THE WORST FOODS FOR ORTHODONTIC PATIENTS: AN IN VITRO MATERIALS STUDY DETERMINING THE MAXIMUM MECHANICAL STRESSES CREATED BY COMMON FOODS

A Thesis

by

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Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2022

Major Subject: Oral Biology

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ABSTRACT

Background: Forces placed on orthodontic appliances by certain foods are problematic during orthodontic treatment. There is no evidence to substantiate recommendations given to orthodontic patients regarding safe food consumption.

Purpose: We aimed to create an evidence-based food recommendation guide by comparing forces created by various food samples to the strength of the orthodontic bond.

Research Design: A novel food testing apparatus was designed using a 3D printed testing cube, an orthodontic bracket soldered to a metallic rod, and an Instron Universal Testing machine. The compressive stress created by fifty common food items of various hardness and morphologies was measured. Forty shear bond strength measurements of brackets bonded to extracted lower first premolars were also measured *in vitro* using the same program. These forces were compared in order to determine which food items are most likely to cause orthodontic bond failures during treatment.

Results: An evidence-based food recommendation chart for orthodontic patients was created that largely mirrors recommendations that orthodontic practitioners give to their patients, with several exceptions.

Conclusion: Food consumption recommendations should be itemized rather than categorical, so as to not limit diets unnecessarily or fail to mention certain problematic food items. The testing apparatus designed in the current study should be used to create a comprehensive food recommendation database for orthodontic patients.

ACKNOWLEDGMENTS

I'd like to thank my committee members, Dr. Peter Buschang, Dr. Yan Jing, Dr. Reginald Taylor, and Dr. Seok Hwan Cho for their support and guidance while designing and executing this project. I'd like to also thank Dr. Matthew Kesterke and Cameron Stevens for their hands-on contributions that made this study possible.

I would like to acknowledge the orthodontic residency class of 2022: Drs. Luke Chastain, Daniel Dooley, Abbey Janssen, Cameron Keylor, and Kativa Strickland. You are the smartest and most talented group of individuals I've ever had the pleasure of being around, and I know that there are great things in store for each of you! I am not only going to be a better orthodontist because of you, but a better person as well.

To my parents, Jon, Arlyne, Greg, and Mariateresa, thank you for always believing in me, supporting me, and inspiring me to chase my dreams. I am so blessed to have a family who is always there for me whenever I need encouragement.

And finally, I would be lost without my wife Kasayla. You are the most special person in my life and your unconditional love and support is the reason I've had the drive to keep moving forward. I cannot be more excited for the future we will share. And to our new baby, I hope that we can inspire you to achieve whatever is it that will make you happy.

CONTRIBUTORS AND FUNDING SOURCES

This work was supported by a thesis committee consisting of Drs. Peter Buschang, Yan Jing, and Reginald Taylor of the Department of Graduate Orthodontics and Dr. Seok Hwan Cho of the Department of Graduate Prosthodontics at Texas A&M College of Dentistry.

All work for the thesis was completed by the student, under the advisement and with assistance of the committee members.

This work was made possible by Dr. Matthew Kesterke and Cameron Stevens for their contributions with specimen and data collection and by Texas A&M University for funding and laboratory equipment.

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LITERATURE REVIEW

Orthodontic Treatment Time and Contribution of Broken Brackets/Bands

Orthodontic treatment time is an important consideration for both orthodontic practitioners and their patients alike. For orthodontists, shorter average treatment times are beneficial for their reputation, finances, office systems, and office growth. For patients, shorter treatment times help avoid the detrimental long-term biological complications of orthodontic therapy such as root resorption[1], white spot lesions[2] and psychological consequences, such as decreased compliance and lower self-esteem related to having fixed appliances into late adolescence.[3] Average orthodontic treatment time is a difficult parameter to calculate as every patient has different needs and every practitioner has a different treatment philosophy. Skidmore et al.[4] and Fink & Smith[5] reported average treatment times of 23.5 and 23.1 months respectively, while Beckwith et al.[6] reported an average of 28.6 months. This difference can be explained by the fact that the later study did not exclude treatment completed in two phases. Overall, mean private practice treatment times have been reported in the US and Northern Europe as being between 23 and 31 months.[7]

Many studies have conducted multiple regression analyses to determine contributory factors to increased treatment time. These studies have been able to explain between 25-50%[4-6] of the variation, most of which include rebonded brackets and bands. Beckwith et al.[6] showed that amongst 140 consecutively treated orthodontic patients from five different offices, 46.9% of the treatment duration could be explained by the investigated variables, 13% of which was associated with replaced brackets and bands due to repositioning or breakage reasons (second largest contributor), with replaced bands contributing the most. Skidmore et al.[4], who looked at 366 consecutively treated patients at one orthodontic office, showed that treatment time is increased on average 2 months in patients with 3 or more bracket failures. This study delineated between brackets and bands replaced for positioning and those replaced due to breakages, with each repositioning contributing more to treatment time (0.6 months added per reposition) than breakages (0.3 months added per breakage). Therefore, although previous research has shown that replacement of broken brackets and bands is usually not the greater contributor to increased treatment time, it is still a significant cofounder, and undoubtedly a financial and workflow nuisance. Beckwith et al.[6] reported an average of 5.1 brackets and 2.4 bands needing replacement per patient, and Skidmore et al. [4] reported that 24.9% of patients had 3 or more failed brackets, all of which would contribute to at least a 2 month increase in treatment time. Other investigated factors that have been found to statistically increase treatment time include: missed appointments, poor oral hygiene, treatment in multiple phases, poor headgear wear, male sex, maxillary crowding >3mm, Class 2 molar relationships, extractions, poor elastic wear, decreased pretreatment mandibular plane angle (MPA), and increased pretreatment ANB.[4-8]

Debonding explained

When an orthodontic bracket debonds, there are many different factors to consider: bracket type, tooth type, adhesive type, location of the failure, type/direction of the debonding force, contamination, and cumulative occlusal load. Typical 24-hour *in vitro* shear bond strengths (SBSs) of brackets bonded to extracted teeth range from 5-16 MPa,[9-16] with the primary location of failure being at the bracket-composite interface.[9-12] Most clinicians would anecdotally agree that the primary location of failure is at this interface, requiring the subsequent removal of composite off of the tooth. Sharma-Sayal et al.[9], however, found that both the bracket-composite interface and enamel-composite interface failed at similar rates, therefore the research, while being one-sided, is not absolute. In a study designed to test the enamel-composite interface, Ozturk et al.[17] found that SBSs of this junction were much higher, and ranged from 25-45 MPa. One possible explanation for this difference is bracket base designs that do not perfectly conform to the tooth, leading to nonuniform coatings and thicknesses of the composite to the bracket base, causing the bond to fail earlier. Another reason is how the debonding force is applied to a bracket versus a uniform mass of composite *in vitro*. Most studies using brackets either pull a metal ligature wrapped around the gingival wings, creating both a shear and tensile force[10-13,15,18], or place a sharpened blade at the bracket base-enamel interface,[9,19] which would differentially test the different bonding interfaces along with creating a wedging force between the enamel and bracket. Both of these methods introduce directions of forces that are unideal for true SBS testing, as was conducted by Ozturk et al.[17], who applied a force transducer at the interface of a composite mass to enamel. Finally, considering that enamel is first etched and then treated with a non-filler primer, whereas brackets simply have filled composite pressed into macroscopic retention, it is reasonable to assume that a greater surface area of contact is achieved between the tooth and composite, leading to increase in SBS at this interface.

Regardless of the interface tested, the *in vitro* literature agrees that the highest mean SBSs are found at the lower 1st molar (and occasionally upper canine), and the lowest are found at the upper first molar[10,17]. It has been suggested that poor quality etch patterns secondary to prismless enamel[20], which is most commonly found in posterior teeth,[21] could influence the strength of the bond. While this would explain differences in bond strengths at the composite-enamel junction, it does not explain those at the bracket-composite junction, which are more common. The differences in SBS at the bracket-composite junction might be explained by the variability of morphologies in teeth of the same type and how well standard orthodontic brackets conform to them. The lower surface area of contact of ill-conforming bracket bases leads to an inconsistent adhesive film thickness which would affect the bond strength.[12]

Another bracket-related factor to consider is the bracket base interface, as this determines the total surface area contact between the bonding composite and the bracket that is going to resist the debonding force. Modern orthodontic brackets typically have either a foil mesh ranging in size from 60 to 100 gauge or machined mechanical undercuts, which are physically or chemically microetched. Both Wang et al.[22] and Sharma-Sayal et al.[9] found that the larger the mesh size (60g as compared to 100g), the better the penetration of the composite into the bracket base and the better the resultant bond strength. As far as the brackets with machined mechanical undercuts, Sharma-Sayal et al.[9] found that American Orthodontics' Time bracket had one of the highest SBS, whereas Wang et al.[22] found that Unitek's Dynalock bracket performed around the range of 80g foil mesh sizes. Additionally, Siomka and Powers[23] found that grooved bases had higher bond strengths than foil mesh. It is also important to note that while larger mesh sizes, machined undercuts, and microetching improve bond strength per unit area, the overall size of the bracket base may also have an effect. However, this effect is controversial as Wang et al.[22] reported that the larger the bracket base the greater its ability to resist debonding forces whereas MacColl et al.[24] stated that this difference is only observed between very small brackets ($2.32mm^2$) and medium bracket bases ($6.82mm^2$), and that there was no difference between medium and large bases ($12.35mm^2$). Although these studies measured debonding force per unit area, it is reasonable to believe that an overall larger area may have an exponential, rather than linear, increase in total bond strength, which would increase the force per unit area relative to a larger bracket base size, however more studies would be required to confirm this.

Another factor to consider is the strength of the bonding material. Fox et al.[11] found that the conventional chemical cure bonding composite Right-On® had the higher mean fracture strength (55.1N, which is to 6.05 MPA for a 3M first premolar bracket) than the fluoride releasing composite Direct® and the glass ionomer cement KETAC-CEM®, which had the lowest fracture strength (33.1N or 3.6 MPa). Linklater and Gordon[12] also used Right-On® conventional bonding composite, but found much higher mean bond strengths for maxillary (11.9 MPa) and mandibular (10.9 MPa) premolars, even though they used a similar methodology. Ozturk et al.[17] compared two different light cured composite adhesives *in vitro* (Transbond XT® and Light Bond®) and found that Transbond XT® has mean SBS values ranging from 25-39 MPa depending on the tooth, and Light Bond® had slightly higher values, ranging from 30-44 MPa. This study provides perhaps a more precise depiction of the true SBS value of these materials, as orthodontic brackets were not used, and therefore only the enamel-composite interface was subjected to testing. As for the remaining literature, most studies use Transbond XT® as their orthodontic bonding resin, potentially due to its widespread clinical usage and subsequent reliability. Hobson et al.[10] confirmed the reliability of Transbond XT®, reporting that 80% probability of failure did not occur for any tooth until at least 10 MPa of stress was applied. Sharma-Sayal et al.[9] also used Transbond XT® and reported lower overall SBS (4-9 MPa for conventional orthodontic brackets), however their testing was conducted using a sharp chisel blade at the enamel-bracket interface, and thus reported a lower clinically acceptable bond strength of 2.86 MPa. To summarize, all chemical and light cure orthodontic composites on the market provide acceptable SBS values, which are even greater when only evaluating the enamel-composite interface. This finding, along with the finding that *in vitro* failures typically occur at the composite-bracket interface, indicates that type of bonding composite has minimal effect on failure rate of brackets, and that if a failure were to occur at the composite-tooth interface, it would be almost certainly due to inadequate clinical bonding procedures.

