained in case attachments require re-bonding later in treatment.

Composite attachments are bonded to the teeth using the acid etch technique, generally using an aligner template and following the manufacturers bonding instructions. The surface of the tooth to be bonded to is etched with 35% phosphoric acid for 30 seconds, rinsed with water for 30 seconds and dried with an air syringe. The bonding agent is then applied to the tooth surface and light cured using a light curing unit. The composite resin is then applied to the attachment wells of the clear aligner template. This is applied and pressed on to the tooths surface, before curing for 40 seconds (Invisalign, 2015).

To improve anchorage and retention of the clear aligners, retentive attachments can be used to overcome undesired displacement of the aligners. A study has demonstrated that aligner retention is affected by the presence and shape of attachments (Dasy *et al*., 2015). They found that bevelled attachments significantly increase aligner retention.

As well as the improvement in retention, the introduction of composite attachments allows for better control of tooth movement, by the transfer of forces from the aligner to the tooth root and crown (Yaosen *et al*., 2021). It has been shown that clear aligners can perform bodily tooth movements and torque as they are able to deliver the force combinations required by utilising attachments (Simon *et al*., 2014). One such example is the significant difference seen in premolar rotation when attachments are used with a clear aligner. This is due to the limited load transfer that can be applied to a cylindrical tooth without an attachment (Simon *et al*., 2014). However, research has shown that the tooth movements achievable with clear aligners remains less than what can be achieved with fixed appliances (Illiadi *et al*., 2019; AlMogbel *et al.,* 2024).

1.6.2 Classification of attachments

Attachment dimensions are directly related to the function the attachments perform within the clear aligner therapy. As the technology behind clear aligner therapy advances, attachments with specific dimensions have become available for specific tooth movements. However, broadly speaking there are three main types of composite attachments used by clear aligner manufacturers. These attachments have been termed "conventional attachments" by the Invisalign system (Invisalign, 2015). These three types of composite attachments are described as ellipsoid, rectangular and bevelled attachments, which are rectangular attachments with a bevelled surface (Invisalign, 2015).

Ellipsoid attachments are 3mm in height, 2mm in width and 1mm prominence, these are placed horizontally or vertically. Rectangular attachments are 3, 4 or 5mm in height, 2mm in width and 1mm prominence and again can be placed horizontally or vertically. Bevelled attachments are rectangular attachments that can be bevelled on different surfaces; horizontal incisal, horizontal gingival, vertical distal or vertical mesial. These are 3, 4 or 5mm in height, 2mm width and 0.50 - 1.25mm prominence (Invisalign, 2015).

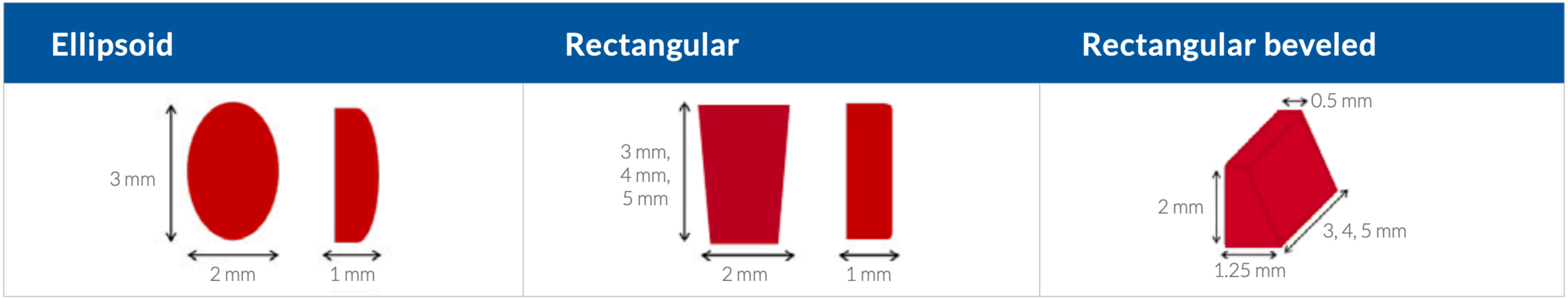

Figure 1.1 Invisalign Conventional Attachments (Invisalign, 2015)

1.6.3 Clinical uses of attachments

The purpose of composite attachments in clear aligner therapy has been postulated in numerous research articles and by clear aligner manufacturers. However, to date there has been little research into verifying whether these suggested movements are actually achieved.

The amount and direction of force that can be applied to a tooth during clear aligner therapy has been increased, by the utilisation of composite attachments. For premolar de-rotation, the presence of composite attachments has been shown to increase the average initial force by seven times (Simon *et al*., 2014). As with fixed appliances, the forces applied to the teeth significantly reduce over time. On aligner insertion the teeth experience a high initial force, followed by an exponential reduction in force; this pattern is repeated with each subsequent aligner.

Ellipsoid attachments can be used singularly or in pairs depending on the required tooth movement. Although one of Invisalign first "conventional" attachments (Invisalign, 2015), the ellipsoid attachments small size and lack of defined edges has led to it being considered one of the least effective attachments (Paquette *et al.,* 2017). However, some studies have shown that singular ellipsoid attachments can be used for greater rotational control to de-rotate teeth and pairs can be utilised for root movement (Hennessy and Al-Awadhi, 2016). Bevelled attachments are most often used when trying to extrude a tooth, the surface that is bevelled can be altered to reflect the tooth movement required. The active border limits slipping and therefore loss of tracking.

Retention of clear aligners can be of concern to clinicians in specific situations, including when clinical crowns are short or where teeth lack sufficient undercuts for retention. Gingival coverage of aligner materials may help aid retention (Invisalign, 2024). However, this comes with periodontal implications. For this reason, tooth-borne appliances and alternative methods of retention are preferred (Weir, 2017). Clear aligner manufacturers offer the use of attachments to aid resistance against vertical displacement (Dasy *et al*., 2015; Invisalign, 2015). A study by Dasy *et al* in 2015 compared aligner retention with use of bevelled and ellipsoid attachments. They concluded that although ellipsoid attachments have no significant effect on aligner retention, the use of bevelled attachments increased retention significantly. This study however did not investigate the effect of rectangular attachments on retention.

Rectangular attachments can be used when large mesio-distal movements of teeth are required, it is suggested that the longer span for force application allows a tooth to be moved bodily (Hennessy and Al-Awadhi, 2016). A multicentre study by Ravera *et al* (2016) investigated whether maxillary molar distalisation was possible with use of Invisalign aligners in conjunction with composite attachments. Their results showed that the use of vertical rectangular attachments on the buccal surfaces of the teeth to be distalised, along with class II elastics can distalise maxillary first molars by 2.25mm, without significant tipping or vertical movement (Ravera *et al*., 2016, Garino *et al*., 2016). Although these results have been confirmed by various case reports, it should be noted that this was a retrospective study with a small sample size of only 20 patients. As well as the orientation of the attachment, the number of rectangular attachments per quadrant on a molar during distalisation is also important (Garino *et al*., 2016). The presence of 5 attachments per quadrant lead to increased distal movement of the first molar and central incisor.

1.7 Composition of composite resin

Composite resin is used to produce attachments during clear aligner therapy. Resin-based composite materials are aesthetic, plastic restorative materials that consist of co-polymerised methacrylate-based resin chains, embedded with filler particles that provide strength and wear resistance properties (Walmsley *et al.,* 2007). Resin-based composite materials have three major components: an organic resin matrix, an inorganic filler and a silane coupling agent. The size and quantity of these filler particles determines the mechanical properties of the composite resin. The composite resin used for aligner attachments needs to be resistant to wear whilst having adequate handling and aesthetic properties (Burgess *et al.*, 2002).

Within the uncured composite material, the organic resin matrix consists of several different types of resin methacrylate monomers. The length of the monomer chains present affects the properties of the composite. The shorter the monomer chain, the less viscous the composite material and the greater the polymerisation shrinkage. The most commonly used monomer for composite resin is Bis-GMA, as it has been shown to reduce polymerisation shrinkage in comparison to the previously used methyl methacrylate (MMA) (Banerjee *et al*., 2011).

Inert filler particles are embedded and bonded within the resin matrix by use of a silane coupling agents. These filler particles determine the mechanical and aesthetic properties of the composite. The filler particles can be made from quartz or, more recently, silica-based glass fillers. The inclusion of barium or strontium provides radiopacity to the composites (Banerjee *et al.,* 2011). The more space within the resin taken up by filler, the less polymerisation shrinkage and more viscous the composite will be. The presence of larger more dense filler particles will increase the wear resistance of the composite. Smaller, softer filler particles will make the composite more polishable but less wear resistant.

In addition to the methacrylate resin, filler particles and silane coupling agents, composites also contain other limited quantities of materials. These include inhibitors to increase material longevity, accelerators to increase the speed of curing, photo stabilisers and colour pigments (Banerjee *et al.,*2011).

1.8 Composite resins

1.8.1 History of composite

The concept of bonding to enamel was made possible by the introduction of the acid etch technique by Buonocore in 1955 (Buonocore, 1955; Walmsley *et al*., 2007) and dimethacrylate polymers such as Bis-GMA in 1961 (Banerjee *et al.,*2011). Subsequently, there has been considerable development in resin and filler technology, to improve the clinical properties of composite.

1.8.2 Developments in filler technology

Early composites were known as macrofilled composites, they contained over 60% by volume of filler particles, that were between 10-20μm. Due to the large dimensions of filler particles, these composites were difficult to polish and had poor aesthetics. Macrofilled composites are most suited for areas that will be exposed to high occlusal loading because they have a higher compressive strength and wear resistance than microfilled composites. However, they tend to be opaquer, and due to the size of the filler particles, it is not possible to polish macrofilled composites to a high lustre, so less suitable for the aesthetic zone (Van Noort, 2013).

Microfilled composites were developed in the 1970's (Van Noort, 2013) and contained colloidal silicia filler particles of size between 0.01-0.05μm, with a filler content between 20-50% by volume (Lynch, 2008). Microfilled composites have a lower filler volume compared with macrofilled composites, producing a lower compressive strength and wear resistance. The very small filler particles contained in microfilled composites allow a high quality of polish (Van Noort, 2013). Therefore, microfilled composites are more suitable anteriorly, where there is likely a high aesthetic demand and lower force application. Hybrid composites attempt to combine the best features of both macrofilled and microfilled composites. They contain larger glass macrofiller particles between 15-20μm and a small amount of colloidal silica, which has a particle size of 0.01-0.05μm. Hybrid composites have between 50-70% filler particles by volume (Lynch, 2008).

Small-particle hybrid composites are made up of glass filler particles that are on average less than 1μm in size, combined with colloidal silica. The glass filler particles used in hybrid composite are made smaller by improved methods of grinding the glass (Van Noort, 2013). The smaller sized filler particles allow these composites to be polished to a higher finish. Advancements in nanofiller technology have resulted in the production of nanocomposites. These are composites with filler particle sizes less than 100nm (Walmsley *et al.,* 2007). Although nanocomposites were introduced in the early 2000's, many composites with filler particles less than 100nm have been previously developed

(Van Noort, 2013). Nanofilled composites, both conventional and flowable, are routinely recommended by aligner manufacturers for composite attachments (Invisalign, 2024). Significant changes in resin technology have also taken place over the last three decades, including changes in polymerisation technique, reducing polymerisation shrinkage by use of fillers, and utilising different resin systems to reduce shrinkage on curing (Van Noort, 2013).

Polymerisation is the process by which the monomeric resin matrix within composite paste turns into a hard restorative material (Van Noort, 2013). For the early generation of composites, this was achieved by supplying two pastes, an initiator and an activator, which when combined allowed for the initiation of polymerisation. In the 1970's, composite polymerisation developed into ultra-violet (UV) light activated composite (Banerjee *et al., ,*2011). UV light is utilised to create free radicals, which are then the catalyst to initiate composite polymerisation. However, the UV light can potentially cause soft tissue burns or damage to the eye. The polymerisation technology was developed further into visible light activated composites, which use camphoroquinone as the source of the free radicals which allows the composite to be polymerised by light with a wavelength in the blue range (460-480nm) (Banerjee *et al.,* 2011). The use of light activated composites has several benefits including that this wavelength of light is less damaging and is easily transmitted through the composite allowing a greater depth of cure (Van Noort, 2013).

Polymerisation shrinkage has been a major drawback of composite resin materials for many years, therefore the ability to reduce polymerisation shrinkage has been an area of intense research. The amount of polymerisation shrinkage is around 2-3% by volume, dependent on the type of resin used and the amount of resin in its unpolymerised form. Generally, composites with a higher proportion of glass filler result in lower final shrinkage. Methods to overcome polymerisation shrinkage include the use of chemically cured composites at the base of restorations, incremental composite placement, and thorough composite curing (Van Noort, 2013).

New resin technologies are being developed that aim to reduce polymerisation shrinkage further. These include modifying existing methacrylates and using stress decreasing resins. Alternative formulations that utilise different setting reactions are being investigated, for example Silorane that hardens by cationic polymerisation, which results in lower polymerisation stress rates during curing (Van Noort, 2013).

1.8.3 Development of handling characteristics

Due to consumer demand, over the last few decades there have been numerous developments in relation to the rheology of composite resins. These include the development of low viscosity, 'flowable' composites, and high viscosity 'packable' or 'conventional' composites (Burgess *et al.,* 2002). The ideal viscosity of a composite for attachments should allow it to be packed into the attachment template, whilst being able to adapt and flow into inaccessible areas of the template. To allow the composite resin to be sculpted it should not flow under its own weight, but flow when pressure is applied (Van Noort, 2013).

Flowable composites with decreased viscosity are produced by reducing the filler content (Van Noort, 2013). As not to reduce the filler content too significantly, the size of the filler particles can be increased. Due to the composition of flowable composites, they have poor mechanical properties and are not recommended for situations with high levels of stress or wear but do flow easily into attachment templates. High viscosity, conventional composites are achieved by increasing the filler content of composite resins and changing the rheology of the resin matrix. Due to the increased filler content, the aesthetic properties of these composite resins are reduced. They tend to be opaquer and have a reduced surface polish. The high viscosity means marginal adaptation is poor, resulting in voids in the restoration or composite attachment (Van Noort, 2013).

1.8.4 Development in wear resistance

One of the most important developments in composite technology has been the reduction in the size of reinforcing filler particles, which improved resistance to wear. Numerous laboratory studies have shown that the wear resistance of composite is related to the composition of the material (Burgess *et al.,* 2002). The wear resistance of composite resin is mainly controlled by composite filler content and particle size. It has been shown that a higher filler content increases the resistance of composite to wear, as the filler particles protect the weaker resin matrix during abrasive wear. However, the composition of the resin monomers also plays a role within composite wear resistance, this means the wear of composite is multifactorial (Dionysopoulos and Gerasimidou, 2022). These developments have led to the production of composite resins with improved properties for composite attachments.

1.9 Composite and attachments

The position, presence and structure of composite attachments plays a critical role in clear aligner therapy, as the composite attachments affect the aligner retention and the force applied to the teeth. Therefore, the mechanical properties of the composite used for attachments are clinically significant. Careful thought should be given to the composite resin chosen (Barreda *et al*., 2017), as the resin chosen for composite attachment fabrication has both clinical and aesthetic implications (Feinberg, 2015).