When analyzing bond failure patterns *in vivo*, it is clear that *in vitro* debonding patterns do not coincide. Linklater and Gordon[25] studied the epidemiology of *in vivo* bonding failures, and found that mandibular bonds failed at a significantly greater rate (9%) than maxillary bonds (4%) with an average overall failure rate of 6.34%, and that posterior teeth had significantly higher rates of failure when compared to anterior teeth. They reported that sex of the patients and their reported fluoridation history did not affect the results, and that the results were likely due to a combination of masticatory forces, isolation, alterations in tooth morphology, and treatment mechanics. This finding was mirrored by all other studies that looked at failure rates *in vivo*.[26-29] This discrepancy between *in vitro* and *in vivo* debonding patterns is not surprisingly due to the uneven distribution of masticatory forces throughout the dentition and the difficulties of preventing moisture contamination in certain areas of the oral cavity. Although both maxillary and mandibular brackets will, on average, succumb to similar cyclical loading from orthodontic appliances, mandibular brackets are subjected to additional cyclical loading from external forces (food, opposing dentition). Studies have shown that cyclical loading of the orthodontic bond significantly decreases its overall bond strength.[13,19,30,31] Furthermore, if the clinician is not diligent with providing adequate clearance of brackets from the occlusion, mandibular brackets could be subject to the full bite force (39-66 N[32]), which, according to the literature, is more than sufficient force to debond any orthodontic bracket under any condition[9-16]. Moisture contamination from blood or saliva has also been shown to dramatically decrease the strength of the orthodontic bond[14,15,18,33], which would differentially affect mandibular bonds due to proximity to the tongue, salivary ducts, and salivary pooling.

All of the factors discussed above have resulted in *in vitro* bond strengths that range from 5-16 MPa at the composite/bracket junction. Considering the obvious differences between *in vitro* and *in vivo* conditions, are these strengths acceptable? Both Hobson et al. and Reynolds reported acceptable clinical bond strengths based on probability testing[10,34]. Reynolds reported that 5.9-7.8 MPa was clinically acceptable, and Hobson et al. stated that 8-9 MPa "more than exceeds the clinical requirement for incisors". With regards to posterior teeth, Hobson et al. found that 5 MPa on posterior teeth results in a failure probability of 8-40%. Therefore, clinical acceptance should be higher than 5 MPa. Although probability testing is not ideal, there is currently no other way to determine clinically acceptable strengths, as there are no tools to conduct SBS testing intraorally. Elides & Brantley suggested that a debonding plier be constructed with the ability to record SBS values, which would greatly improve our understanding of clinical debonds.[35] That being said, clinical acceptance must be between 5-16 MPa, or perhaps even lower, as we would not be using any of the orthodontic brackets and composites used in *in vitro* testing otherwise.

Bite Analysis During Mastication

The final, and perhaps most important factors to consider in relation to orthodontic bracket failures is the patient's occlusion and masticatory forces. While the strength of the bond is an important factor, it is not only limited by the materials and brackets available, but also by the simple fact that they need to be efficiently and safely removed by the end of orthodontic treatment without enamel fracture[13] (13.5-14.5 MPa[36,37]). When determining the amount of force being placed on an orthodontic bracket, one consideration is the patient's closing velocity, as force is a function of mass and acceleration. Lassauzay et al. used an electromagnetic induction machine with receiver coils glued to subject's upper and lower central incisors to record jaw movements during the first 5 chewing cycles, and found that the average velocity of the first cycle was 52 mm/s (range 34-64) and average vertical amplitude of the first bite was 22mm.[38] They found that both opening and closing were faster during the first cycle, which also had the largest vertical amplitude than subsequent cycles. Foster et al.[39] used the exact same jaw recording mechanism, and recorded closing bite velocities between 47-60mm/s. Meullenet et al.[40] also used a jaw tracking instrument (BioResearch JT-3 Jaw Tracker Array) with magnets secured to subject's incisors and recorded biting velocities between 19.8-35.1 mm/s. The recorded bite velocities in this study were likely lower as the subjects were individuals trained in descriptive analysis and instructed to chew at a rate of 1 bite per second, which likely led to more deliberate, slower chewing. Dan & Kohyama[41] criticized the past literature on closing velocity, citing that the closing cycle is not a single event, but binary; composing of a fast close prior to food contact, and a slow close or "power stroke", in which the resistance provided by the food slows the biting velocity and stimulates greater muscle activity from the closing muscles of mastication (medial pterygoid, temporalis, masseter).[41] The literature has found that when the slow close was calculated independently, lower values of closing velocity were recorded. Dan & Kohyama reported average slow close velocities between 4.8 and 7.5mm/s, which may be slightly low because in their study, much like Meullenet et al., the subjects were given specific biting instructions, telling them to bite "in the optimal way to perceive the hardness [of the sample]". However, Snipes et al. concurred that around 5mm/s marked the transition to slow closing.[43] In other studies, these values were slightly higher. Buschang et al. tracked the speed of the jaw during the chewing cycle, and the power stroke appeared to occur at velocities between 10-15 mm/s[44] and Peyron et al. calculated much higher slow close velocities of 34 mm/s for carrots and 26 mm/s for cheese.[45] If the true human slow close velocities approximate those found by Dan & Kohyama, Snipes et al., and Buschang et al., then this is a variable that could be reasonably replicated *in vitro*, as the maximum testing speed of the Instron 5542 is 8.5 mm/s.

There are many patient-based factors that make quantitative analysis of the human chewing cycle inconsistent in the literature. Some are immeasurable. As the suggestion by Foster et al., every individual's memory and experiences with the particular food item could adapt their chewing cycle prior to placement of the food into their mouth.[39] Even if patients had no prior experience with the particular food, just seeing and feeling the food item beforehand likely plays a role in their chewing of it. The main measurable factor deals in science of psycho-rheology, which studies the feedback mechanism between the texture of materials and sensory responses.[40] Not only do humans have proprioceptors in the periodontal ligament which detect the hardness of the bolus during the first chewing cycle, thereby affecting subsequent cycles,[38,41] but we also have afferent fibers in the tongue, cheeks, and lips, which alter the chewing cycle based off of the bolus's texture. In order to analyze how certain mechanical properties of food affect the chewing cycle, several studies have been conducted using plastic (low elastic modulus) and elastic (high elastic modulus) model foods, cheeses, or gums of differing hardness/textures. Lassauzay et al.[38] found that closing speeds increased with increasing hardness of the food product, and that the harder the product, the more variability there was. Peyron et al.[46] also found a mild increase in closing velocity with increasing hardness of food, but concluded that the most substantial adaptations to increasing bolus hardness were increases in chewing cycles, EMG activity, and vertical amplitudes of the bite. Foster et al., who tested both elastic and plastic food products, confirmed the finding that increasing the product's hardness increased the number of chewing cycles and muscular work, but found that it had very little effect on the closing velocity.[39] Getting a little more specific, Anderson et al. found that differing gum hardness only affected the closing and opening velocities in specific portions of the chewing cycle. They found that hard gum only showed a faster closing velocity between the first 10-40% of the closing cycles, and then again in the last 20%, which would approximate the power stroke. However, the difference between the velocity during the power stroke of the hard and soft gum was minimal, at about 1 mm/s.[47] As far as the food's rheology, Foster et al. found that plastic products were chewed at a slower frequency than elastic, with larger vertical and lateral amplitudes, but that there was no difference in closing velocity between the two.[39] Therefore, it is clear that the mechanical properties of food play a role in the chewing cycle, and that using a universal testing machine clearly has limitations in replicating the human bite. That being said, closing velocity does not appear to be affected greatly by psycho-rheology, especially during the first cycle and power stroke, making at a more appropriate variable to replicate *in vitro*.

Summary of the Literature and Introduction to the Current Study

Orthodontic treatment has been reported to last generally between 2 and 2.5 years, usually taking place during a crucial time in a young adolescent's life in terms of social development. While orthodontic treatment generally affects a young person's psyche in a positive way upon completion, it is important for treatment to be conducted efficiently to prevent psychological sequelae of having braces late into high school, as well as biological consequences such as white spot lesions and external root resorption. Replacement of broken brackets and bands has been shown in the literature to be a significant contributor to overall treatment time. With as much as 25% of patients requiring the replacement of 3 or more brackets due to failures, treatment time can be dramatically increased, leading to frustration from the patient, parent, and practitioner. It is the orthodontist’s duty to their patients to investigate the methodology behind bracket failures, and adapt both the bonding procedures as well as the instruction given to patients and parents accordingly.

The SBS of the orthodontic bond and factors that contribute to it have been heavily analyzed in the literature. Factors that are almost universally agreed upon to increase the strength of the bond are: bracket base designs with either large machined undercuts or large mesh sizes (60g), use of chemical or light cured orthodontic resin as opposed to other bonding agents such as glass ionomer, proper isolation during bonding, and a consistent adhesive film thickness secondary to a close adaptation of the bracket base to the tooth surface. Other factors that have been hypothesized to increase bond strength are the presence of prismatic enamel with consistent etch patterns and teeth with less morphological variability. However, this is where the first discrepancy lies between failure patterns *in vitro* and *in vivo*, as epidemiological patterns suggest that lower posterior teeth have the highest rate of bonding failures, even with highly prismatic enamel and relatively consistent tooth contours. Furthermore, with a majority of orthodontic bonding failures occurring at the bracket-composite interface, this would suggest that the etch pattern of enamel is generally not a factor. Therefore, it starts to become clear that with generally acceptable *in vitro* bond strengths provided by currently available orthodontic materials, the reason for the higher failure rate in the mandibular posterior teeth, if the failure is at the bracket-composite junction, is from heavy occlusal forces.