As the composite attachments are visible underneath aligners and are frequently bonded to the anterior teeth for the duration of treatment, the aesthetic properties of the composite resin chosen are important, particularly to patients who are seeking a more aesthetic orthodontic treatment. These properties include the resistance to stain and the translucency (Barreda *et al*., 2017). For the composite attachment to be aesthetic, it needs to match the colour of the adjacent teeth or possess adequate translucency to blend with the underlying tooth. The benefit of using a composite resin with adequate translucency means the same composite resin can be used for all composite attachments on different shade teeth (Feinberg, 2015). Microfilled or nanofilled composites, with smaller filler particles allow a higher quality of surface finish and therefore resistance to marginal and surface discolouration (Van Noort, 2013). Surface discolouration of composite attachments particularly anteriorly, is a potential source of patient dissatisfaction so resistance to staining is an important property of the composite resin. The translucency of composite resin is affected by the colour pigments, which reflect light and filler particles. Studies have shown flowable composite has a higher translucency, likely due to the lower filler content, so attachments can blend with the adjacent teeth (Feinberg, 2015)

As composite attachments are a crucial auxiliary element to clear aligner therapy, the mechanical properties of composite used are clinically important. These mechanical properties include wear resistance, detail reproducibility and ease of use. Wear resistance is an important property of the composite resin chosen, as the composite attachments are subject to wear during mastication, toothbrushing and as the patient repeatedly removes and inserts the aligners (Feinberg, 2015). The shape and structural integrity of the attachments needs to be accurate and kept constant throughout treatment. This is to ensure adequate aligner adaptation and accurate force application, as not to compromise the efficiency and accuracy of the tooth movements achieved (Kravitz *et al.,* 2008; Dasy *et al.*, 2015; D'Anto *et al.,* 2019). A previous study has shown that the shape of an attachment affects the retention of the aligner, therefore any wear of the attachments could also lead to less efficient tooth movements (Feinberg, 2015) and affect the clinical outcome of treatment. Clear aligner manufacturers generally leave the final choice of composite resin for attachments to clinician preference. However, Invisalign does recommend several conventional and flowable nanofill composites that can be used (Invisalign, 2015). These recommendations are based on dimensional stability, bond strength and wear resistance (Gopffarth, 2022). In practice, the materials chosen tend to be affected by price, availability, and ease of use.

The filler particle size in nanofill composites ranges from 20nm to 5μm and the filler phase can be up to 70% in volume (Barreda *et al.,* 2017; Gazzani *et al.,* 2022). Attachments can be created with either flowable or conventional nanofill composite, which differ mainly by viscosity and filler volume. Conventional nanofill composites have a high viscosity due to small particle sizes and high filler volume. Flowable nanofill composite has a lower viscosity due to a lower filler volume and increased resin content (Burgess, *et al.,* 2002; Gazzani *et al*., 2022).

Flowable composite resin is an attractive choice for clinicians because of its handling properties, mainly the increased viscosity. It easily adapts to attachment template but its lower filler volume can have a negative effect on the wear resistance (Chen *et al.,* 2021; Gazzani *et al.,* 2022). Studies have demonstrated that composite viscosity does not influence the shape and volume of attachments produced (D'Anto *et al*., 2019). The use of conventional composites with higher filler content increases the hardness and wear resistance in comparison to flowable composite (Chen *et al.,* 2021). This may be attributed to filler particles being approximately 10 times harder than the surrounding resin matrix (Feinberg, 2015). Gazzini *et al* (2022) concluded that conventional nanofill composites show greater performance and resistance to mechanical stresses than flowable ones, resulting in superior mechanical properties for composite attachment production (Gazzani *et al.,* 2022). However, flowable composites are easier to adapt to attachment templates and have better translucency, and therefore are more aesthetically discrete.

1.10 Wear of composite resin

1.10.1 How composite resin wears

Wear is defined as the damaging, gradual loss or deformation of a material at a solid surface. Wear, along with other processes such as fatigue and creep, can cause the functional surfaces of composite to degrade, leading to loss of function

(Dionysopoulos and Gerasimidou, 2022). In the oral environment, there are four categories of wear depending on the mechanism involved; abrasive, adhesive, fatigue and corrosive (Mair *et al*., 1996). The structural integrity and resistance to wear of the composite used for the fabrication of attachments is important, as the efficacy of an attachment depends on maintenance of its shape over a course of treatment (Dasy *et al.,* 2015).

Abrasive wear is the loss of material when hard particles or hard protuberances on a surface are forced against an opposing, solid surface (Mair *et al.,* 1996). The harder of the two materials may indent or cut away material from the other surface resulting in loss of the material (Van Noort, 2013). This direct contact is known as two-body abrasion. During aligner treatment, two-body abrasion can occur to attachments when aligners are inserted or removed. As attachments are placed in non-occlusal contact areas, occlusal forces do not cause additional two-body abrasion. Three-body abrasion is when an abrasive slurry is interposed between two surfaces that are not actually in contact. In aligner treatment, three-body abrasion may occur to the composite attachments during toothbrushing with toothpaste (as the abrasive slurry) and during mastication with the food acting as the abrasive agent (Van Noort, 2013).

Fatigue wear occurs due to the repeated loading of teeth and composite attachments, this produces cyclic stresses that can lead to the growth of fatigue cracks. Corrosive wear of composite occurs due to a variety of mechanisms but is caused by a chemical reaction between a worn surface and the corrosive agent (Dionysopoulos and Gerasimidou, 2022). Corrosive wear can occur due to hydrolytic breakdown of the composite resin due to chemical attack, breakdown of the resin-filler interface or erosion of the surface due to acid (Mair *et al.*, 1996). Adhesive wear does not seem to be relevant to the wear of composites attachments, especially as its mode of action is significantly reduced by the presence of saliva (Mandel, 1987).

Wear is a multifaceted process and therefore it is difficult to measure with any one test. The mechanical properties of composite correlate poorly with its wear resistance. There are many patient-dependent factors that affect the wear of composite attachments including, diet, lubrication, and toothbrush abrasion (Gopffarth, 2022).

1.10.2 Wear of composite used as attachments

A variety of composite resins are recommended by Invisalign for use as composite attachments, these are all nanohybrid materials (Invisalign, 2015). An *in vivo* study by Barreda *et al* in 2017, evaluated the surface wear of two composite materials used as attachments, a nanofilled material (Filtek Z350 XT) and a micro-hybrid composite (Amelogen Plus TW). The study concluded that statistically significant differences in surface texture were found between the composite attachments, the nanofilled material displayed less surface wear after the first six months' (Barreda *et al.,* 2017).

The recommended nanohybrid composites include both conventional and flowable composites. Gazzani *et al* in 2022 compared the *in vitro* wear of a flowable nanohybrid composite in comparison to a conventional nanohybrid composite. A greater degree of wear was observed when the attachment was produced using the flowable composite. Evaluation of wear in this study was completed using a contact probe surface profiler. The study concluded that further studies should simulate and reproduce wear due to the insertion and removal of clear aligners (Gazzani *et al*., 2022). The wear of conventional and flowable composites were compared *in vivo* and it was reported that more attachment damage was seen in the flowable composite group (14.79%) compared to the conventional group (9.7%) (Lin *et al.,* 2021).

In practice, often for reasons of practicality or accessibility, many clinicians utilise orthodontic adhesives to produce composite attachments. Bowman *et al* (2015) compared the hardness of two nanofilled composites in comparison with three orthodontic adhesives (Bowman *et al*., 2015). Filtek Supreme Ultra, a nanofilled composite, outperformed all other materials in terms of hardness. However, all the orthodontic adhesives displayed similar or greater hardness than another nanofilled composite, Tetric EvoCeram (Feinberg, 2015). This suggests that orthodontic adhesives may have suitable mechanical properties to function as composite attachments without affecting the planned retention or tooth movement.

Borth *et al* in 2021 investigated attachment wear, simulated over the course of 30 weeks of aligner therapy, using flowable composites and orthodontic bracket adhesives as attachments. Although the study found that each material used demonstrated differences in wear, time was not a significant factor (Borth *et al*., 2021). It is noteworthy that this study however did not investigate the wear of conventional composites.

Gopffarth (2022) conducted an *in vivo* study comparing intraoral optical scanning with scanning electron microscopy as a method of assessing abrasive wear of a conventional composite (Tetric EvoCeram®; Ivoclar Vivadent, Amherst, NY) used for attachments with clear aligners. Utilising SEM, the study concluded that out of the 37 composite attachments that were placed, 14 had slight or unnoticeable wear, 15 had moderate wear and 8 had noticeable change, include cracks or fractures (Gopffarth, 2022). The study established that intraoral scans were an effective method for assessing wear of composite attachments when compared with scanning electron microscopy.

1.10.3 Effect of wear of attachments on tooth movement

The anticipated benefits of composite attachments rely on the engagement of the attachment within the aligner; therefore any wear of the composite attachment will reduce the engagement within the aligner (D'Anto *et al.,* 2019) and have a detrimental impact on the force applied by the aligner to the tooth. This is because the precise force required to retain or move the teeth will not be accurately transferred (Chen *et al*., 2021). As all the aligners are planned and produced with the attachments from the initial template, composite wear resulting in incorrect tooth movements cannot be rectified during later aligner treatment (Weckmann *et al*., 2019).

Currently, there is very little research published investigating how the wear of composite attachments affects the clinical efficiency of clear aligner therapy. A systematic review by Rossini *et al*. concluded that clear aligner therapy requires the use of composite attachments to improve treatment predictability (Rossini *et al*., 2015). Therefore, it can be postulated that any wear of the composite attachments would also reduce the predictability of orthodontic tooth movement. Previous studies have shown that the shape of an attachment affects retention, therefore any wear of the attachments could lead to less efficient tooth movements due to anchorage loss (Feinberg, 2015).

It has been widely published that ellipsoid attachments are the least effective of the conventional attachments, due to their lack of defined edges (Dasy *et al*., 2015; Paquette *et al.,* 2017). In comparison, research has shown that rectangular attachments are clinically effective in aiding bodily movement of teeth (Hennessy and Al-Awadhi, 2016), molar distalisation (Ravera *et al.*, 2016) and enhancing posterior anchorage (Garino *et al*., 2016). It has also been shown that sharp attachment edges, such as bevelled and rectangular attachments, maximise retention (Dasy *et al*., 2015) and specific tooth movements, such as derotation (Durrett, 2004).

Previous studies have shown that when rectangular attachments wear, this wear occurs at the defined edges (Gopffarth, 2022). If a rectangular attachment wears at its edges and corners, it will then resemble an ellipsoid attachment and as discussed, ellipsoid attachments are ineffective for tooth movement (Paquette *et al.,* 2017). The change in geometry of a rectangular attachment due to composite wear during treatment, has the potential to reduce the efficiency and predictability of tooth movement. Therefore, the precise maintenance of composite attachment geometry, throughout treatment, is of clinical importance.

Due to the wide variety of composite materials commercially available there are many options for clinicians when placing composite attachments. The composite material chosen is related to the efficiency and retention of the aligner, therefore careful material consideration is required. This study aims to compare of the surface wear resistance of nanofilled composite materials used as clear aligner attachments, to aid clinicians' decision making.

1.11 Summary

In summary, clear aligners are removable orthodontic appliances constructed from thermoplastic materials, that facilitate orthodontic tooth movement (Gold *et al*., 2021). Tooth movement during clear aligner therapy is due to the interaction between the aligner, the tooth and the composite attachments placed (Simon *et al*., 2014; Garino *et al*., 2016). Composite attachments are specific geometries of composite that increase aligner retention and apply precise forces to teeth, in order to provide improved control and to achieve more complex orthodontic tooth movements (Dasy *et al*., 2015; Rossini *et al*., 2015). It has been shown that clear aligners can perform complex tooth movements such as bodily tooth movements and torque, by the transfer of force to the teeth through the composite attachments (Simon *et al*., 2014; Yaosen *et al*., 2021).

Composite resin is used to fabricate composite attachments for use during clear aligner therapy. Composite resins are plastic restorative materials that consist of co-polymerised methacrylate-based resin chains, embedded with filler particles (Walmsley *et al*., 2007). Studies have shown that the strength and wear resistance of composite resin is controlled by the filler content and particle size (Burgess *et al.,* 2002). Nanofilled composites with filler particles smaller than 100nm are routinely recommended by aligner manufacturers for the production of composite attachments (Invisalign, 2024).

The resistance of a composite resin to wear is important, to ensure the structural integrity of the composite attachment is maintained throughout the treatment and forces are applied accurately to teeth (Kravitz *et al*., 2008; Dasy *et al*., 2015; D'Anto *et al.,* 2019). This is because any wear of the composite attachments could lead to less efficient tooth movements and affect the clinical outcome of treatment (Feinberg, 2015).

CHAPTER 2

AIMS AND NULL HYPOTHESIS

2.1 Aims

The aim of this study was to quantify the amount of surface wear of four different composite resins, when used as attachments during simulated clear aligner removal and insertion.

The primary outcome measure was the median difference in wear of the composite in millimetres (mm).

2.2 Null Hypothesis

There was no statistically significant difference ($p<0.05$) in the amount of composite wear between the four different composite materials used for attachments following simulated clear aligner removal and insertion.

CHAPTER 3

MATERIAL AND METHODS

3.1 Study design

The was an *in vitro* laboratory-based study undertaken to assess the surface loss (wear) of composite attachments, in millimetres, after repeated insertion and removal of a clear aligner using a typodont model.

3.2 Experimental design

3.2.1 Development of experimental apparatus

Various machine set ups were trialled, to best replicate how the aligners are removed from the teeth during *in vivo* use. The first set up included screws placed through the occlusal surface of the aligner, resting on the occlusal surface of the first permanent molars, which were attached to the upper clamp of the MTS machine, Figure 3.1. This was pilot tested but abandoned as it was felt it did not replicate intra oral aligner removal. As aligners are generally removed by applying pressure underneath the edge of the aligner in an occlusal direction, the final experiment design opted to mimic this *in vitro* making the experimental protocol more clinically valid. Aligner removal tools are commercially available plastic tools that have a hook at the tip, which engages in the undercut beneath the aligner edge so force can be applied. These were positioned with the hook placed in the undercut at the edge of the aligner, bilaterally between the upper first and second premolars. To ensure the placement of the aligner removal tools was reproducible, they were held in position, cemented between two pieces of rigid plastic. This set up could then be placed into the upper clamp of the MTS machine, Figure 3.2.

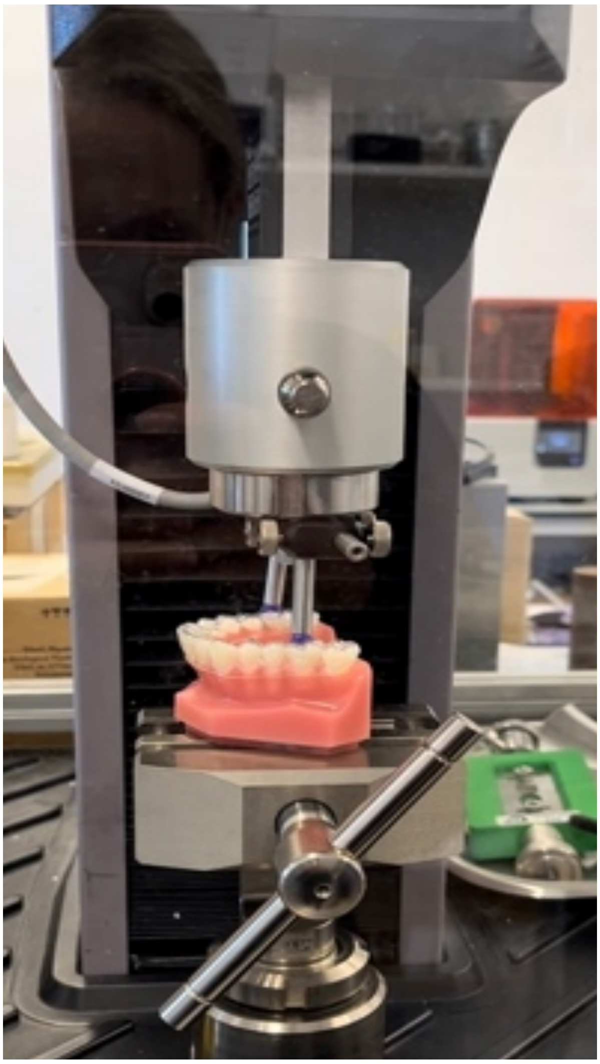

Figure 3.1 Test apparatus – Pilot set up

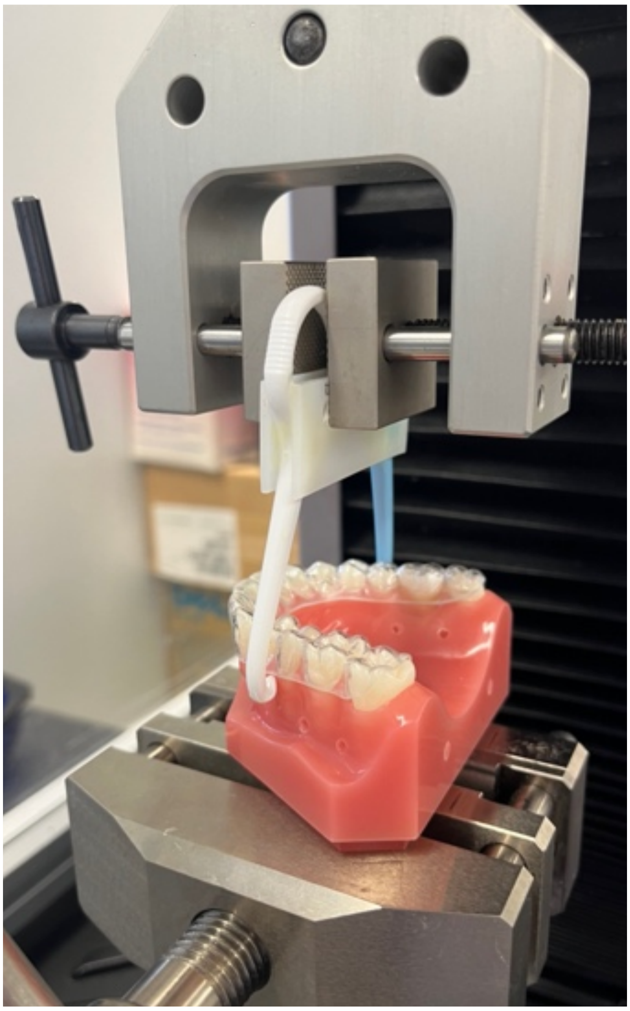

Figure 3.2 Test apparatus – Aligner removal tools

3.2.2 Final Experimental design

A fully dentate maxillary acrylic typodont model was used to simulate the upper dentition (DB Orthodontics). The acrylic upper left first permanent molar tooth was removed from the typodont and replaced with an extracted human upper left first permanent molar tooth (UL6). This was secured in place with heat cured acrylic resin making sure it was in the correct anatomical position within the typodont, Figure 3.3. The previously extracted UL6 tooth was sound, with no structural enamel defects, caries or other pathology present. Utilisation of this sample was approved after application to the Dentistry Research Tissue Bank at University of Birmingham, School of Dentistry (BCHCDent035.2024). To aid superimposition of the typodont 3D scans, 5mm holes were drilled bilaterally buccally and palatally within the acrylic. An additional hole was drilled through the centre of the typodont 'palate', which allowed the typodont to be screwed to the lower clamp of the Instron testing machine

3.3 Attachment template fabrication

A three-dimensional scan was taken of the typodont model, using an intra-oral scanner Primescan (Dentsply Sirona, Charlotte, NC, USA) and a stereolithography (STL) file of the typodont generated. This STL file was then sent to an aligner manufacturer (DB Orthodontics) for virtual placement of a rectangular attachment, positioned horizontally, centred on the buccal surface of the UL6. The rectangular attachment was 4mm in length, 2mm in width and 1mm in projection, Figure 3.4. This was then utilised to manufacture an attachment template and multiple identical aligners. The attachment template was constructed of 1.0mm thickness Ethyl vinyl acetate of and the aligner was manufactured in 1.0mm thickness pharmaceutical Co-polyester polymer.

Figure 3.3 Photographs of typodont set up in occlusal and left lateral view

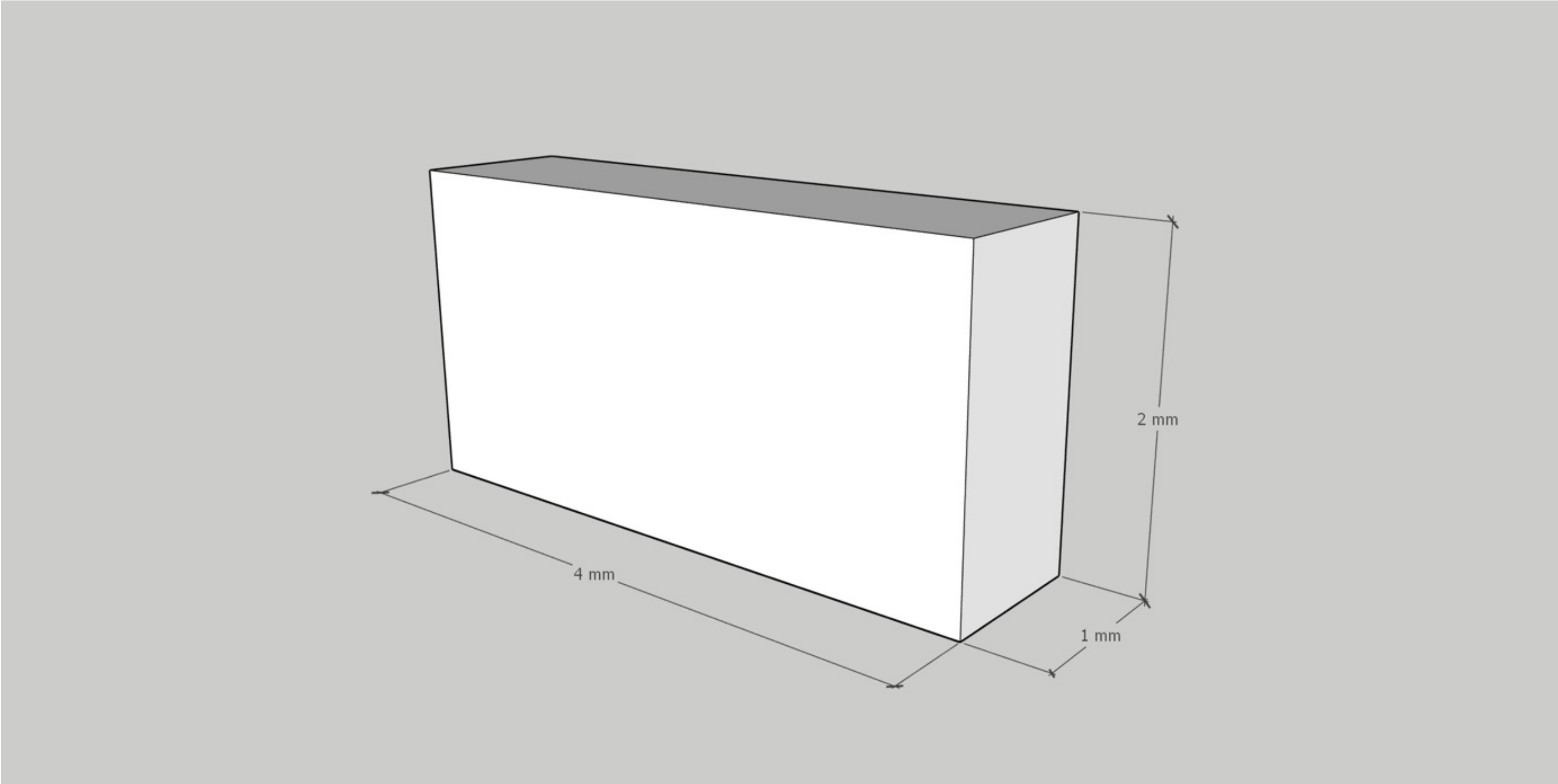

Figure 3.4 Graphic illustration of attachment dimensions

3.4 Attachment placement

Using the attachment template provided, the composite attachment was bonded to the UL6 using a standardised acid-etch technique and manufacturer's instructions. The buccal surface of the tooth was etched with 35% phosphoric acid for 30 seconds, then rinsed with water for 30 seconds and then dried with a 3 in 1 air syringe. The bonding agent was then applied to the buccal surface of the tooth using a microbrush and light cured using an LED light curing unit (Lynch, 2008). The composite resin being tested was then loaded into the attachment template, ensuring no voids or air bubbles were present and avoiding excess flash by not overloading the attachment template. The composite resin is applied to the attachment template utilising a syringe tip for flowable composites, or dental instruments for conventional composites and orthodontic adhesives. The fabricated attachment was then examined for deficiencies under 2.5x magnification. If deficiencies or voids were present the attachment was removed with a tungsten carbide debonding bur and replaced. A base line scan of the entire maxillary typodont was taken once the attachment had been placed using the Primescan intra-oral scanner.

3.5 Pilot studies

Once the experimental test apparatus had been confirmed, initial pilot testing was carried out. This was for proof of concept, to determine the precise location of wear on the composite attachments for measuring and to determine the number of test cycles. The number of times the aligner was cyclically removed and replaced was confirmed experimentally by pilot testing. The number of cycles chosen was enough to produce measurable wear, but within the limits of practicality as the procedure was not fully automated. For each experiment, each aligner was removed and replaced 500 times in total. On average if a patient removes and inserts an aligner five times a day and wears each aligner for 10 days, then 500 cycles represents a treatment plan sequence of 10 aligners, less than the average clear aligner treatment plan. Pilot testing with the experimental set up and a test composite, was carried out with 1600 cycles. This proved that sufficient, measurable was found on the gingival surface of the attachments after 500 cycles. So for this reason the experimental protocol was confirmed as 500 cycles for each composite, to be repeated four times for reproducibility.

To determine the precise location of the wear, an attachment was created using Venus Pearl and 500 cycles of insertion and removal carried out. Initial and final scans were superimposed and measurements taken. This confirmed that insignificant wear occurs on all surfaces, except the gingival edge of the attachment, Figure 3.5. For this reason linear measurements were taken at three points, the distal corner of the gingival surface edge, the midpoint of the gingival surface edge and the mesial corner of the gingival surface edge, demonstrated by lines intersecting the measurement sites in Figure 3.6.

3.6 Testing procedure

To test the surface wear of the attachments, an MTS Criterion Model 42 machine (Model 42, MTS Criterion® Series 40 Electromechanical universal test systems, MTS systems corporation, Minnesota, USA) was utilised. This machine reproducibly removed the aligner from the typodont, to replicate clinical aligner removal. The typodont was secured to the lower clamp assembly of the MTS machine, to ensure the direction and force of the pull was standardised. The typodont and clamp relationship were such that the typodont could only be placed in one position in the clamp. To ensure the aligner was reproducibly removed vertically a custom-made device was developed, clamped to the upper head assembly of the machine, Figure 3.7. The custom-made device consisted of two