The most widely accepted device used to measure bite force is the strain-gage bite force transducer. Using this device, a large range of bite force has been estimated between subjects from 446 to 1221 Newtons (N).[48] This translates to 49-134 MPa of stress in a 3M mandibular 1st premolar bracket with a bracket base area of 9.1mm^2. Tate et al. is one of the few studies that measured the average, rather than maximum, bite force during mastication, and discovered that averages range from 57-66 MPa in males and 39-46 MPa in females.[32] Even the lowest value exceeds the SBS limit of any adhesive/bracket system in optimal *in vitro* conditions. Although proprioceptive fibers in the PDL as well as a patient's subconscious biting pattern would limit this amount of force being placed directly on a bracket in a situation where there is no tooth/bracket clearance, similar forces would be placed on food that would be in contact with the brackets. The amount of force distributed to the bracket through the bolus of food depends on the food's hardness, and to a minor extent the closing bite velocity.

Despite the likelihood that occlusal forces distributed through food is the most plausible reason for clinical bond failures at the composite-bracket interface, these forces have never been evaluated in the literature. Furthermore, while the American Association of Orthodontists (AAO), the Food and Drug Administration (FDA), and Oral-B have recommendations for food consumption during orthodontic treatment on their websites, these recommendations are both brief and substantiated only by professional opinion. The AAO recommendation, which is the most thorough, is cited below.

> “You are encouraged to enjoy a variety of healthful, easy-to-chew foods during orthodontic treatment. Soups, stews, casseroles, pasta, scrambled eggs and smoothies are good choices. You can enjoy fresh fruit like apples and pears, but they should be sliced rather than bitten into. Similarly, sandwiches and pizza are OK, but they should be cut into bite-sized pieces. Cut corn off the cob before serving. Stay away from foods that are hard, sticky, crunchy or chewy for the duration of treatment. Sugary and starchy foods should be avoided, too. Ban foods such as hard pretzels, hard pizza crust, crusty bread, taco chips, caramels, popcorn, licorice, taffy, suckers, hard candies or mints and nuts for the duration of your treatment.”[49]

Without measuring the force distributed to orthodontic brackets from a variety of food items and comparing those forces to debonding forces, these recommendations are both unsubstantiated and noncomprehensive. Therefore, the aim of the proposed study is to quantify the amount of occlusal force distributed through common foods, and compare the results between samples as well as to forces necessary to debond a bracket *in vitro*. This should allow for the creation of an evidence-based food recommendation guide for orthodontic patients.

MATERIALS AND METHODS

Part 1 – Food Sample Testing

Testing Setup

A lower 1st premolar bracket (0.022x0.028" slotted 3M Victory Series Twin MBT) was tack welded and soldered to a 5x5x100mm rectangular cuboid metal rod (Figure 1a). This bracket was chosen for a multitude of reasons, outside of it simply being a very commonly used bracket. Firstly, with a microetched 80g foil mesh and 9.1mm^2 base area, it is average in terms of these measurements when compared to other bracket systems. Secondly, being a posterior mandibular bracket, it will be among the teeth most subject to high occlusal forces.[25,27-29] A premolar was chosen due to the ease of collection of sound extracted teeth likely from the same demographic to which this study pertains.[12] Finally, the 1st premolar was chosen over the 2nd premolar as it is less likely to exhibit extreme morphological variation between subjects.[50]

A 5.5mm length piece of 0.021x0.025" stainless steel wire was placed into the bracket slot and ligated with a figure 8 elastomeric O-tie in order to best represent the distribution of force to the bracket base, as well as to prevent distortion of the wings that would alter the stress values on food impact and shortly thereafter. The rod, with the gingival wings of the bracket pointing downward, was then mounted to the upper arm of an Instron® 5582 universal testing machine opposite a 3D printed 20x20x30mm resin cube with a mounting tail and slot for the rod to slide (Figure 1b,d). A 3D printed resin back cover was then secured tightly to the slotted surface of the cube with a metallic clamp, so that the rod would be secured within the confines of the slot during testing (Figure 1c,e). The rod was designed to be brought into the slot of the testing cube, and re-secured into the upper arms of the Instron® to ensure that it would move vertically without interferences or friction. The rod was to be depressed until the occlusal wings of the bracket were at the height of the testing cube (Figure 1e), and the machine height and force would be tared.

Food Selection and Preparation

50 common food items were purchased at neighboring grocery stores (Kroger, Walmart Neighborhood Market, Aldi). Within each category of food, at least one soft and semi-soft item was obtained, along with multiple hard items that would reasonably be in contention for causing an orthodontic breakage. These categories are shown in Table 1. Foods that are always eaten cooked were cooked to the recommended temperature prior to testing, and foods that can be eaten raw or cooked, such as carrots, were tested raw as that would produce the greatest risk for orthodontic bond failure. Foods were refrigerated at 37°F if indicated. Food items were ideally prepared into 20x20x10-15mm^3 samples for testing, which is a standard dimension used in masticatory cycle testing (Figure 2a).[38,39,41] However, some foods, due to their size, shape, or consistency, were loaded into the testing cube using 18mm wide/30mm tall 3D printed rectangular spacers of different thicknesses that would secure the food item to the slotted wall of the testing cube (Figure 2b). The full descriptions of the food items along with how they were prepared, stored, and loaded into the testing cube is listed in Table 2. Foods were also divided descriptively into two categories depending on whether they had a consistent or inconsistent morphologies, such as air pockets or differing hardness, either internally or on the testing surface (Table 3).

Food Testing

Once the samples were prepared, they were loaded into the testing cube as described in Table 2. The rod was then depressed at a rate of 7.5mm/s for a total of 23mm,[38] penetrating between one-half and two-thirds of the sample. This testing speed, which is much higher than traditional SBS testing speeds (0.5-2mm/min),[9-14,17-19,22,33,51] was used to best recreate an initial impact force with the sample that coincides with the estimated human slow close velocities found in the literature.[41,43,44] The testing program was made custom using the Instron® software Bluehill®. The test was repeated 20 times for each food item to provide a stable estimate of the force and variability. Tests were only excluded if there was a clear and obvious failure of the mechanism during testing, such as excessive initial friction due to a sticky internal surface, or premature fracture or shifting of the sample during loading. The shear stress that would be distributed to the bracket pad was calculated by dividing the resulting force by 9.1mm^2, which is the area of the bracket pad.

Reliability

As the same test cannot be performed on the exact same food sample, the relative reliability of the different foods was described by their coefficient of variation. We hypothesized that variability would be higher for the harder and the more amorphous food items. Reliability of the testing mechanism was calculated by running 10 consecutive tests 2 days apart on the mozzarella cheese sample. This sample was chosen for reliability due to its consistent morphology and low hardness, which would make it very sensitive to external changes, as well as the ease of sample preparation. Intraclass correlation was calculated to be 0.91, substantiating the use of the novel food testing mechanism for the remainder of the experiment.

Part 2 – Shear Bond Strength Testing

Sample preparation.

40 recently extracted lower 1st premolars (23L, 17R) without evidence of caries, white spot lesions, or fluorosis on the facial surface were collected from a local oral and maxillofacial surgery practice and from the oral surgery and periodontal departments at the Texas A&M College of Dentistry. They were stored in 0.01% thymol until use. Most critical reviews agree that both time of extraction and storage medium have minimal effect on the strength of the achieved bond, and that a storage time of 6 months or less is adequate.[35] Prior to testing, the teeth were mounted with Type IV dental stone (PrimaRock©) into 10x10x15mm 3D printed cubes. The teeth were mounted along the long axis of the crown, with 2mm of cementum visible under the cementoenamel junction (Figure 3a). The facial surface of the teeth was first pumiced and rinsed, then etched with 37% Phosphoric acid for 30 seconds, rinsed, and dried. Assure Plus bonding agent was then applied to the etched surface and air thinned for 5 seconds. Lower 1st premolar brackets (0.022x0.028 slotted 3M Victory Series Twin MBT pre-pasted) were bonded to the facial surfaces of the teeth (Figure 3c). All excess composite was removed around the bracket pad prior to light curing the bracket for 5 seconds on the mesial and distal surfaces. All of these bonding procedures were per the manufacturer's instruction. The mounted teeth were then fully submerged in 37°C 1X phosphate buffered saline (PBS) for 24 hours per past studies.[10-12,16,18,22,23,33]

SBS Testing

The mounted teeth were removed from the solution and mounted to the lower arm of the Instron® 5582 universal testing machine. A 5.5mm length of 0.021x0.025 stainless steel rectangular wire was placed in the slot and ligated with a figure 8 elastomeric O-tie. A 5x5x100mm metallic rod was mounted in the upper arm of the machine, with the bottom surface 20.5mm away from the occlusal surface of the bracket, so as to imitate the average vertical amplitude of the first chewing cycle (Figure 3d).[38] Using the same program as in part 1, the rod was depressed 23mm at a rate of 7.5mm/s, and the resulting debonding compressive stress was recorded. While this differs from traditional SBS testing that loops a metal ligature under the tie wings or places a chisel at the bracket/tooth margin, [9-13,15,18,19] this vector will best simulate what occurs clinically, and satisfy the criticism of traditional SBS testing that it does not account for higher impact velocities and non-shear forces which are likely to be the reason for clinical failures. Teeth were inspected visually after the test to determine whether the failure occurred at the tooth-composite junction (TCJ) or bracket-composite junction (BCJ) (Figure 3e). This test was repeated 40 times.

Statistics

The food testing data was normally distributed. Therefore, the mean and standard deviation were used as descriptive parameters. Statistical differences between food items were observed visually by comparing 95% confidence interval bars around the means. Spearman's *rho* correlation was used to determine whether food hardness was related to increased variability of compressive stress calculations. Mann-Whitney U test was used to establish whether foods with amorphous internal or testing surface morphologies had increased variability of compressive stresses.

The data for SBS testing was not normally distributed due to several high outliers. Therefore, nonparametric statistics were used. Mann-Whitney U tests were used to determine whether there was any difference in the data collected at different timepoints, and whether a difference in SBS existed between left and right lower first premolars.

RESULTS

Part 1 – Food Testing

Mean compressive stresses placed on orthodontic bracket wings and translated to the bracket pads ranged from 0.35 to 33.9 MPa (Table 4, Figure 4). Strawberries recorded the lowest value and LifeSaver ® mints recorded the highest. Statistical differences between food items can be visualized by overlapping 95% confidence interval bars shown in Figure 4. LifeSaver® mints, popcorn kernels, cough drops, and Jolley Rancher candies created statistically higher compressive stresses than the remainder of the food items. All other food items become statistically different from one another in intervals of approximately 2 MPa values.

Variability of each sample is shown in Figure 5. Crispy bacon and Eclipse® gum had the highest (0.44) and lowest (0.05) variability respectively. Increased variability was not correlated with increased compressive stress (hardness) of the sample (r=-0.02). Foods that were described as amorphous had statistically higher variabilities (Med=0.25) when compared to those with consistent internal morphologies and testing surfaces (Med=0.16, p=0.002).