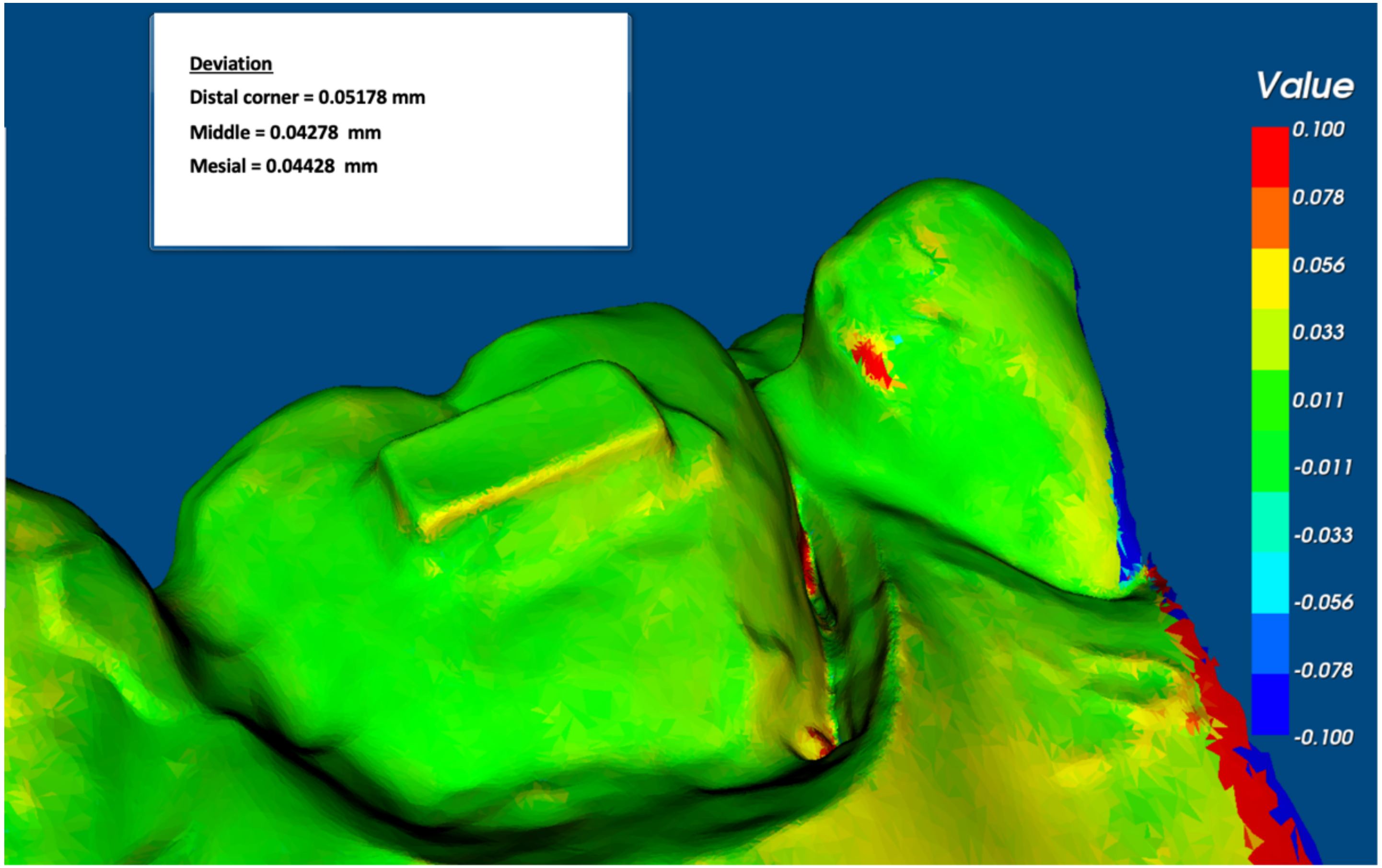

Figure 3.5 Image of scanned Venus Pearl attachment to demonstrate wear

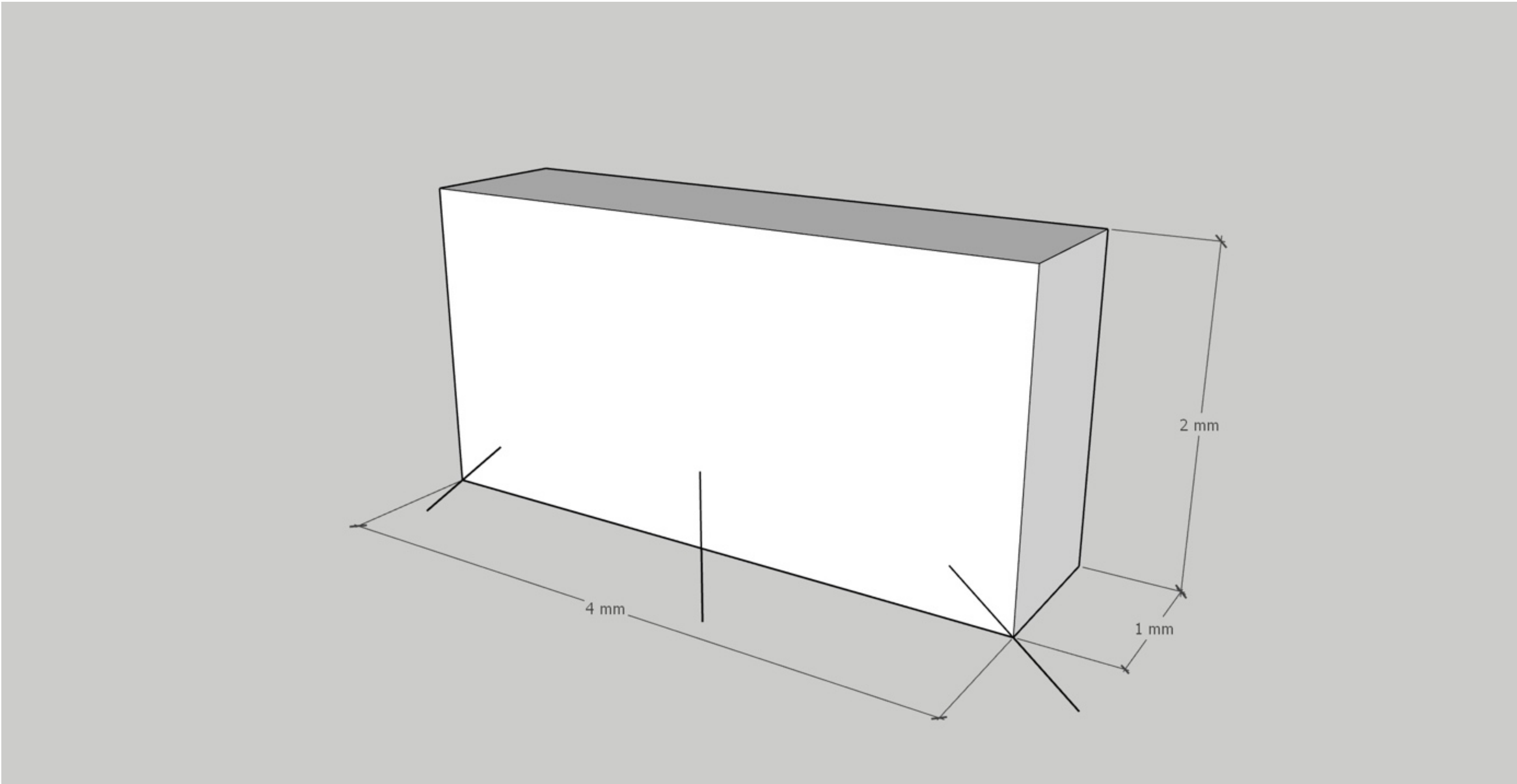

Figure 3.6 Graphical illustration of measurement sites on gingival surface

Figure 3.7 Final Test apparatus

Apparatus is formed of two aligner removal tools hooked bilaterally under the gingival aspect of the aligner, positioned between the first and second premolars and clamped into the upper arm of the machine.

available aligner removal tools, bonded together between two sheets of plastic and clamped into the upper head assembly. The aligner removal tools were positioned bilaterally underneath the aligner extension between the upper first and second premolars to mimic patient aligner removal, Figure 3.2. The MTS machine was set up using a 250N load cell, with an upper crosshead speed of 240mm/min. The crosshead limit stop was adjusted so that when the crosshead reached the maximum pre-set travel, crosshead motion automatically stopped. Once the aligner had been removed the machine automatically reset. The aligner was then manually replaced in preparation for the next repetition.

For each experimental cycle, the aligner was removed and replaced 500 times, to replicate 100 days of aligner wear. A baseline scan was taken, followed by a scan after 250 insertions and at the end point, 500 insertions. The number of times the aligner was cyclically removed and replaced was confirmed experimentally by pilot testing, as it was found after 500 cycles significant enough wear was noted to allow comparison between differing composites. In total four nanohybrid composite materials were tested, chosen to cover a broad variety of commercially available composite resins, with a range of filler content. These include two conventional composites, Venus Pearl (Heraeus-Kulzer, GmbH) and Tetric EvoCeram (Ivoclar Vivadent, Liechtenstein), one flowable composite Wave (SDI Limited, Bayswater, Victoria, Australia) and BracePaste an orthodontic adhesive (American Orthodontics, Sheboygan, CA, USA).

3.7 Variables

The independent variable for this study is the composite resin used to fabricate the composite attachments and the dependent variable is the amount of wear. This will be tested for four different composite resins. There were numerous constant variables that have been controlled to allow testing of the independent variable. These control variables were:

- The upper head assembly was pulled upwards at a constant rate of 240mm/min, utilising a set load cell of 250N.
- The upper and lower clamp assemblies remained in a set position throughout all tests, to maintain a constant distance between the typodont and aligner removal tools.
- The aligner removal tools were bonded between two sheets of plastic in a set position and angulation to ensure constant positioning underneath the aligner extension.
- A new, identical aligner was utilised for each test to account for any wear on the inner aligner surface.
- The same attachment template was used to produce all tested composite attachments, to ensure dimensions remained constant.

3.8 Three-dimensional (3D) typodont scanning

The typodont was re-scanned utilising the intra-oral scanner by the same clinician after 250 insertions and then at the end point, 500 insertions. In total 3 scans were taken: baseline, after 250 insertions and after 500 insertions. Each individual scan was saved in .STL format for analysis.

3.9 Error Study

Intra-operator scanner reliability was assessed by the same operator scanning the typodont five times and utilising the surface difference following superimposition.

VRMesh software was utilised to align the five surface images and determine if any differences between the two images were present. Random error and systemic error were determined.

3.10 Analysis

3.10.1 Image superimposition

The baseline scan was loaded into VRMesh Studio (VirtualGrid, Seattle City, Washington), the attachment on the UL6 was then digitally removed from the baseline image and a new version saved in .STL format. VRMesh was re-opened and the baseline image minus attachment was imported as well as the 250-insertion image. The same three points were chosen on both images and using the "manual alignment tool" the 250-insertion image (source image) was automatically superimposed (translated and rotated) over the baseline image minus attachment (target image), based only on the three corresponding landmarks. Following manual alignment, further "fine alignment" was undertaken in VRMesh. This involved further movement of the source image over the target based on "best fit" of the entire mesh surface. During this process the target image remained in the same 3D space it was imported into, whilst the source image moved to achieve the best fit ignoring any changes in the attachment as it was not present on the scan. The 250 insertion image was saved in .STL format in its new position in 3D space.

3.10.2 Measurements

The baseline scan was imported into VRMesh, in its original position and the 250-insertion image was imported, in its new superimposed position. This meant that the attachment was now present on both superimposed images whilst not being involved in the superimposition process, as this was carried out on the baseline image minus attachment image. This allowed changes in the position and shape of the attachment to be compared between the baseline and 250 insertions images. Using the "Distance between surface tool", measurements were taken at the disto-gingival corner, middle and mesio-gingival corner of the attachment. This determined the amount composite that had been lost as a linear measurement change in millimetres between the baseline and 250 insertion images, Figure 3.5. This was repeated 4 times of each composite tested and between the baseline image and 500 insertion images.

3. 11 Statistical analysis

A Kruskal-Wallis test was performed to determine if the amount of median wear of the disto-gingival corner of the attachment was statistically significantly different between each of the four composite resins tested, after 250 and at 500 cycles.

CHAPTER 4

RESULTS

4.1 Wear characteristics

The amount of wear on each attachment was measured at three points, the mesial-gingival, mid-gingival and distal-gingival surface, and recorded after 250 and 500 cycles. This was repeated four times to derive a median value and then repeated for each of the four composites tested. Overall, the results show that for each composite tested, after 250 and 500 cycles the most significant amount of wear occurs on the distal-gingival surface. The greatest amount of wear was found on the distal-gingival surface of Wave, demonstrating up to 0.08mm of wear. Overall, for each composite test wear is progressive from 250 to 500 cycles and between each of the four attempts wear is relatively constant. As the data was non-normally distributed, the measure of central tendency utilised was the median values and the measure of the spread of the data was inter quartile range. After initial analysis, analysis focussed on the wear measured on the distal-gingival surface of each attachment, as this was the location of the most measurable wear to allow comparison between composite resins.

For Tetric EvoCeram, at both 250 and 500 cycles, the least amount of wear occurs on the mid-gingival surface, with 0.01mm of wear being found at 250 and 500 cycles on each of the four attempts, Figure 4.1 and 4.2. Indicating very minimal wear, which did not increase with an additional 250 cycles. The mesial-gingival surface experienced a median value of 0.015mm of wear after 250 cycles, which increased to 0.02mm after 500 cycles. The area of most wear for Tetric EvoCeram was the distal-gingival surface, which at 250 cycles showed a median value of 0.04, and a median value of 0.06 at 500 cycles.

Comparatively, the wear of Venus Pearl was less than the other composite resins tested, Figure 4.3. Similarly to Tetric EvoCeram, after 250 and 500 cycles the least amount of

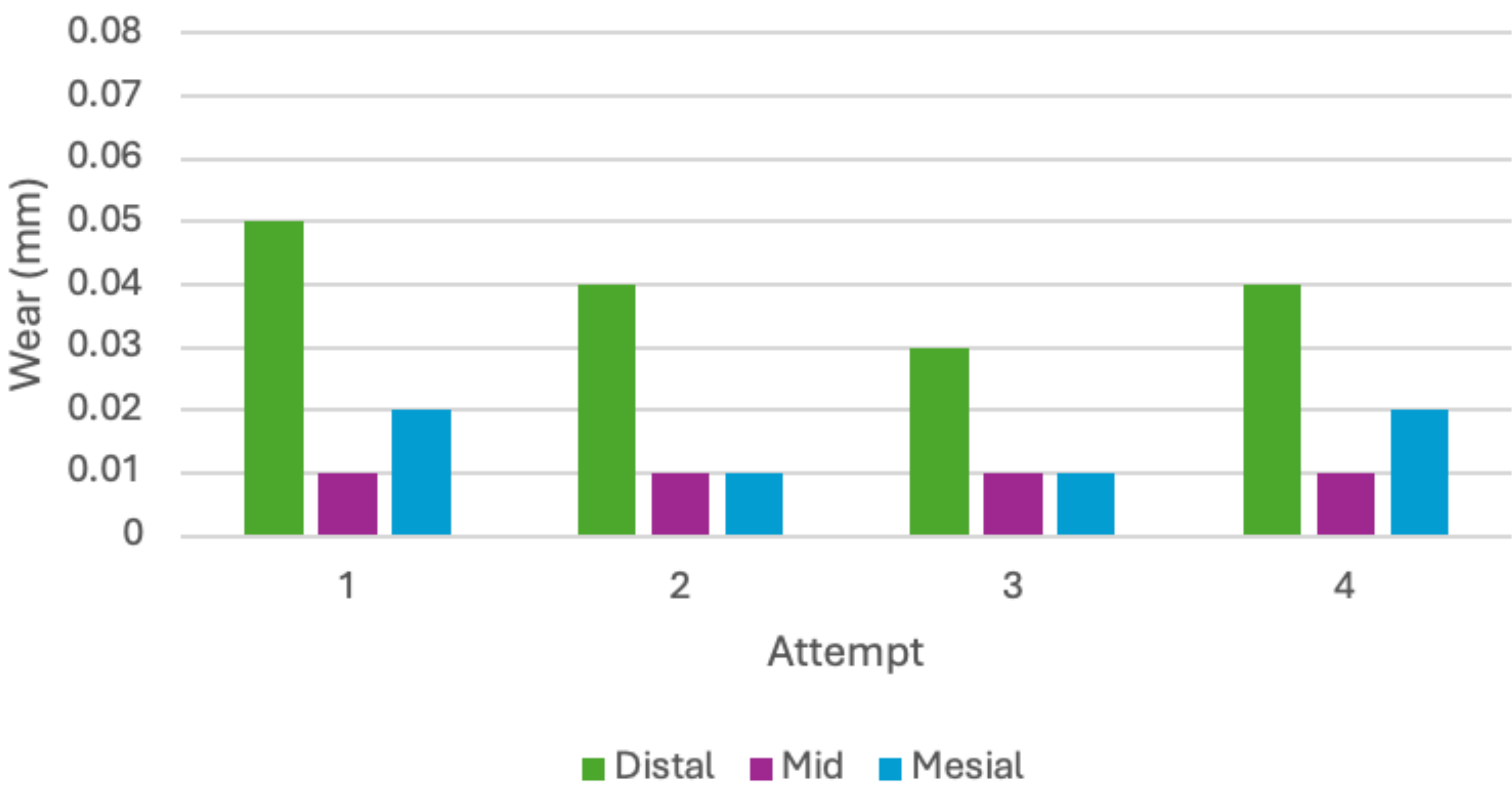

Figure 4.1 Graph showing wear of Tetric EvoCeram after 250 cycles at the three gingival locations of the attachment

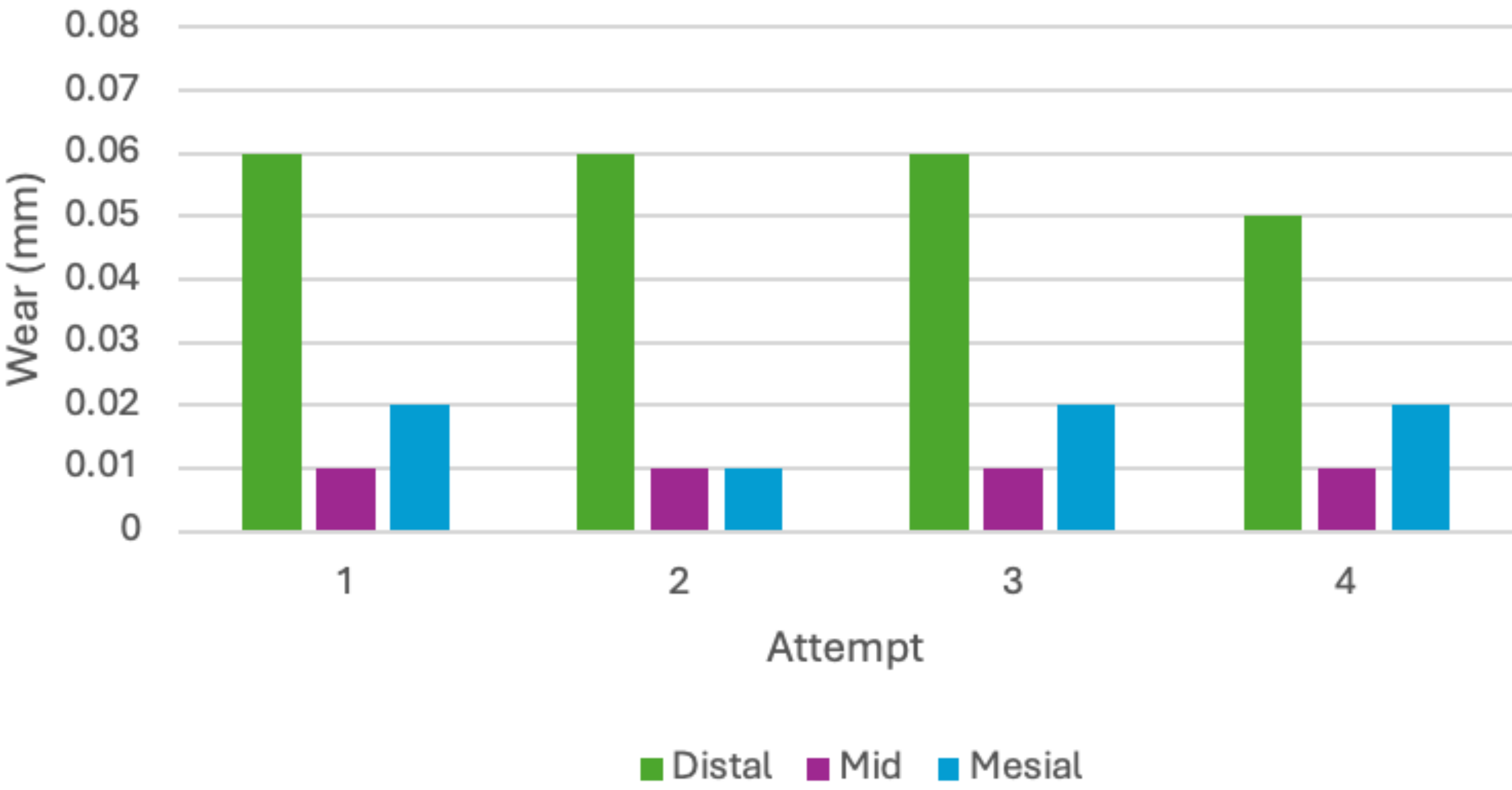

Figure 4.2 Graph showing wear of Tetric EvoCeram after 500 cycles at the three gingival locations of the attachment

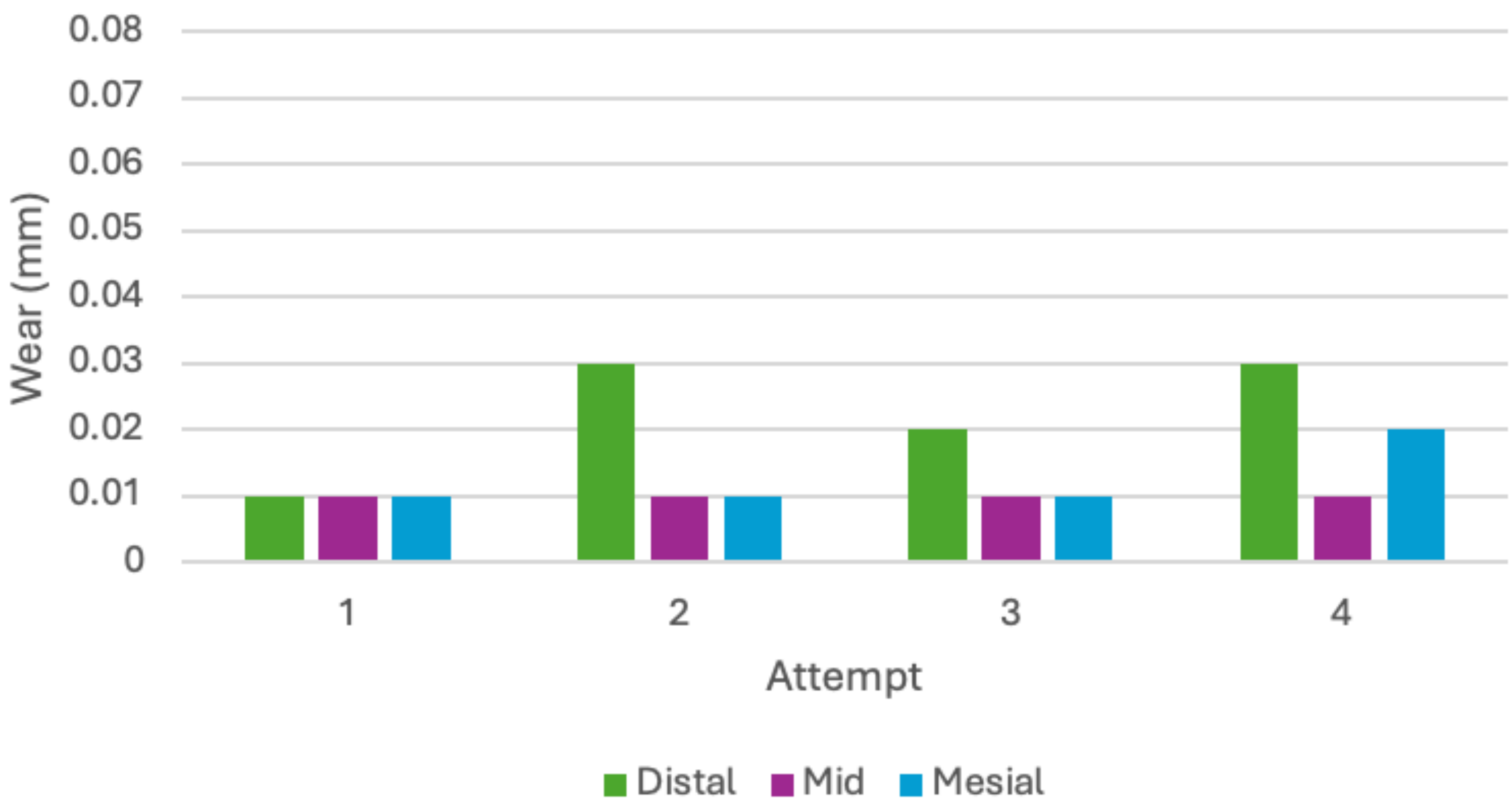

Figure 4.3 Graph showing wear of Venus Pearl after 250 cycles at the three gingival locations of the attachment

wear was found on the mid-gingival surface. For 500 cycles, the distal-gingival surface of the Venus Pearl attachment consistently had the greatest wear, with a median value of 0.04mm after 500 cycles, Figure 4.4.

As shown in Figure 4.5 and 4.6, Wave composite showed greater wear on all three surfaces at 250 and 500 cycles in comparison to the other composites tested. The greatest amount of wear was seen on the distal-gingival surface with median values of 0.06mm and 0.08mm, at 250 and 500 cycles respectively. Similar wear was demonstrated on the mid-gingival and mesial-gingival surfaces, with median values after 500 cycles being 0.03mm for both surfaces.

For BracePaste orthodontic adhesive, as with the other composites tested the distal-gingival surface experienced the greatest wear, with the median values being 0.04mm and 0.06mm after 250 and 500 cycles respectively. The mesial-gingival and mid-gingival surfaces experienced equal but comparatively less wear when compared to the distal-gingival surface. The median amount of wear of the mid-gingival and mesial-gingival surfaces after 250 and 500 cycles was 0.01mm, Figure 4.7 and 4.8.

Figures 4.9 and 4.10 show the results for each composite at 250 and 500 cycles presented as box and whisker plots. This highlights the distribution of wear of each composite over the four repetitions, showing the median values and interquartile ranges. As demonstrated, there are no outlier points, meaning there are no data points that fell outside of the typical range. The distribution of the data varied by the composite tested and the location of the measurement. As seen in Figure 4.10, the greatest variability of the data was found after 500 cycles for Wave composite on the distal-gingival and mid-

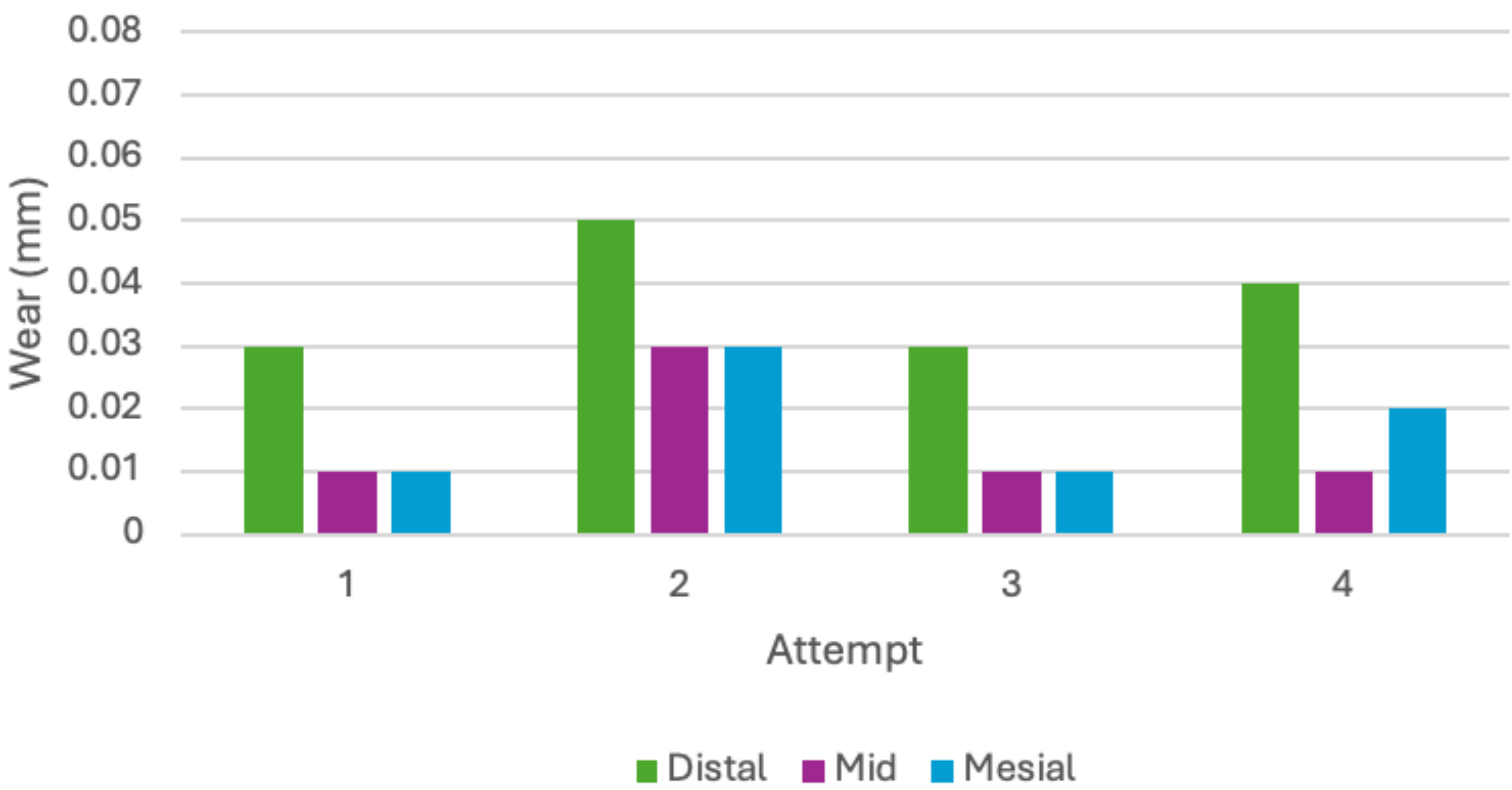

Figure 4.4 Graph showing wear of Venus Pearl after 500 cycles at the three gingival locations of the attachment

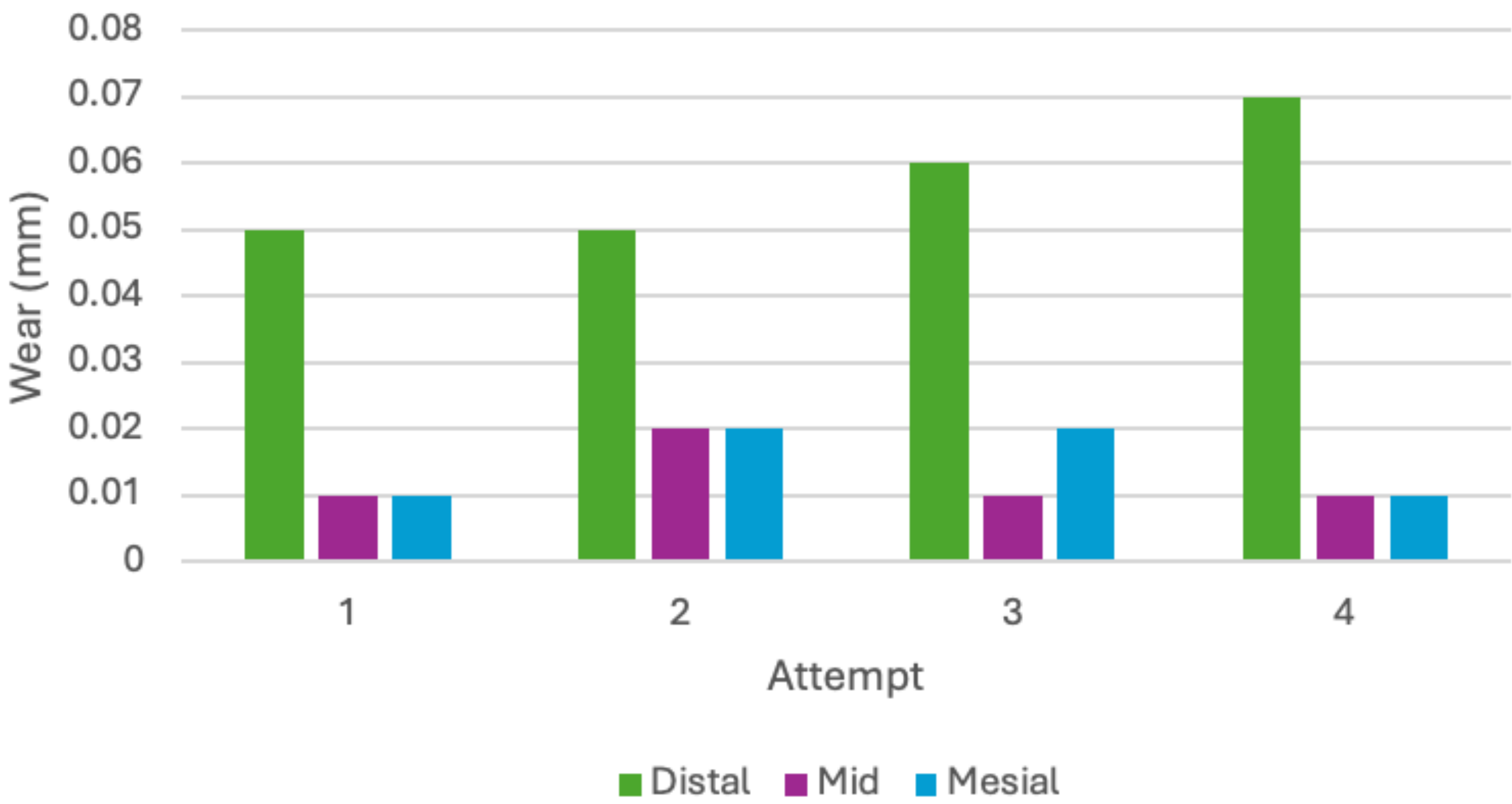

Figure 4.5 Graph showing wear of Wave after 250 cycles at the three gingival locations of the attachment