Examples of compressive stress readings over time during each test are shown in Figure 6. In general, hard plastic foods (a) would demonstrate a rapid initial increase in compressive stress upon collision, followed by a rapid decrease after fracture. Soft plastic foods (b) would show a steady increase in MPa following collision, and then maintain this reading for the remainder of the test, as the samples typically did not fracture. Chewy elastic foods (c) would demonstrate an initial rapid increase in stress, followed by a subsequent lag period and finally a period of steady increase. Crunchy plastic foods (d) had the least predictable patterns of compressive stress readings over time, showing random and abrupt peaks depending on the food's internal morphology.

Part 2 – Shear Bond Strength Testing

The study sample consisted of 40 mandibular 1st premolars. Of these, 23 were lower left premolars, and 17 were lower right. The median shear orthodontic bond strength was 10.37±2.72 MPa. Table 5 shows the median shear bond strength and interquartile range for all of the samples, as well as for the right and left sides. No significant differences were found between right and left premolars (p=0.859). Additionally, no significant differences were found between premolars tested at two different timepoints (p=0.109), ensuring reliability of the novel methodology. All 40 bracket failures occurred at the bracket-composite junction.

DISCUSSION

The new methodology for measuring orthodontic bond strength developed in this study was shown to provide reliable data that better represented clinical situations. The new methodology was designed to recreate an impact force at human slow close velocity, which occurs during each chewing cycle *in vivo.* This has never been done in previous studies.[9-16] Additionally, the current study addressed many of the criticisms of traditional SBS testing outlined by Elides & Brantley (2000). Larger sample size compared to the majority of past studies helped ensure reliability of the data. [9,10,12,14-17,21,22,33] Also, teeth were all collected within 6 months of testing and stored in the same storage medium for consistency of the sample. The brackets were pre-pasted, ensuring an even distribution of the bonding interface. Finally, the debonding force was applied to the occlusal wings rather than the bracket base, [9-13,15,16,18,19] more closely simulating what occurs clinically.

The calculated force required to debond a lower first premolar bracket in this study was within the range of values found in the literature (5-16 MPa).[9-16] Additionally, the location of failure for all 40 tests was at the bracket/composite interface, which was also consistent with previous studies.[9-12] Therefore, changes that were made to address criticisms of traditional SBS testing and improve its clinical relevance did not have a dramatic impact on the results. However, as this study’s methodology is more clinically applicable, than the results will assist practitioners in narrowing down the large range of SBS values found in the literature. Orthodontists can therefore expect bonds to fail at approximately 10.5 MPa of force application, if the bracket was bonded with appropriate bonding protocols with good isolation.

Future studies should continue to address the differences between *in vitro* SBS testing and clinical situations. There are several of these differences that the current study did not address. Clinically, brackets are subjected to cyclic loading for up to three years during treatment, which has been shown *in vitro* to significantly decrease SBS.[13,19,30,31] Also, the pH and temperature changes that normally occur, as well as microbial insult, were not simulated, and could influence the mechanical properties of the adhesive. [51-56] Finally, bonding was performed under ideal conditions without any possibility of contamination, which has been shown in the literature to decrease bond strength. [14,15,18,33] These limitations suggest that the clinical SBS of brackets might be lower than that measured *in vitro*.

The novel food testing apparatus created in the current study was able to reliably measure the compressive stresses distributed to bracket bases by common food items that could be cross referenced with the results from SBS testing. Using the data, an evidence-based food recommendation chart for orthodontic patients was created (Figure 7). The highest compressive stress recorded for each food item in the present study was used so that recommendations would be based on the worst possible clinical scenario. The red section includes foods that should never be consumed during orthodontic treatment. These food items created maximum compressive stresses that exceeded the median force required to debond a bracket, as measured in the current study. The orange/yellow section delineates foods for which patients should exercise caution while eating. These samples created maximum stress values that exceeded the lowest mean force required to debond any orthodontic bracket bonded with composite in the literature (4.8 MPa).[11] The green section includes food items that are safe for consumption during treatment when compared to any SBS values found in the literature for any tooth, assuming that the bracket was bonded with proper bonding protocols.

Heavy orthodontic forces create additional stresses that are an important consideration for food consumption recommendations. The dark orange and light-yellow sections of the chart account for these forces. During the end stages of treatment, bends are usually placed into a stainless steel archwire that create forces on the bracket base that could contribute to bracket failures. A 0.5mm occlusal-gingival deflection in a 0.019-0.025" stainless steel archwire creates approximately 1000g of force,[58] which is equivalent to 1.07 MPa for a lower 1st premolar bracket. The food in dark orange (thick pizza crust) created a maximum stress value that exceeded the median force required to debond a bracket in this study accounting for this orthodontic force. Hence, it should be absolutely avoided when heavy forces are present. Similarly, the foods in light yellow created maximum stresses exceeding the lowest mean debonding force reported in the literature, minus the heavy orthodontic force. These foods are probably safe to consume during treatment, and it is only until heavy individual forces are applied in stiff wires that a patient should exercise caution. The contribution of initial orthodontic forces from nitinol wires was not considered, as these are too light to be a significant contributor (0.09MPa for 0.014" superelastic NiTi and 0.43 MPa for 0.019x0.025" superelastic NiTi).[57]

The results of the current study suggest that forces translated to the bracket base were largely a function of hardness, rather than other proposed physical characteristics. Since there is no literature on the physical properties of common food items, the results of this study can only be compared to orthodontic opinions that have guided recommendations given to patients. Orthodontists often have food consumption guides on their practice websites that differ slightly between themselves, but generally reflect the recommendations made by the American Association of Orthodontists (AAO). The AAO recommends that patients avoid foods that are hard, sticky, crunchy, or chewy. It lists the following foods that should be banned: hard pretzels, hard pizza crust, crusty bread, taco chips, caramel, popcorn, licorice, taffy, suckers, hard candies or mints, and nuts.[49] The present study only partially supports these recommendations. Hard foods such as mints, hard candies, and hard breads recorded the highest readings and should certainly be avoided during orthodontic treatment. Crunchy foods only produced high stress values if they were also hard. For example, Cheerios, Rice Krispy Treats, and Frosted Flakes are crunchy food items that all produced mean compressive stresses ≤ 2 MPa. This would suggest that problematic foods need to be both hard and dense.

Chewy foods, except those that eventually tear, produced increasing stresses during the test. However, even with the steady increase in stress, the highest mean stress recorded from a chewy food item was 6.6 MPa (Starburst), which was well under the stress required to debond a bracket *in vitro,* and much lower than the stress produced by the most dangerous foods tested. Because the brackets that were compressed onto the food items stopped 3mm shy of passing completely through, some of the chewy items that never failed could have produced higher stresses when passing through the remaining 3 mm. It is unlikely, however, that the stresses would ever be comparable to the those of hard plastic foods.

While "stickiness" of the food did not play a role in the present study, the methodology was not ideal for testing adhesive properties of the samples, because they were not tested in tension.

Orthodontic recommendations should be based on properties of the food rather than type of food. For example, orthodontists frequently tell patients to avoid chips during treatment, but the present study shows that the debonding force created by a chip is largely dependent on its thickness. All chips were positioned with their long axes perpendicular to the bracket slot, which should produce the highest stress. However, if the sample was not thick enough, it would fracture immediately before it could produce forces sufficient for bracket failure. This was true for saltines, Cheese-Itz, and tortilla chips, all which produced mean compressive stresses under 5 MPa. Large and significant categorical distinctions could also be made between different nuts, gum, chewy candy, and toasted breads. Therefore, patients should be given a list of individual food items rather than the broad categories that are currently being provided.

Three specific samples that recorded surprisingly low values were ice, bagels, and steak. These foods are typically banned from consumption during orthodontic treatment. While patients should be cautious when chewing on ice, it produced lower than expected stress values because the outer surface would soften immediately, allowing for a fracture point to form without significant force. This fracture point would relief the strength required to pass through the dense center of the sample. This would occur even more readily intraorally due to the increased temperature of the mouth compared to the testing cube. Bagels created a low mean stress of 2 MPa, even when placing the bracket against the outer toasted surface. However, these were brand name bagels with preservatives and minimal crust that make them softer than those purchased at a bakery. Patients should refer to the stress values for hard French bread when consuming bakery bagels, and thus they should be avoided. Finally, according to the present study, steak is safe to consume during treatment. Despite the fact that the steak samples were overcooked and seared, and the bracket was dragged through the outer layer in order to recreate a worst-case scenario, the forces produced only averaged 1.4 MPa, which is safe to consume, as long as the patient is careful to not contact a tenacious tendon or bone.

The novel food testing apparatus was proficient in creating consistent measurements for many of the samples. When a soft, structurally consistent food item was tested at two separate time points, the measurements were predictable. This was even true for hard samples, as increased hardness was not correlated to increased variability. One of the hardest samples

(Eclipse Gum, Mean = 14.3 MPa) had the lowest variability amongst all samples (0.05). Only foods that were tested under inconsistent conditions, due to irregular testing surfaces or internal morphologies, produced greater variabilities. This shows that the food testing apparatus was reliable, and that certain samples simply had inherent variability that is difficult to adjust for.

The novel food testing apparatus designed in the present study was reliable and should be used for future studies. As a result, an even more comprehensive recommendation chart could be created. The 3D design and rigid back stop allowed for the force to be placed on each sample from the same vector, and thus created the same location of impact with the wings of the bracket. Furthermore, this mechanism replicated the average vertical amplitude and slow close velocity of the human bite.[38, 41,43,44]

However, there are several differences when comparing this setup to what happens *in vivo*. Intraorally, there is saliva that coats the food, and more than one chewing cycle is used to process food. These factors were intentionally not accounted for as they would only decrease the resultant stress values and increase variability. The food items tested were prepared to a standard dimension, often times much smaller than the bolus would be *in vivo*. Larger boluses would be compressed against not only the bracket wings, but also several millimeters of supported wire on either side, which may increase the force applied to the bracket base. This would likely be more pronounced for sticky and chewy samples, which is why these items recorded lower stresses in this study, but are not regularly endorsed to patients. Furthermore, the use of a container for testing has the potential for creating pressure as the samples are compressed, which could create higher stress values than what would occur *in vivo.* The spacers that had to be used for certain samples would exacerbate this effect by creating a smaller testing volume. Effort was made to create a balance between holding the sample still and creating too much pressure, including the use of a small elastomeric spacer behind the hard 3D printed spacers in order to allow for the container to expand slightly during compression. Another limitation to the testing apparatus was that forces were recorded against the gingival rather than the occlusal wings, which is opposite of what happens intraorally. This was done because the occlusal wings did not protrude enough to dig into each sample in the same manner, and would often simply push the sample away rather than colliding with it. This could have, in certain instances, created higher compressive stresses. Finally, similarly to previous literature, the sample was not fully compressed,[38,39,41] and this could have limited the data for chewy samples, which created increasingly higher stresses until failure. Future studies should evaluate the contribution of these limitations and address them accordingly.