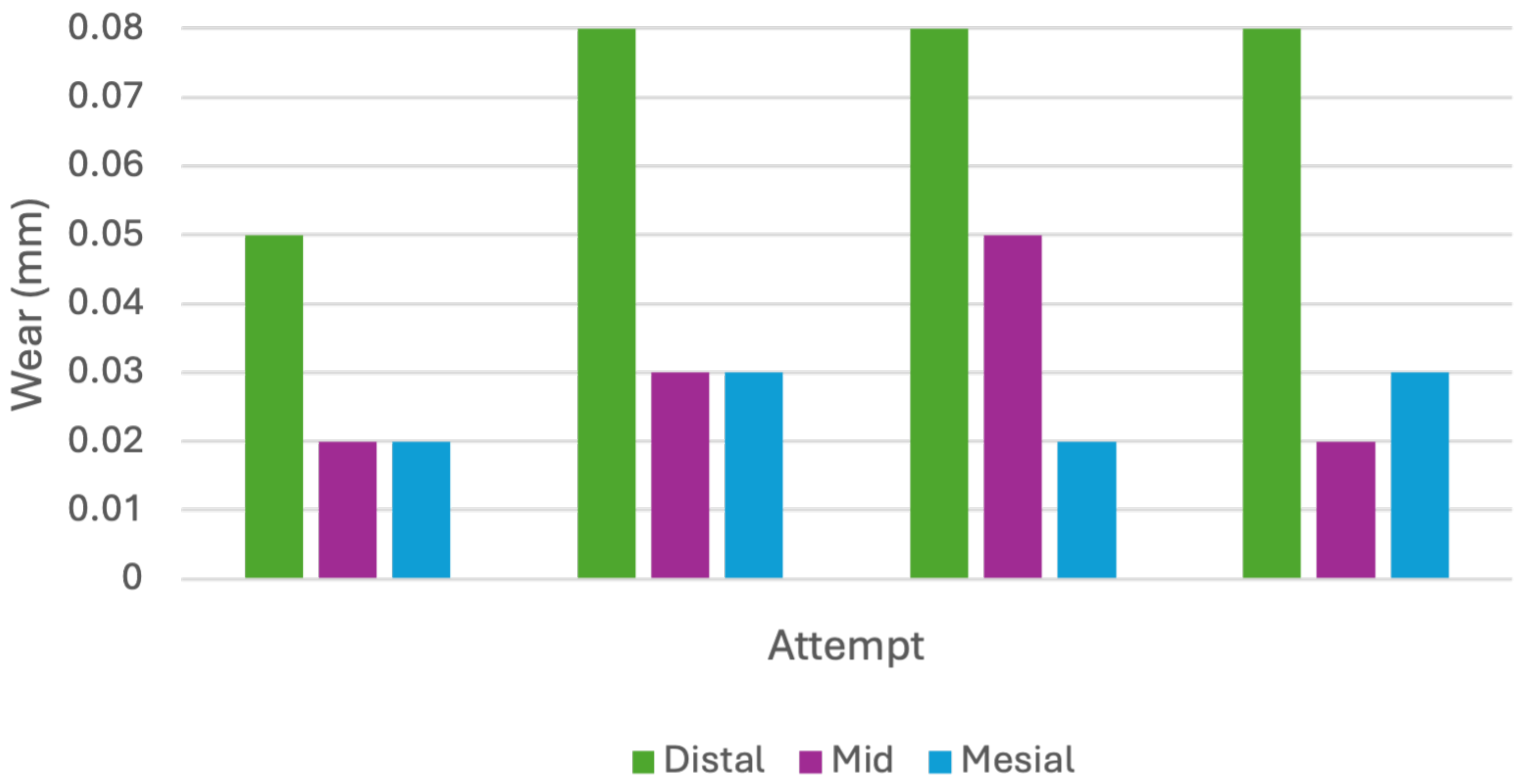

Figure 4.6 Graph showing wear of Wave after 500 cycles at the three gingival locations of the attachment

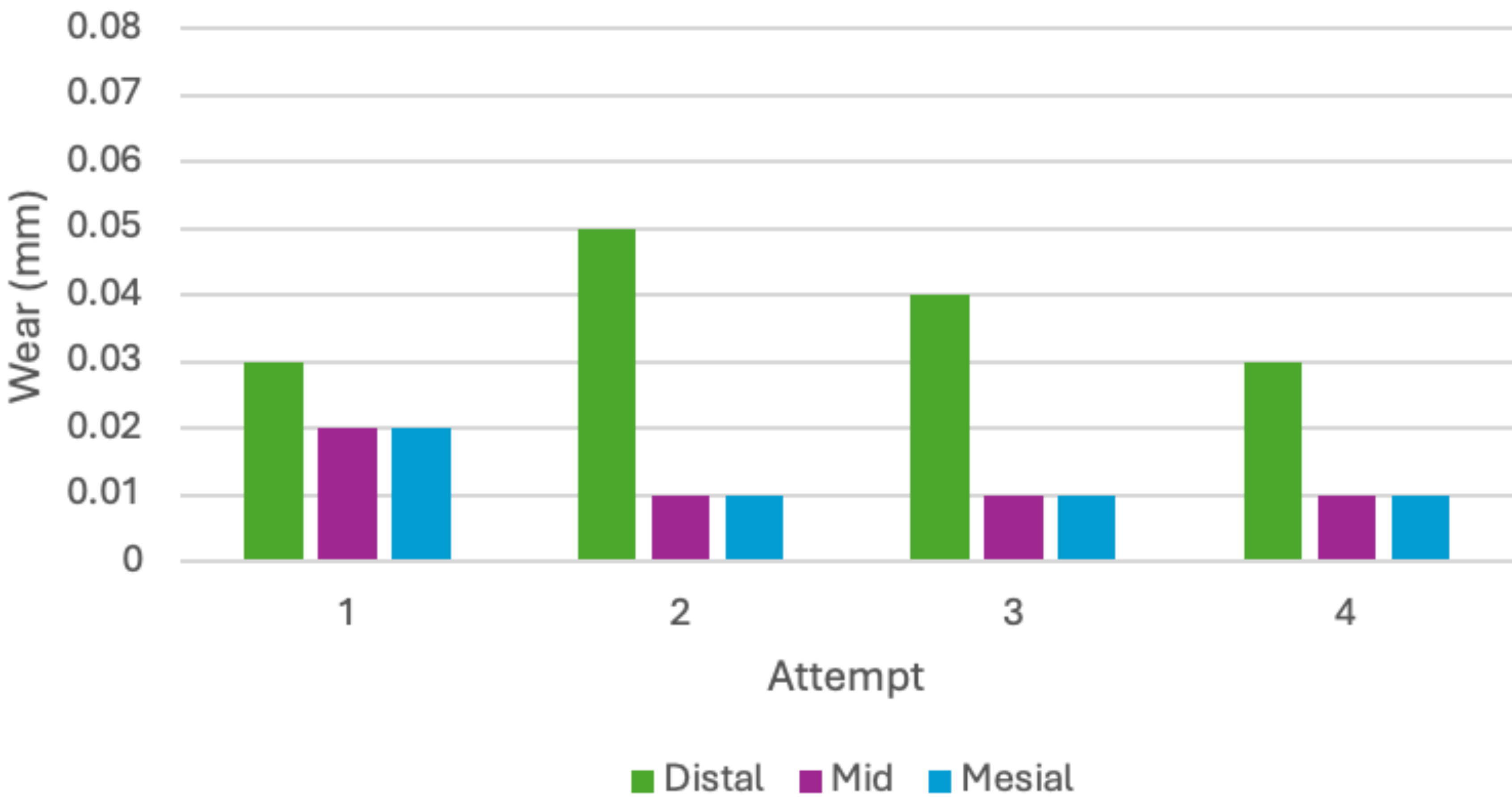

Figure 4.7 Graph showing wear of BracePaste after 250 cycles at the three gingival locations of the attachment

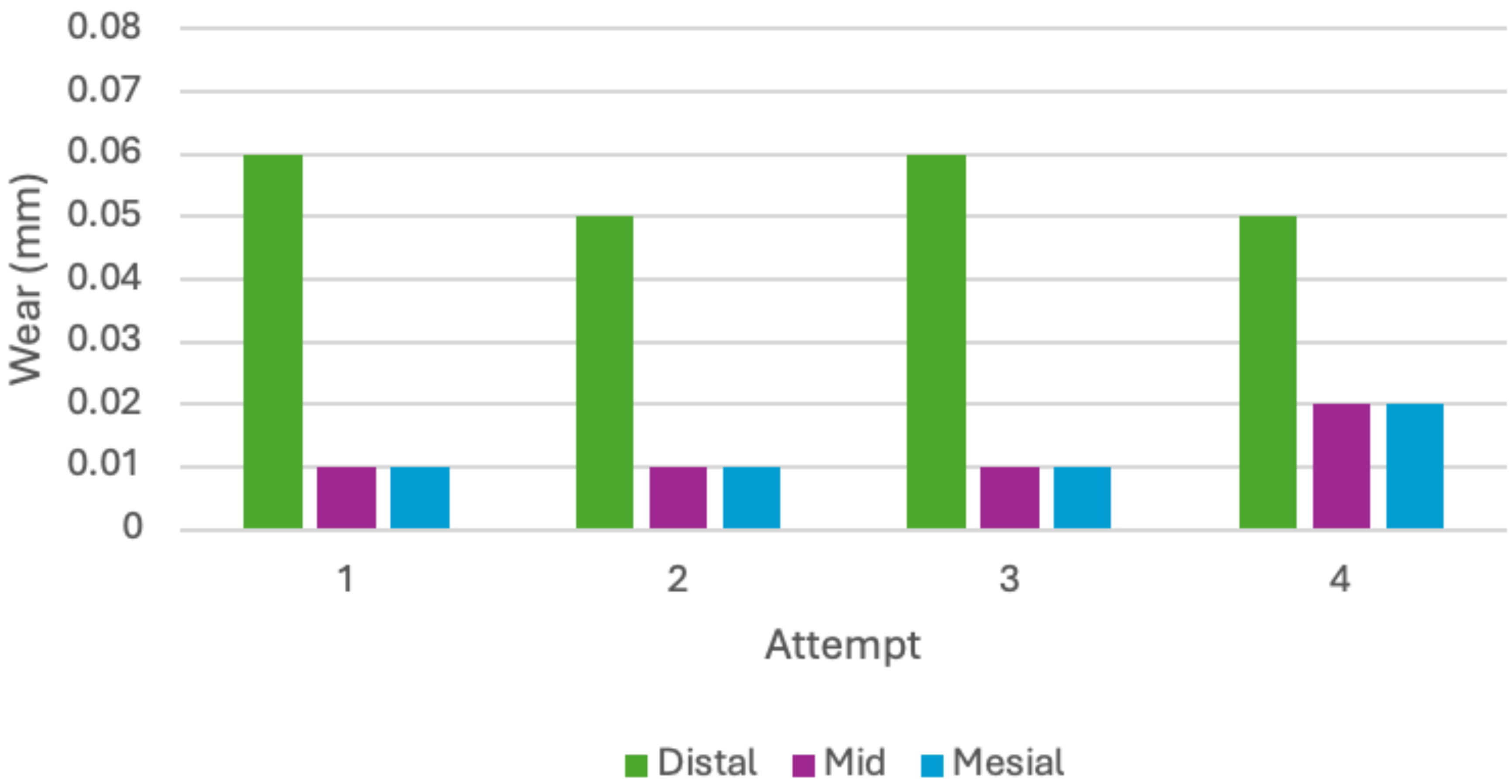

Figure 4.8 Graph showing wear of BracePaste after 500 cycles at the three gingival locations of the attachment

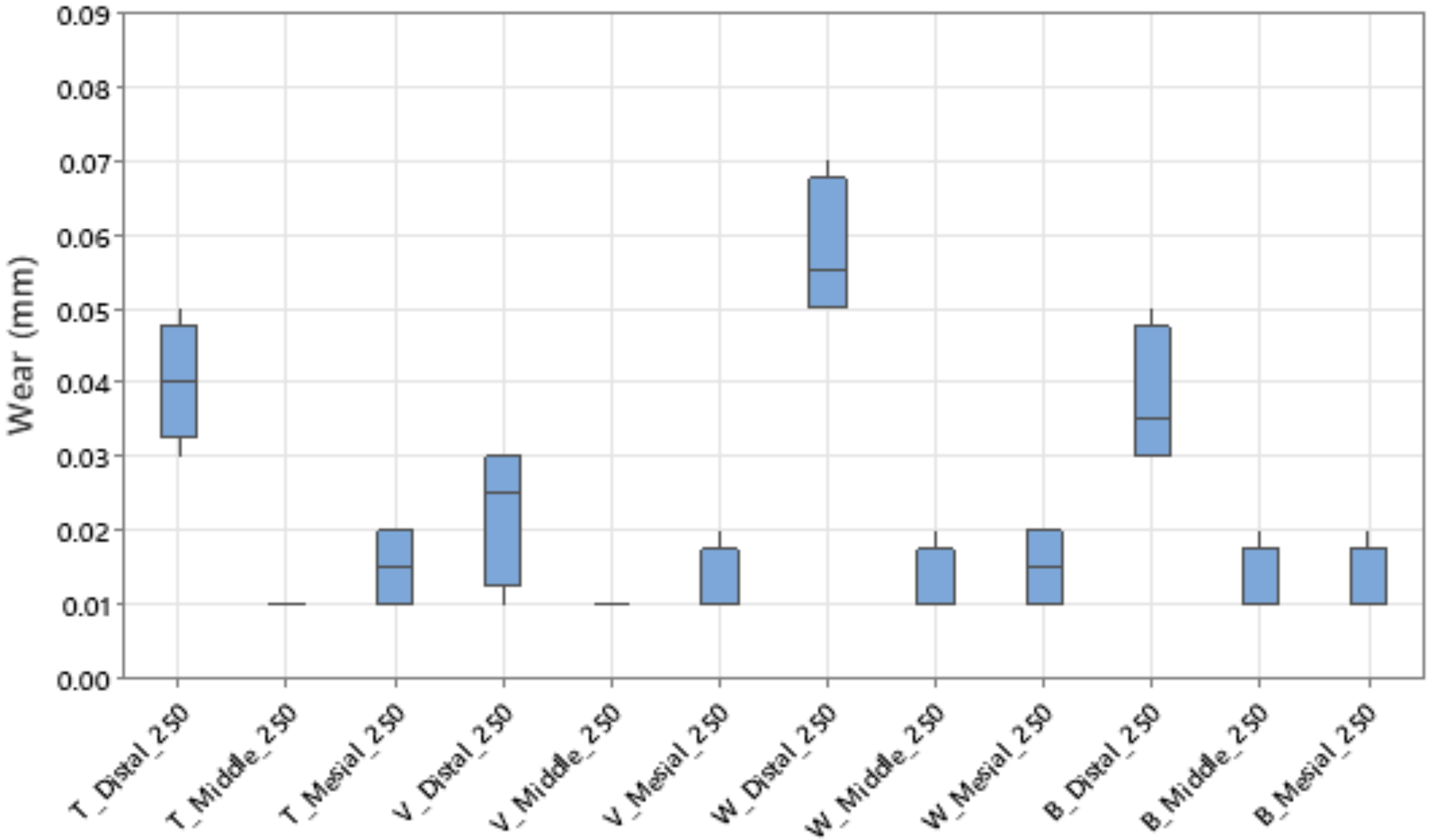

Figure 4.9 Graph showing wear at the three gingival locations of the attachment after 250 cycles

The data in this graph is represented with box and whisker plots. The line in the middle of the box shows the median value, the top and bottom of the boxes (where present) show the upper and lower quartile values and the whiskers (where present) represent the range of the rest of the data.

T = Tetric EvoCeram W = Wave
V = Venus Pearl B = BracePaste

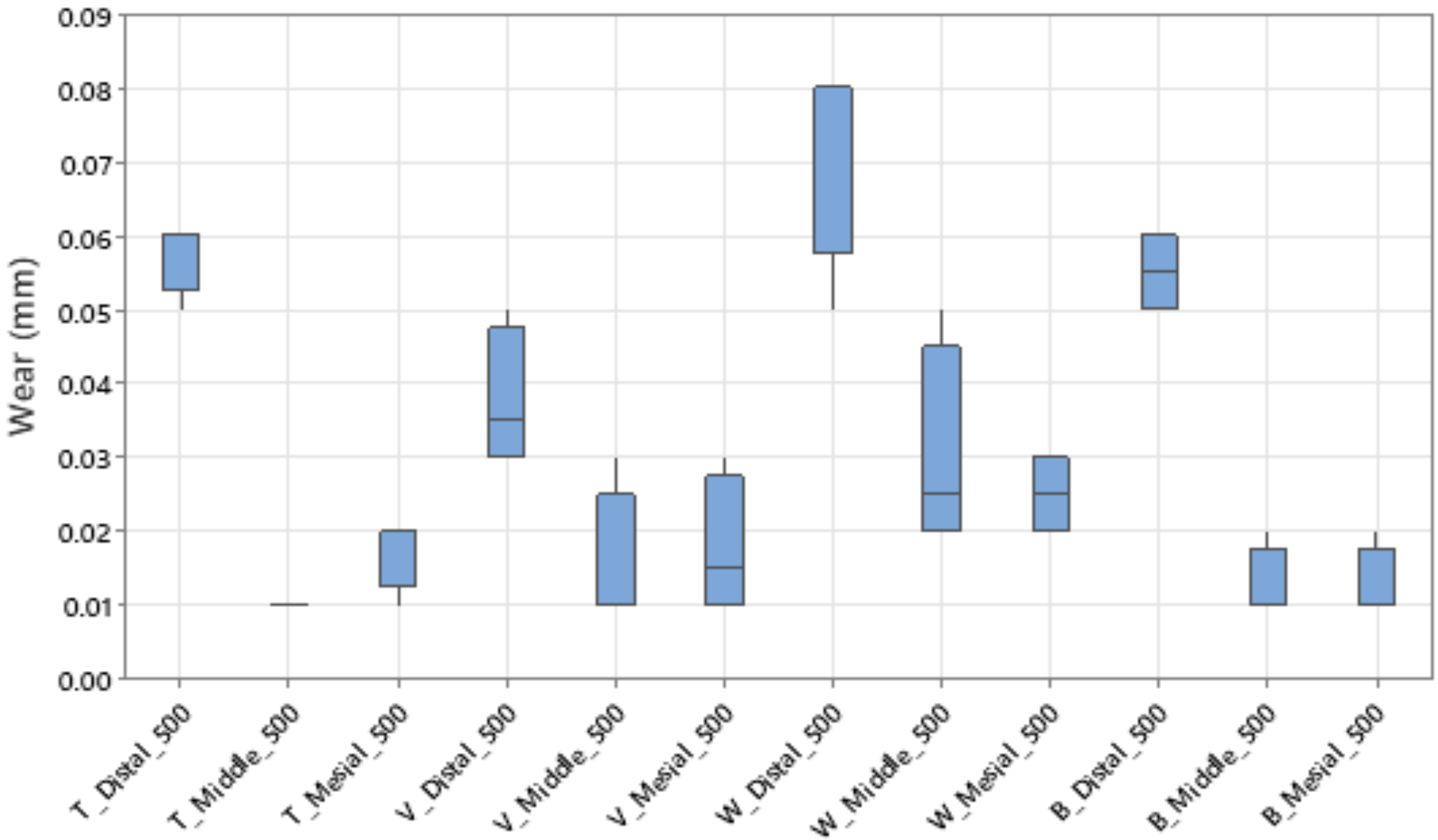

Figure 4.10 Graph showing wear at the three gingival locations of the attachment after 500 cycles

The data in this graph is represented with box and whisker plots. The line in the middle of the box shows the median value, the top and bottom of the boxes (where present) show the upper and lower quartile values and the whiskers (where present) represent the range of the rest of the data.

T = Tetric EvoCeram W = Wave
V = Venus Pearl B = BracePaste

gingival measurements. For each composite tested, the interquartile range was greater on the distal-gingival surface than the mesial or mid-gingival surfaces. At 250 and 500 cycles, the mid gingival measurement for Tetric EvoCeram was constant throughout each of the four tests, with the wear being measured at 0.01mm.

For each composite and each test at both 250 and 500 cycles, the distal-gingival surface showed the greatest amount of wear, in comparison to the mid and mesial-gingival surfaces. Given that the distal-gingival corner showed the greatest amount of wear, moving forwards only this surface was analysed. Figure 4.11 shows for each composite, the results of the wear on the distal-gingival surface, at 250 and 500 cycles. The greatest variability in the data was for Wave composite after 500 cycles. There was a 0.03mm difference between the minimum and maximum values.

4.2 Statistical analysis

Kruskal-Wallis tests were utilised to test the null hypothesis and assess the presence of a statistically significant difference between each of the four composite resins tests, at both 250 and 500 cycles. Kruskal-Wallis tests were utilised due to the small sample size and as the data is formed of non-normally distributed data, with more than two unpaired groups. For both 250 and 500 cycles the significance level was set at $p < 0.05$. An independent samples Kruskal-Wallis test was carried out, the resulting significance was $p = 0.013$ for 250 cycles and $p = 0.024$ for 500 cycles. Therefore, the null hypothesis was rejected as the p-value for 250 and 500 cycles were less than 0.05. The Kruskal-Wallis tests showed the presence of a statistically significant difference between the wear of two of the four composites but does not determine where this difference lies.

To determine which of the composites have a significantly significant difference in wear, post-hoc tests were carried out at both 250 and 500 cycles, with the significance level set at $p < 0.05$. The results of the pairwise comparisons were then adjusted with the Bonferroni correction, to account for multiple statistical tests being carried out on the data. At 250 cycles, the only statistically significant value ($p < 0.05$), was the pairwise comparison between Venus Pearl and Wave. This had a significance value of $p = 0.001$ and after adjustment with the Bonferroni correction was $p = 0.006$, Table 4.1. At 500 cycles, the only statistically significant value ($p < 0.05$), was again the pairwise comparison between Venus Pearl and Wave. The significance value was $p = 0.003$, after adjustment with the Bonferroni correction the significance value was $p = 0.016$, Table 4.2. This showed that there was a statistically significant difference in wear between Venus Pearl and Wave at both 250 and 500 cycles.

4.3 Error Study

Following re-scanning and superimposition of the typodont model five times and utilising the surface difference following superimposition there was no systematic or random error. The mean measurement error of alignment and superimposition was 0.00294mm.

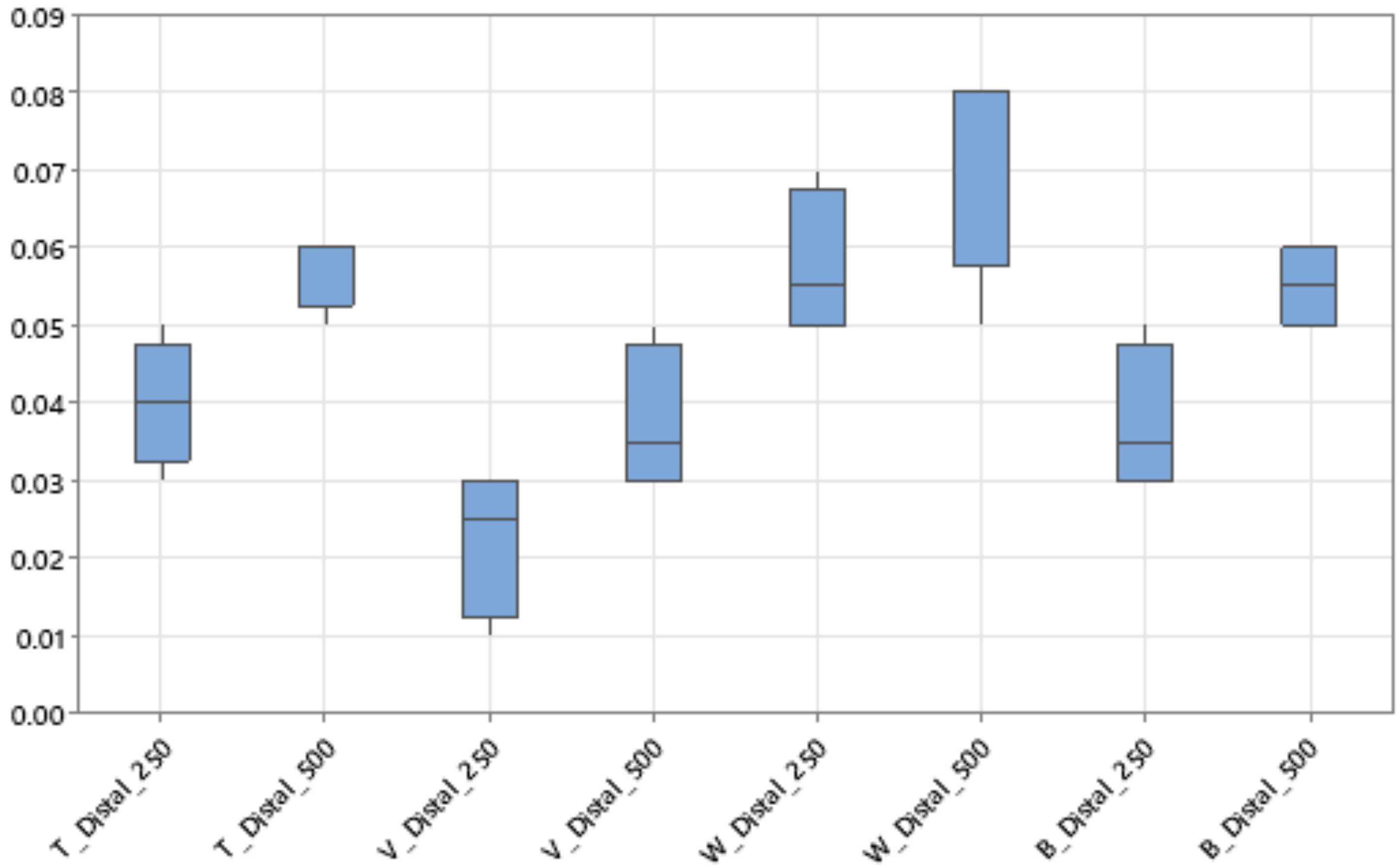

Figure 4.11 Graph showing wear at the distal-gingival location of the attachment after 250 and 500 cycles

The data in this graph is represented with box and whisker plots. The line in the middle of the box shows the median value, the top and bottom of the boxes (where present) show the upper and lower quartile values and the whiskers (where present) represent the range of the rest of the data.

T = Tetric EvoCeram W = Wave
V = Venus Pearl B = BracePaste

Pairwise Comparisons of Composite_type

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Venus-Bracepaste	-4.625	3.281	-1.410	.159	.952
Venus-Tetric	5.625	3.281	1.714	.086	.519
Venus-Wave	-10.750	3.281	-3.276	.001	.006
Bracepaste-Tetric	1.000	3.281	.305	.761	1.000
Bracepaste-Wave	6.125	3.281	1.867	.062	.372
Tetric-Wave	-5.125	3.281	-1.562	.118	.710

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 4.1 Pairwise comparisons of the four composites after 250 cycles

Pairwise Comparisons of Composite_type

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Venus-Bracepaste	-5.500	3.253	-1.691	.091	.545
Venus-Tetric	6.750	3.253	2.075	.038	.228
Venus-Wave	-9.750	3.253	-2.997	.003	.016
Bracepaste-Tetric	1.250	3.253	.384	.701	1.000
Bracepaste-Wave	4.250	3.253	1.306	.191	1.000
Tetric-Wave	-3.000	3.253	-.922	.356	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 4.2 Pairwise comparisons of the four composites after 500 cycles

CHAPTER 5

DISCUSSION

5.1 Discussion

The purpose of this study design was to isolate the effect that the composite resin chosen has on the amount of wear of composite attachments. Previous research has shown aligner removal and insertion has the potential to wear composite attachments (Borth *et al*., 2021). Therefore, assessing the wear of attachments due to aligner insertion and removal in isolation was investigated, to help inform clinicians if the composite resin chosen has any significant impact on attachment wear and therefore function.

5.2 Attachment wear

Clear aligner therapy requires the use of composite attachments to improve the predictability of orthodontic tooth movement (Simon *et al*., 2014; Rossini *et al*., 2015). The composite material chosen for fabrication of attachments needs to be able to withstand mechanical wear due to the effects of aligner insertion and removal, tooth brushing and mastication. The effect of attachment wear on the predictability of orthodontic tooth movement has not been clinically investigated, so no maximum limit of wear that still permits optimum performance has been established (Feinberg, 2015). Therefore, it is crucial that the composite chosen can withstand wear, to remain clinically effective throughout treatment. This lab based study aimed to compare the wear of four commercially available composite resins when utilised as composite attachments.

To evaluate the location and extent of wear on the composite attachments, the attachments were scanned after 250 and 500 cycles using a digital intraoral scanner (Prime Scan, Dentsply Sirona). This method has previously been found to be accurate and reproducible compared with scanning electron microscopy (Borth *et al*., 2021; Gopffarth, 2022). The digital scans were superimposed on the baseline scan to determine the extent of wear experienced by each composite material tested. Prior to superimposition the attachment itself was removed so it was not involved in the superimposition process. Superimposition relies on the "best fit" algorithm and as such if the attachment was present and marked wear had occurred, the algorithm would pull the scans away from one another to achieve best-fit of all the surface including the worn attachment, this is termed the "Pinocchio effect" (Hallgrimsson, 2015).