CONCLUSIONS

1. The recommendation chart created in this study should be used as evidence-based justification for the recommendations orthodontists make to their patients.

2. Rather than recommending broad categories of foods, specific foods should be provided so as to not limit diets unnecessarily or neglect certain problematic food items.

3. The novel food testing apparatus should be used to add more food items to the recommendation chart, in order to move towards the creation of a comprehensive reference database for orthodontics patients.

4. Future shear bond strength studies of orthodontic bonds should continue to work towards increased simulation of clinical settings, so that increasingly accurate values can be cross-referenced with compressive stress readings of food items.

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APPENDIX A: FIGURES

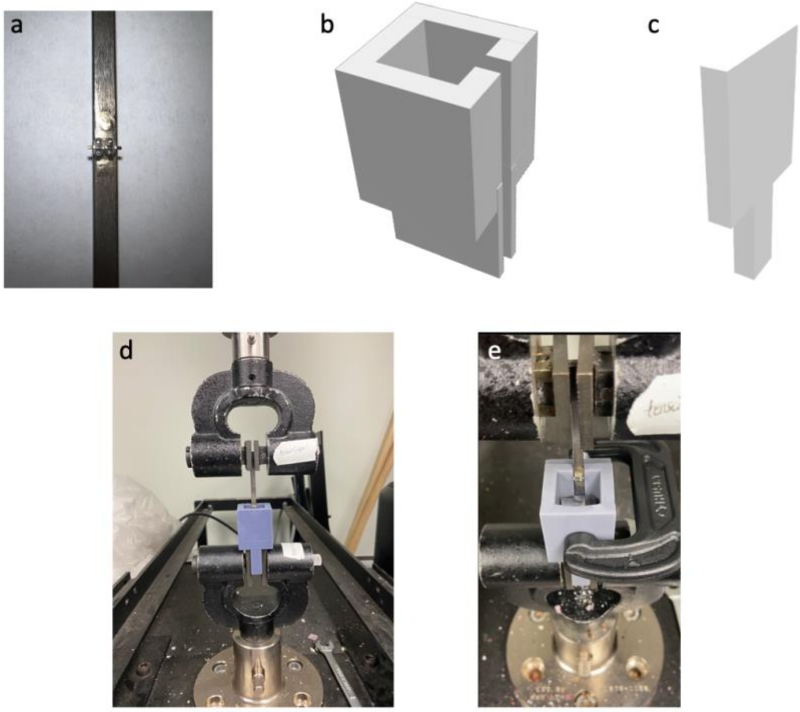


Figure 1. (a) Metallic rod with soldered bracket/5.5mm length 21x25 SS wire/”Figure 8” elastomeric O-tie, (b) custom 3D printed 20x20x30mm resin testing cube with mounting tail and rod slot, (c) custom 3D printed back cover, (d) Intron mounting without clamp and food item, and (e) complete food testing setup with ice as sample

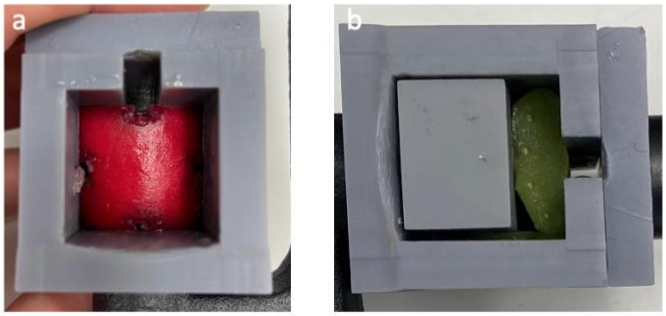


Figure 2. (a) 20x20x10-15mm sample of apple loaded into testing cube post testing and (b) celery loaded into testing cube and secured with a spacer due to size limitation pre testing

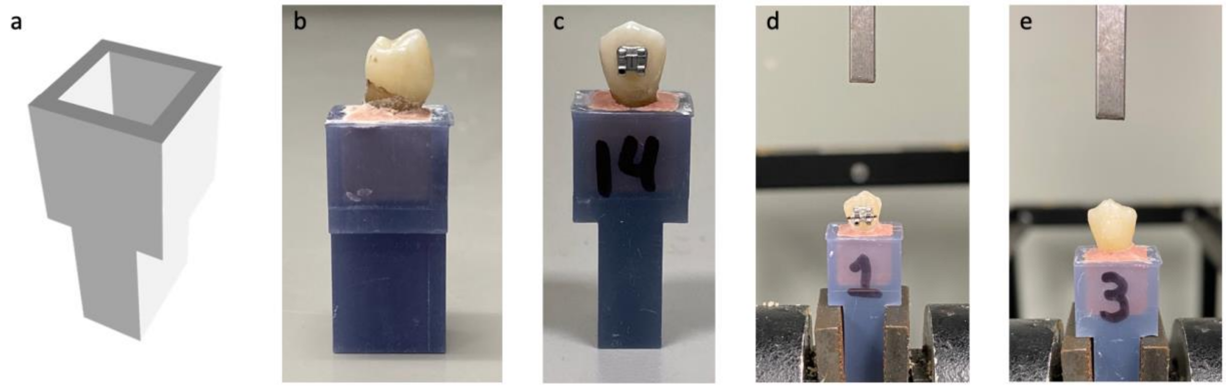


Figure 3. (a) Custom 3D printed 10mm^3 resin cube, (b) mounting along long axis of the crown in Type IV dental stone, (c) 3M Victory L4 Twin bracket bonded to specimen, (d) Instron mounting pretest after 24h in 37 °C PBS, and (e) Instron mounting posttest showing failure at bracket-composite junction

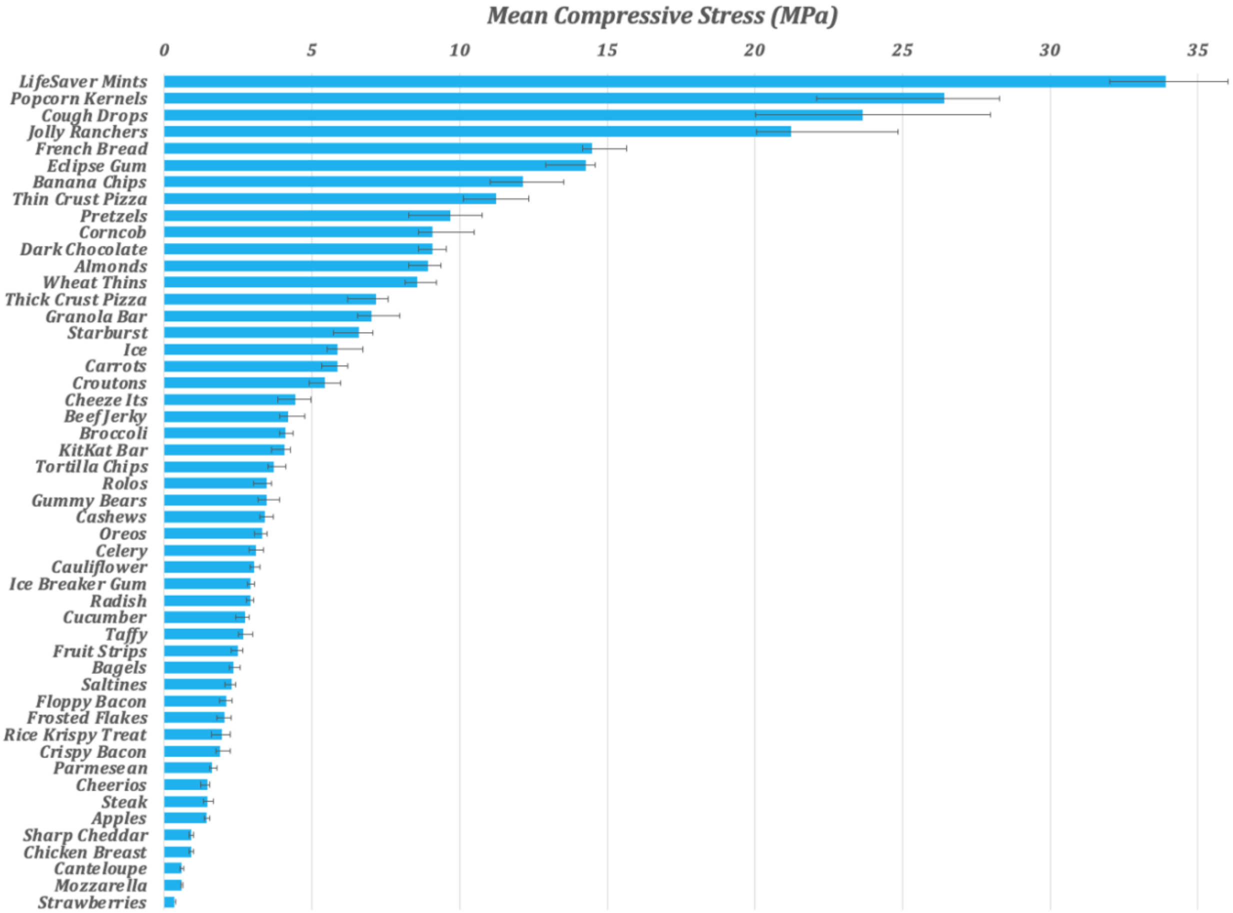


Figure 4. Mean compressive stress (±1.96*SE) placed on an orthodontic bracket pad by 50 common food items

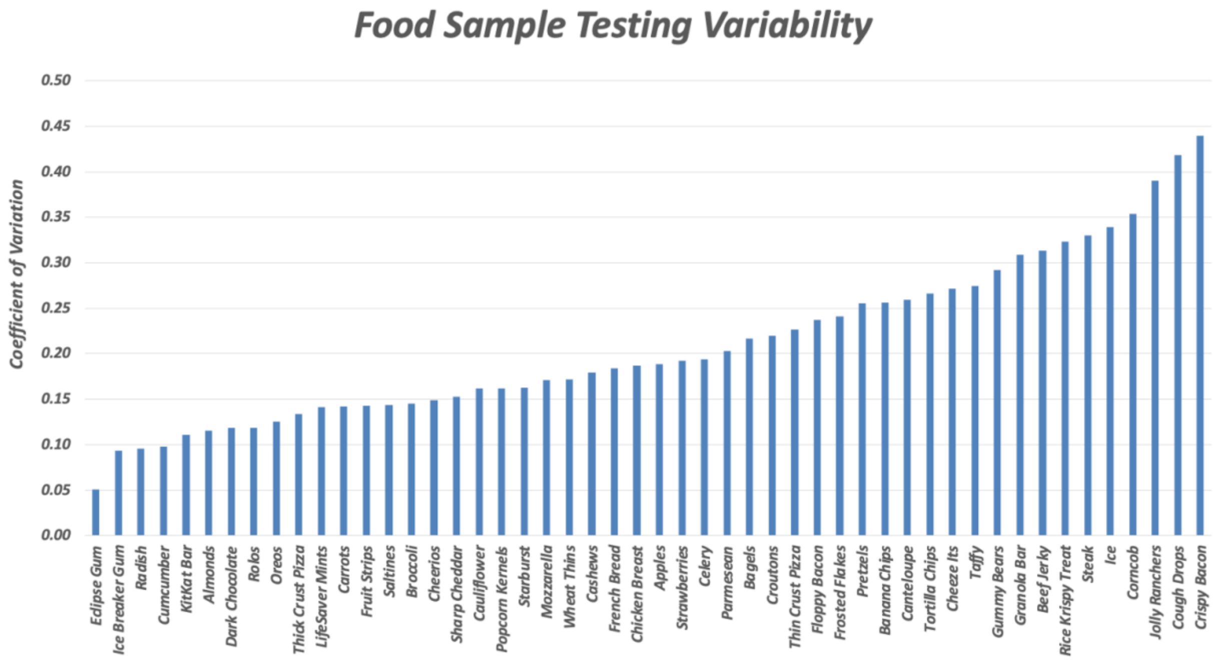


Figure 5. Variability of food sample testing

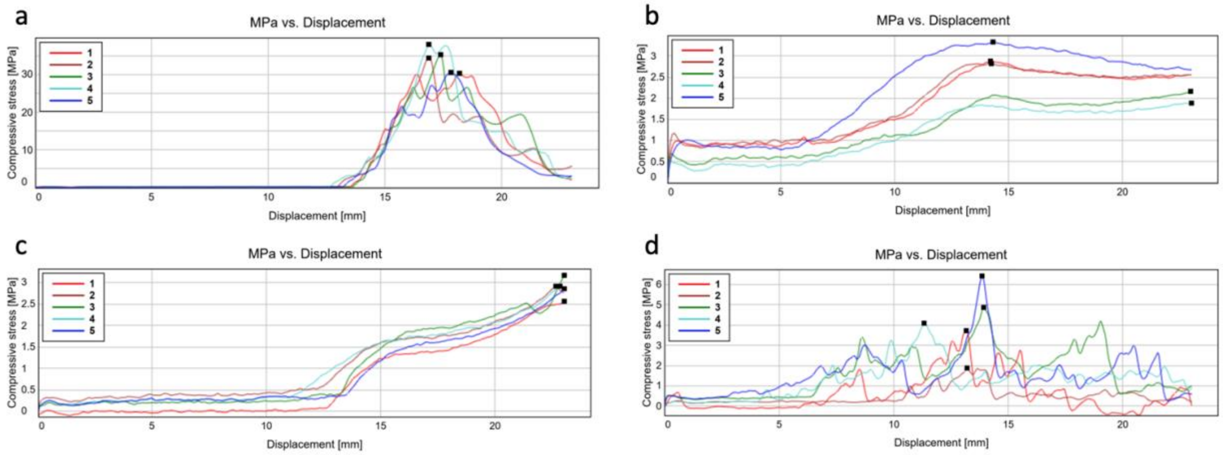


Figure 6. General patterns of compressive stress readings over time for (a) hard plastic food [LifeSaver® mints], (b) soft plastic food [fruit strips], (c) chewy elastic food [IceBreakers® gum] and (d) crunchy plastic food [croutons]

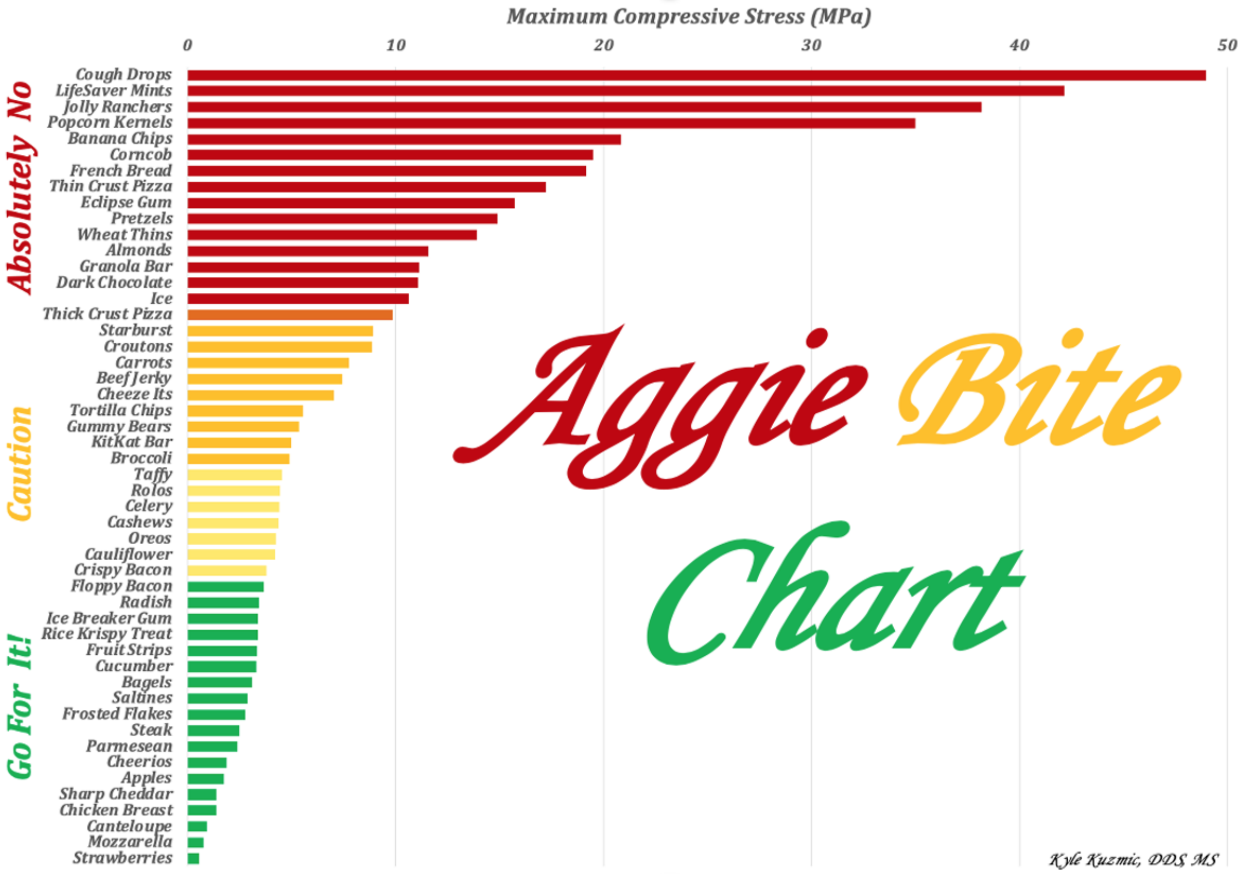
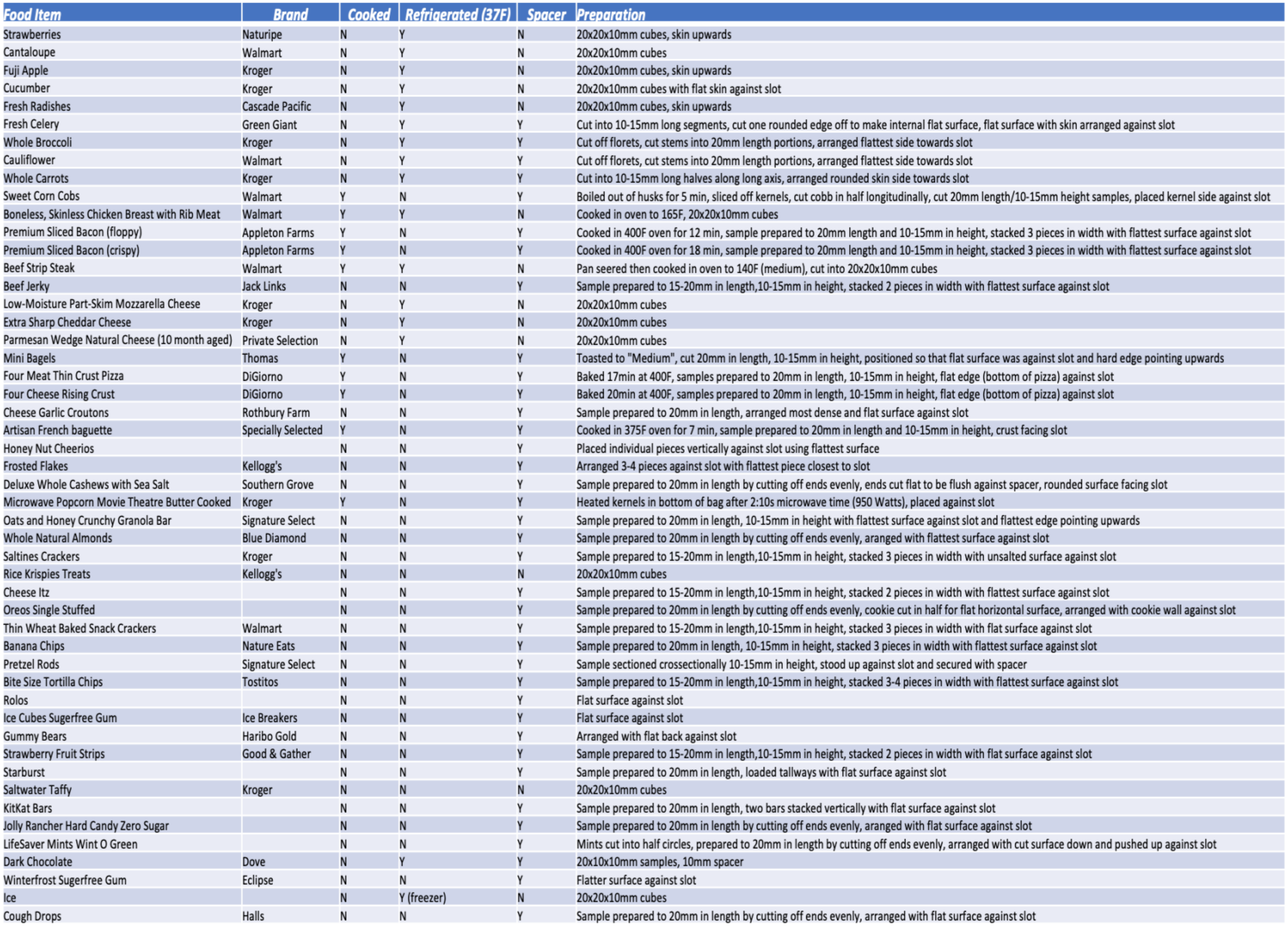


Figure 7. "Aggie Bite Chart". Evidence-based food recommendation chart for orthodontic patients.