In this study, all attachments after 250 and 500 cycles showed surface loss due to wear generated when inserting and removing the aligner. After 500 cycles, which equates to approximately 14 weeks of aligner wear, attachment wear ranged between 0.01-0.08mm. There was minimal change of attachment shape for all the investigated composite materials. These results are in agreement with a similar *in vivo* study which showed no significant change in attachment shape over six months of use aligner wear (Barreda *et al*., 2017). Another similar study found on average, less than 0.05mm of wear over the course of 30 weeks (Borth *et al*., 2021). To compare the four composite resins investigated, statistical analysis focussed on the distal-gingival surface of the composite resins because this was the site of the most measurable wear. Analysis of the surface with the greatest measurable wear allowed direct comparison of the composite resins, without diluting the results.

The results of the present studies showed that at both 250 and 500 cycles there was a statistically significant difference ($p < 0.05$) between the four composites used. Following post-hoc testing, after 250 cycles, there was statistically significantly more wear of the distal-gingival surface of Wave ($p = 0.006$) compared to Venus Pearl. After 500 cycles, this statistically significantly greater median wear of Wave compared to

Venus Pearl remained (p = 0.016). However, due to the small amount of measurable wear found throughout this study, with a maximum of 0.08mm being found in Wave composite and a maximum of 0.05mm being found in Venus Pearl, it is assumed that this amount of wear is unlikely to be clinically significant.

5.3 Site of wear on attachment

Superimposition of several pilot scans found that significant visual wear occurred predominantly on the gingival surface of the attachment and negligible wear occurred on the occlusal, mesial or distal surfaces. This site of wear was also recently reported in a recent prospective clinical study that aimed to quantitatively evaluate the surface wear of attachments (Li and Yang, 2024). The most wear was reported at the corners of gingival edges which is in agreement with the present study. However, wear occurring only on the gingival surface is logical due to the position of the undercut around the attachment and force produced from aligner removal. When the aligner is removed, the aligner disengages from the undercut on the gingival surface of the attachment first. This present study found that the most significant wear occurred on the distal-gingival surface of the attachment, most likely due to the forcer vector involved in aligner removal.

In the present study aligner removal reproducibly disengaged from the posterior aspect of the typodont first. So, similarly to how the gingival surface wore more than the occlusal surface, the distal surface wore more than the mesial surface as this is the position the aligner disengages first. This is a product of the experimental set up. It can be hypothesised that altering the experimental set up or alternative positioning of the aligner removal tools would alter the position of greatest wear. After numerous prototype experimental set ups, the final experimental set up was chosen to best simulate how aligners are removed clinically. From clinical experience it was felt that most patients remove aligners by applying force in the premolar region, which then disengages aligners posteriorly. These finding regarding the pattern of wear supports the validity of the *in vitro* model and experimental set up best replicated the clinical scenario.

5.4 Comparison to previous studies

The methodology of the present study was similar to an earlier laboratory-based study (Borth *et al*., 2021). The methodology involved placement of an attachment on a typodont model and repeatedly inserting and removing the aligners. However the aligners were inserted and removed manually over the course of 30 weeks of simulated wear (Borth *et al*., 2021). This creates potential variabilities in the path of aligner insertion and removal, the force required to remove the aligners or the initial site of aligner disengaged. However, the study did utilise a similar method of measuring wear, using superimposed 3D scans, allowing direct comparison of results. The study concluded that the material used for attachment fabrication has a significant effect on the dimensional changes observed. The greatest wear was found in a flowable composite (Filtek Supreme Ultra Flowable, 3M ESPE) which showed 0.0479 ± 0.0704mm of wear and the least wear experienced in an orthodontic adhesive (BracePaste, American Orthodontics) which had 0.0206 ± 0.014mm of wear (Borth *et al*., 2021). The study reported a greater variation of attachment wear, with numerous outlying data points and material fragmentation. These issues were not encountered in the present study. Comparing the results from Borth *et al* with the results of the study, the greatest wear found in both studies was with a flowable composite, with a median value of 0.08mm of surface loss and the least wear found in a conventional composite (Venus Pearl), with a median value of 0.035mm. Although these results seem comparable, the study by Borth *et al* was conducted over 30 weeks of simulated aligner wear, which equates to 2100 cycles of aligner insertion and removal (Borth *et al.*, 2021). This present study measured after 500 cycles of aligner insertion and removal which equates to approximately 14 weeks of simulated wear. So comparable amounts of wear were found in this present study, even though investigated over a shorter period of simulated aligner wear. This may suggest that to a certain extent composite attachment wear plateaus over time.

A clinical study investigated the wear of two conventional composite materials used as attachments over the course of 6 months (Barreda *et al.*, 2017). The methodology included taking silicone impressions of the attachments and producing initial and final photographs of the attachments through Scanning Electron Microscopy (SEM). The degree of surface texture and shape change was then assessed visually on a three-point scale, slight or unnoticeable change, moderate change or noticeable change. This method of utilisation of SEM is subjective. The study reported 3 out of 40 attachments underwent noticeable change and 9 out of the 40 attachments underwent moderate change and concluded no significant changes in the attachment shape were noted for either composite tested. However the results were subjective in nature and makes comparisons of results between studies difficult.

5.5 Effect of filler content on attachment wear

Filler particles are inert particles that are embedded within resin matrix, they determine the mechanical properties of the composite resin and provide wear resistance. Flowable composites contain a lower filler content, which means they have a lower viscosity but this has a detrimental impact on the resistance to wear (Burgess, Walker and Davidson, 2002). In the present study, four composites were tested with filler content ranging from 57% filler content by weight (Wave composite) to 80% filler content by weight (Venus Pearl composite) as shown in Table 5.1. Analysing the area of greatest wear, the disto-gingival surface of the attachment, the results from this study have shown that Wave, with the lowest filler content, had the greatest median wear of 0.08mm. In comparison, Venus Pearl with the highest filler content experienced the least wear, with a median value of 0.035mm. BracePaste with a filler content of 72% by weight, had a median value of surface loss of 0.055mm on the distal-gingival surface. This is comparable to Tetric EvoCeram, which has a slightly higher filler content of 75.5% but had a slightly increased median wear value of 0.06mm. Wave and Venus Pearl demonstrated that when the filler content in a composite resin is increased, the median surface loss decreases. However, BracePaste and Tetric EvoCeram did not follow this same pattern, but the difference in filler content by weight only was minimal and only differed by 3.5%. This relatively small difference can be attributed to the different composition and structure of the composite resin, which influences the overall resistance to wear.

The only statistically significant difference in wear between the four composite resins tested was between Wave and Venus Pearl. These are the two composite resins with the greatest difference in filler content, with a difference of 23%. The statistically significant difference can be attributed to the difference in filler content and therefore the mechanical properties of the material. This result agrees with other previous research that the wear of composite resin is affected by the filler content (Borth *et al*., 2021; Dionysopoulos and Gerasimidou, 2022; Gazzani *et al*., 2022). A previous lab based study

Composite	Filler Content (% by weight)	Wear after 500 cycles on distal-gingival surface (median value in mm)
Tetric EvoCeram	75.5	0.06
Venus Pearl	80	0.04
Wave	57	0.08
BracePaste	72	0.06

Table 5.1 Table to demonstrate composite filler content and wear after 500 cycles.

has investigated the surface wear of two flowable composite resins (Tetric EvoFlow and Filtek Supreme Ultra Flowable) and two orthodontic adhesives (BracePaste and Transbond XT) used as composite attachments (Borth *et al*., 2021). The filler content for Tetric EvoFlow and Filtek Supreme Ultra Flowable, were 41% and 65% by weight respectively. The study found that both composites showed a higher mean wear than the orthodontic adhesives with a greater filler content. Tetric EvoFlow wore by a mean value of 0.039mm and Filtek Supreme Ultra Flowable by 0.048mm, after 2100 cycles. The orthodontic adhesives: BracePaste which had a filler content of 72% by weight, wore on average by 0.021mm and Transbond XT which had a varying filler content of 70-82%, wore on average by 0.022mm (Borth *et al*., 2021). Similar to the present study, Borth *et al* (2021) also investigated the wear of BracePaste and found that after 2100 cycles of aligner insertion and removal, the mean wear was 0.021mm (Borth *et al*., 2021). The present study found a median value of 0.05mm of surface loss after 500 cycles. Considerably more wear was found in the present study, even after less cycles of aligner insertion and removal. This difference in the extent of wear found could be attributed to the differences in methodology.

A study by Gazzani *et al* utilised tribometry and a contact probe surface profiler to compare the wear of a conventional and flowable composite (Gazzani *et al*., 2022). Their results concluded that greater wear was experienced by the flowable composite in comparison to the conventional composite (Gazzani *et al*., 2022), supporting the results found in this study. Although the experimental design significantly differs from that in the current study, it is promising that the results are in agreement, with flowable composite resin experiencing greater wear than conventional composite (Gazzani *et al*., 2022).

Barreda *et al*. (2017) investigated two conventional composite resins, Filtek Z350 XT, a nanofilled material with 72.5% filler content by weight, and Amelogen Plus TW, a micro-hybrid material with 76% filler by weight. This contrasted with the results found in the present study and those found in previous studies (Borth *et al*., 2021 and Gazzani *et al*., 2022). Barreda *et al*. (2017) found significantly more surface wear and change in surface texture in Amelogen Plus TW, the composite with the higher filler content (Barreda *et al*., 2017). The difference in results could be due to the differences in methodology, as this study was conducted clinically, so confounding factors such as toothbrushing and mastication could be contributing to the measurable wear (Barreda *et al*.,2007) and the others were laboratory based. In addition, the outcome measures of the studies were different, one based on subjective evaluation of SEM scans (Barreda *et al.,* 2017); whereas the present study and previous studies were *in vitro* studies based on 3D source imaging (Borth *et al*., 2021).

5.6 Clinical relevance

The greatest amount of wear found in this study was 0.08mm on the distal-gingival surface of Wave composite. This difference was only detected and measured by superimposition of the 3D digital scan taken with an intra-oral scanner. As a proportion of the overall size of the attachment, the wear found in this study, which is in agreement with previous studies, was only a small fraction of the overall size. It can be assumed that the effect on clinical performance will be negligible, with other factors playing a more significant role in the success of treatment with clear aligners. For example, patient compliance with full-time wear of the aligners. Therefore, all four composite resins tested in this study could be used for attachments with clear aligner therapy.

Of financial importance to clinicians, is the cost effectiveness of the materials utilised, balancing the properties and quality of a composite resin with the affordability. The ideal composite resin chosen would not only have the greatest resistance to wear when utilised as an attachment but have optimal handling characteristics and be cost effective. Table 5.2 illustrates the composites investigated in this study, the filler content, wear experienced (mm) and price per gram. At £8.50 per gram, BracePaste was the cheapest investigated material and performed second best out of the four composites in this study. Venus Pearl experienced the least wear during this study but at £16.98 per gram is the third most expensive composite tested, being almost double the cost of BracePaste. Tetric EvoCeram was the most expensive material in this study and after Wave composite experienced the greatest wear. This suggests that BracePaste may be the most cost-effective option, at a low cost whilst maintaining high wear resistance and clinical performance.

5.7 Limitations

Whilst this current study provides evidence that the composite resin utilised for fabrication of attachments influences the surface loss due to repeated aligner insertion and removal, there are certain elements of the methodology that affect the generalisability of the results.

Unlike similar laboratory-based studies, this study aimed to replicate the clinical scenario as closely as possible. This meant the experimental set up could not be fully automated and due to the limitations of practicality, 500 cycles of aligner insertion and removal were utilised. Pilot testing confirmed that this was enough cycles to elicit measurable wear, whilst maintaining practicality. Estimating aligners are removed and

Composite	Type	Price (per gram)	Filler Content (by weight %)	Median wear on distal-gingival surface after 500 cycles (mm)
Venus Pearl	Conventional composite	£16.98	80.0	0.04
Tetric EvoCeram	Conventional composite	£20.56	75.0 - 76.0	0.06
Wave	Flowable composite	£13.14	57.0	0.08
BracePaste	Orthodontic adhesive	£8.50	72.0	0.05

Table 5.2 Table to demonstrate composite filler content, price and wear after 500 cycles.

aligner wear, or a short course of treatment lasting 10 aligners. A limitation of this study is that ideally more cycles would have been completed to replicate a normal course of clear aligner therapy. It is estimated that the average course of clear aligner therapy lasts around 20 aligners, so completion of 1000 cycles would have better replicated the wear experienced during clear aligner therapy. Partial automation of the MTS Criterion Model 42 machine reduced the time required for testing; however full automation was not possible. To achieve full automation, a customised machine would need to be developed which was not possible within the constraints of this project or to utilise an *in vivo* clinical study design.

A potential limitation of this research is the laboratory-based nature of the study design, which can never fully replicate the oral environment. The experimental set up developed does not assess the impact of other factors that can wear attachments during clinical use, for example mastication and toothbrushing. Although, previous research has already investigated the effect of toothbrushing on composite attachments (Vas and Varghese, 2024). It was concluded that there are no clinically significant changes in the surface morphology of composite attachments due to toothbrushing.

Ideally, all commercially available composites for the fabrication of aligner attachments would be tested. However, in the time constraints of this research project this was not feasible. To help overcome this shortcoming, a broad selection of composites was chosen with a wide variety of composite properties, to give a representative sample of the composite resins available on the market that clinicians may choose to use.

5.8 Future Research

This study along with previous studies, have provided evidence that composite attachments wear during clear aligner therapy (Borth *et al.*, 2021). The results of previous research hypothesise that any wear of composite attachments will reduce the efficiency and predictability of orthodontic tooth movement (Simon *et al.*, 2014; Rossini *et al.*, 2015). However, there is no high-quality literature examining this and this hypothesis has not yet been proven (Feinberg, 2015). Future research should include clinical trials, examining the effect of composite attachment wear on the efficiency and predictability of tooth movement. The results of this research will allow us to fully understand the potential impact and significance attachment wear has on orthodontic tooth movement and will guide future research in this area.

Previous evidence in the literature has shown that no clinically significant changes in the surface morphology of composite attachments occur due to toothbrushing (Vas and Varghese, 2024). However, research in this area has utilised lab-based techniques to simulate the wear of toothbrushing without considering the effect toothpaste has on the wear of composite attachments. It is widely known that toothpastes, particularly those with a high relative dentine abrasion value, increase the wear and surface roughness of composites (Augusto *et al.*, 2018). Future work could investigate the effect of toothbrushing and abrasion from toothpaste on the wear of composite attachments, this would allow clinicians to better advise their patients on oral hygiene measures during clear aligner treatment.

The effect of saliva on attachment wear and aligner degradation has not been investigated as part of this study but could provide useful information on how absorption of water during wear alters the mechanical properties of clear aligners or act as lubricant during aligner insertion and removal.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

Within the limitations of the current study the following conclusions can be made. Using the current *in vitro* model of aligner insertion and removal, the distal gingival surface of the attachments showed the greatest wear. After 500 cycles of aligner insertion and removal, which equates to approximately 14 weeks of aligner wear, attachment wear ranged between 0.01 - 0.08mm. Therefore, there was no marked clinically detectable change in any attachment shape for any of the four composite materials investigated. Statistical analysis showed that the wear of Wave on the disto-gingival surface was statistically significantly ($p < 0.05$) greater than Venus Pearl. However, it is doubtful that this difference is clinically significant. Therefore, it can be postulated that any of the composite resins investigated would be clinically adequate to act as composite attachments in clear aligner therapy.

CHAPTER 7

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