APPENDIX B: TABLES

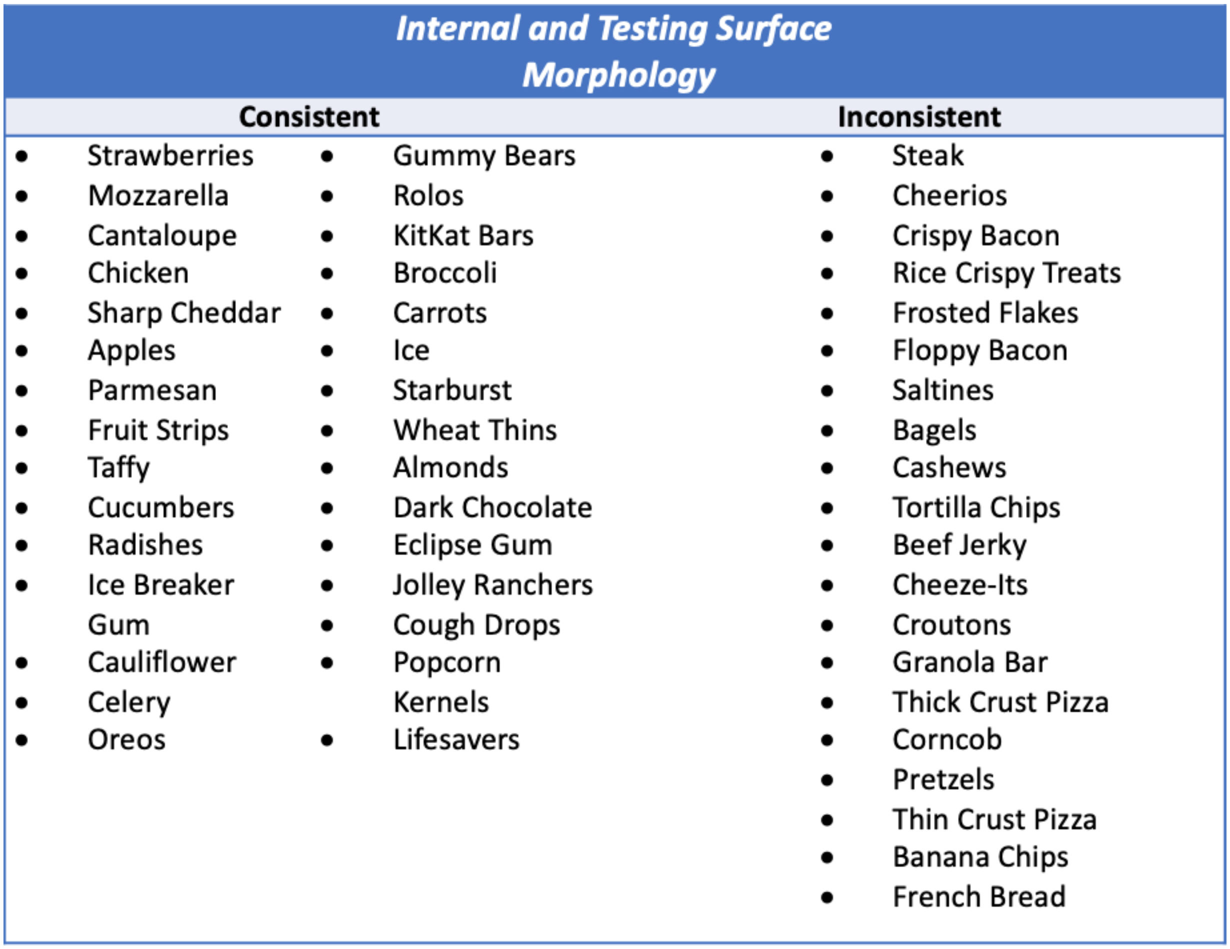
Category	Soft	Semi-Soft	Hard
Fruits	Strawberries	Cantaloupe	Apples
Vegetables	Cucumber Radish	Celery Broccoli Cauliflower	Carrots Corncob
Proteins	Chicken Breast Floppy Bacon	Crispy Bacon	Steak Beef Jerky
Cheeses	Mozzarella	Cheddar	Parmesan
Breads	Bagels	Pizza Crust	Croutons Baguette
Nuts/Kernels/Grains	Cheerios Frosted Flakes	Cashews	Popcorn Kernels Granola Bars Almonds
Crackers/Chips/Cookies	Saltines Rice Crispy Treats	Cheeze Its Oreos Wheat Thins	Banana Chips Pretzel Rods Tortilla Chips
Candy	Rolos Ice Breaker Gum Gummy Bears Fruit Strips	Starburst Saltwater Taffy KitKat Bars	Jolly Ranchers LifeSaver Mints Dark Chocolate Eclipse Gum
Miscellaneous			Ice Cough Drops

Table 1. Food samples by category and assumed hardness.



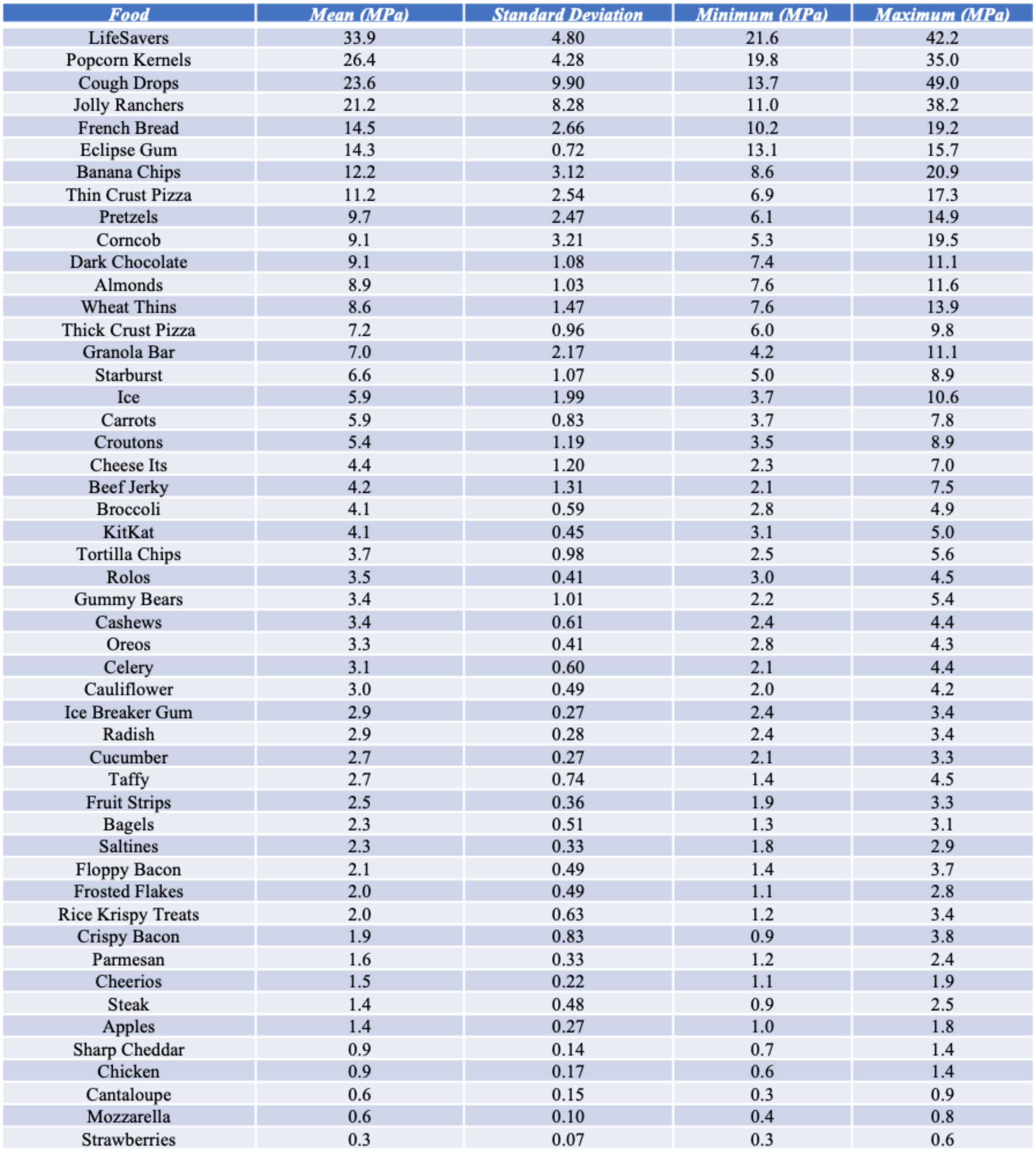
Food Item	Brand	Cooked	Refrigerated (37F)	Spacer	Preparation
Strawberries	Naturipe	N	Y	N	20x20x10mm cubes, skin upwards
Cantaloupe	Walmart	N	Y	N	20x20x10mm cubes
Fuji Apple	Kroger	N	Y	N	20x20x10mm cubes, skin upwards
Cucumber	Kroger	N	Y	N	20x20x10mm cubes with flat skin against slot
Fresh Radishes	Cascade Pacific	N	Y	N	20x20x10mm cubes, skin upwards
Fresh Celery	Green Giant	N	Y	Y	Cut into 10-15mm long segments, cut one rounded edge off to make internal flat surface, flat surface with skin arranged against slot
Whole Broccoli	Kroger	N	Y	Y	Cut off florets, cut stems into 20mm length portions, arranged flattest side towards slot
Cauliflower	Walmart	N	Y	Y	Cut off florets, cut stems into 20mm length portions, arranged flattest side towards slot
Whole Carrots	Kroger	N	Y	Y	Cut into 10-15mm long halves along long axis, arranged rounded skin side towards slot
Sweet Corn Cobs	Walmart	Y	N	Y	Boiled out of husks for 5 min, sliced off kernels, cut cobb in half longitudinally, cut 20mm length/10-15mm height samples, placed kernel side against slot
Boneless, Skinless Chicken Breast with Rib Meat	Walmart	Y	Y	N	Cooked in oven to 165F, 20x20x10mm cubes
Premium Sliced Bacon (floppy)	Appleton Farms	Y	N	Y	Cooked in 400F oven for 12 min, sample prepared to 20mm length and 10-15mm in height, stacked 3 pieces in width with flattest surface against slot
Premium Sliced Bacon (crispy)	Appleton Farms	Y	N	Y	Cooked in 400F oven for 18 min, sample prepared to 20mm length and 10-15mm in height, stacked 3 pieces in width with flattest surface against slot
Beef Strip Steak	Walmart	Y	Y	N	Pan seered then cooked in oven to 140F (medium), cut into 20x20x10mm cubes
Beef Jerky	Jack Links	N	N	Y	Sample prepared to 15-20mm in length,10-15mm in height, stacked 2 pieces in width with flattest surface against slot
Low-Moisture Part-Skim Mozzarella Cheese	Kroger	N	Y	N	20x20x10mm cubes
Extra Sharp Cheddar Cheese	Kroger	N	Y	N	20x20x10mm cubes
Parmesan Wedge Natural Cheese (10 month aged)	Private Selection	N	Y	N	20x20x10mm cubes
Mini Bagels	Thomas	Y	N	Y	Toasted to "Medium", cut 20mm in length, 10-15mm in height, positioned so that flat surface was against slot and hard edge pointing upwards
Four Meat Thin Crust Pizza	DiGiorno	Y	N	Y	Baked 17min at 400F, samples prepared to 20mm in length, 10-15mm in height, flat edge (bottom of pizza) against slot
Four Cheese Rising Crust	DiGiorno	Y	N	Y	Baked 20min at 400F, samples prepared to 20mm in length, 10-15mm in height, flat edge (bottom of pizza) against slot
Cheese Garlic Croutons	Rothbury Farm	N	N	Y	Sample prepared to 20mm in length, arranged most dense and flat surface against slot
Artisan French baguette	Specially Selected	Y	N	Y	Cooked in 375F oven for 7 min, sample prepared to 20mm in length and 10-15mm in height, crust facing slot
Honey Nut Cheerios		N	N	Y	Placed individual pieces vertically against slot using flattest surface
Frosted Flakes	Kellogg's	N	N	Y	Arranged 3-4 pieces against slot with flattest piece closest to slot
Deluxe Whole Cashews with Sea Salt	Southern Grove	N	N	Y	Sample prepared to 20mm in length by cutting off ends evenly, ends cut flat to be flush against spacer, rounded surface facing slot
Microwave Popcorn Movie Theatre Butter Cooked	Kroger	Y	N	Y	Heated kernels in bottom of bag after 2:10s microwave time (950 Watts), placed against slot
Oats and Honey Crunchy Granola Bar	Signature Select	N	N	Y	Sample prepared to 20mm in length, 10-15mm in height with flattest surface against slot and flattest edge pointing upwards
Whole Natural Almonds	Blue Diamond	N	N	Y	Sample prepared to 20mm in length by cutting off ends evenly, aranged with flattest surface against slot
Saltines Crackers	Kroger	N	N	Y	Sample prepared to 15-20mm in length,10-15mm in height, stacked 3 pieces in width with unsalted surface against slot
Rice Krispies Treats	Kellogg's	N	N	N	20x20x10mm cubes
Cheese Itz		N	N	Y	Sample prepared to 15-20mm in length,10-15mm in height, stacked 2 pieces in width with flattest surface against slot
Oreos Single Stuffed		N	N	Y	Sample prepared to 20mm in length by cutting off ends evenly, cookie cut in half for flat horizontal surface, arranged with cookie wall against slot
Thin Wheat Baked Snack Crackers	Walmart	N	N	Y	Sample prepared to 15-20mm in length,10-15mm in height, stacked 3 pieces in width with flat surface against slot
Banana Chips	Nature Eats	N	N	Y	Sample prepared to 20mm in length, 10-15mm in height, stacked 3 pieces in width with flattest surface against slot
Pretzel Rods	Signature Select	N	N	Y	Sample sectioned crossectionally 10-15mm in height, stood up against slot and secured with spacer
Bite Size Tortilla Chips	Tostitos	N	N	Y	Sample prepared to 15-20mm in length,10-15mm in height, stacked 3-4 pieces in width with flattest surface against slot
Rolos		N	N	Y	Flat surface against slot
Ice Cubes Sugerfree Gum	Ice Breakers	N	N	Y	Flat surface against slot
Gummy Bears	Haribo Gold	N	N	Y	Arranged with flat back against slot
Strawberry Fruit Strips	Good & Gather	N	N	Y	Sample prepared to 15-20mm in length,10-15mm in height, stacked 2 pieces in width with flat surface against slot
Starburst		N	N	Y	Sample prepared to 20mm in length, loaded tallways with flat surface against slot
Saltwater Taffy	Kroger	N	N	N	20x20x10mm cubes
KitKat Bars		N	N	Y	Sample prepared to 20mm in length, two bars stacked vertically with flat surface against slot
Jolly Rancher Hard Candy Zero Sugar		N	N	Y	Sample prepared to 20mm in length by cutting off ends evenly, aranged with flat surface against slot
LifeSaver Mints Wint O Green		N	N	Y	Mints cut into half circles, prepared to 20mm in length by cutting off ends evenly, arranged with cut surface down and pushed up against slot
Dark Chocolate	Dove	N	Y	Y	20x10x10mm samples, 10mm spacer
Winterfrost Sugerfree Gum	Eclipse	N	N	Y	Flatter surface against slot
Ice		N	Y (freezer)	N	20x20x10mm cubes
Cough Drops	Halls	N	N	Y	Sample prepared to 20mm in length by cutting off ends evenly, arranged with flat surface against slot

Table 2. Food sample full titles, brand names, testing conditions and preparation



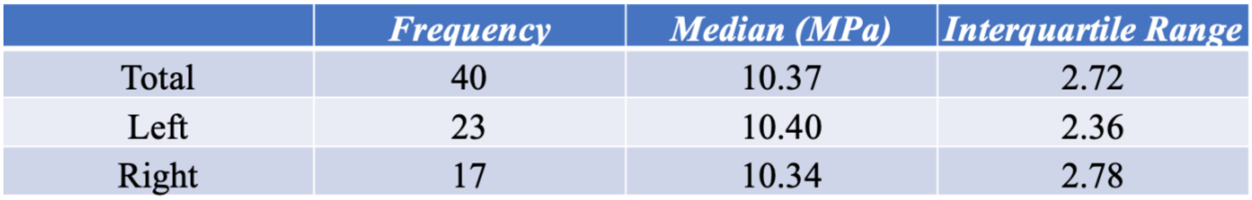
Internal and Testing Surface Morphology		
Consistent		**Inconsistent**
Strawberries	Gummy Bears	Steak
Mozzarella	Rolos	Cheerios
Cantaloupe	KitKat Bars	Crispy Bacon
Chicken	Broccoli	Rice Crispy Treats
Sharp Cheddar	Carrots	Frosted Flakes
Apples	Ice	Floppy Bacon
Parmesan	Starburst	Saltines
Fruit Strips	Wheat Thins	Bagels
Taffy	Almonds	Cashews
Cucumbers	Dark Chocolate	Tortilla Chips
Radishes	Eclipse Gum	Beef Jerky
Ice Breaker Gum	Jolley Ranchers	Cheeze-Its
Cauliflower	Cough Drops	Croutons
Celery	Popcorn Kernels	Granola Bar
Oreos	Lifesavers	Thick Crust Pizza
		Corncob
		Pretzels
		Thin Crust Pizza
		Banana Chips
		French Bread

Table 3. Food samples by morphology of internal and/or testing surface. Samples with inconsistent morphologies were more highly variable (p=0.002)



Food	*Mean (MPa)*	*Standard Deviation*	*Minimum (MPa)*	*Maximum (MPa)*
LifeSavers	33.9	4.80	21.6	42.2
Popcorn Kernels	26.4	4.28	19.8	35.0
Cough Drops	23.6	9.90	13.7	49.0
Jolly Ranchers	21.2	8.28	11.0	38.2
French Bread	14.5	2.66	10.2	19.2
Eclipse Gum	14.3	0.72	13.1	15.7
Banana Chips	12.2	3.12	8.6	20.9
Thin Crust Pizza	11.2	2.54	6.9	17.3
Pretzels	9.7	2.47	6.1	14.9
Corncob	9.1	3.21	5.3	19.5
Dark Chocolate	9.1	1.08	7.4	11.1
Almonds	8.9	1.03	7.6	11.6
Wheat Thins	8.6	1.47	7.6	13.9
Thick Crust Pizza	7.2	0.96	6.0	9.8
Granola Bar	7.0	2.17	4.2	11.1
Starburst	6.6	1.07	5.0	8.9
Ice	5.9	1.99	3.7	10.6
Carrots	5.9	0.83	3.7	7.8
Croutons	5.4	1.19	3.5	8.9
Cheese Its	4.4	1.20	2.3	7.0
Beef Jerky	4.2	1.31	2.1	7.5
Broccoli	4.1	0.59	2.8	4.9
KitKat	4.1	0.45	3.1	5.0
Tortilla Chips	3.7	0.98	2.5	5.6
Rolos	3.5	0.41	3.0	4.5
Gummy Bears	3.4	1.01	2.2	5.4
Cashews	3.4	0.61	2.4	4.4
Oreos	3.3	0.41	2.8	4.3
Celery	3.1	0.60	2.1	4.4
Cauliflower	3.0	0.49	2.0	4.2
Ice Breaker Gum	2.9	0.27	2.4	3.4
Radish	2.9	0.28	2.4	3.4
Cucumber	2.7	0.27	2.1	3.3
Taffy	2.7	0.74	1.4	4.5
Fruit Strips	2.5	0.36	1.9	3.3
Bagels	2.3	0.51	1.3	3.1
Saltines	2.3	0.33	1.8	2.9
Floppy Bacon	2.1	0.49	1.4	3.7
Frosted Flakes	2.0	0.49	1.1	2.8
Rice Krispy Treats	2.0	0.63	1.2	3.4
Crispy Bacon	1.9	0.83	0.9	3.8
Parmesan	1.6	0.33	1.2	2.4
Cheerios	1.5	0.22	1.1	1.9
Steak	1.4	0.48	0.9	2.5
Apples	1.4	0.27	1.0	1.8
Sharp Cheddar	0.9	0.14	0.7	1.4
Chicken	0.9	0.17	0.6	1.4
Cantaloupe	0.6	0.15	0.3	0.9
Mozzarella	0.6	0.10	0.4	0.8
Strawberries	0.3	0.07	0.3	0.6

Table 4. Mean, standard deviation, minimum, and maximum compressive stresses distributed to an orthodontic bracket pad by 50 common food items listed from highest to lowest mean. Mean compressive stress was not correlated with variability (r=-0.02, p=0.892).



	Frequency	*Median (MPa)*	*Interquartile Range*
Total	40	10.37	2.72
Left	23	10.40	2.36
Right	17	10.34	2.78

Table 5. Shear bond strength of lower 1st premolar orthodontic brackets. Left vs. right premolar brackets was not statistically significant (p=0.859). Bond strengths tested at two different timepoints (10/12/21 [n=17] vs. 12/09/21 [n=16]) were not statistically significant (p=0.109)