

Using Electromagnetic Articulography to Measure Denture Micromovement during Chewing with and without Denture Adhesive

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Keywords

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Abstract

Purpose: To study the effects of denture adhesive upon denture micromovements in three dimensions during the chewing of hard, sticky, and tough food items observed using a novel method involving an electromagnetic articulograph (EMA) speech research system.

Materials and Methods: Ten volunteers (mean age 60.9 ± 10.4 years) with fair- or poor-fitting complete maxillary dentures were enrolled. Chewing experiments were conducted using two treatments (adhesive or no-adhesive control) and three foods: carrots (hard), raisins (sticky), and processed meat stick (tough). Denture micromovement was measured through a novel application of a Northern Digital Wave EMA System. Three-dimensional denture position was captured during mastication using three sensors embedded into a replica denture for each subject. Following individual characterization of a “home” reference position, the Euclidean Distances from Home (DfH) were calculated for each recorded sample of the chewing experiments. The DfH at each sample represented the denture movement for that 1/100th of a second of the activity. The DfH data were then summarized as the mean DfH, the maximum DfH, and total distance traveled by the denture. Several thresholds were also analyzed, including the percent of time that the DfH ≥ 1.5 mm, ≥ 2.0 mm, and ≥ 2.5 mm.

Results: With adhesive treatment, the mean DfH of dentures during chewing was reduced by 26.8% for carrot, 30.3% for raisin, and 31.0% for meat stick, when compared with no-adhesive treatment ($p < 0.001$ for all comparisons). Similar results were also seen for the maximum DfH and total distance travelled endpoints across foods. For the threshold endpoints, adhesive treatment was associated with a statistically significant reduction in denture micromovements at all three thresholds across foods. At the threshold of DfH ≥ 1.5 mm, adhesive treatment was associated with a reduction in micromovement by 61.6%, 56.2%, and 70.0% with carrot, raisin, and meat stick, respectively ($p \leq 0.004$ for all comparisons).

Conclusions: Observations of denture movement using the Wave EMA System were able to differentiate systematically between adhesive treatment and no-adhesive treatment for denture micromovements during different chewing challenges. Use of adhesive was associated with statistically significant reductions in denture micromovements for hard, sticky, and tough foods as measured with both distance and threshold endpoints.

Although the rate of edentulism has been progressively declining in the United States, it remains an important public health problem. Between 2009 and 2012, the overall prevalence was about 4.9%, increasing to 13.7% for people 65 to 74 years of age, and 24.1% for those 75 and older.¹ The consequences of edentulism are varied and complex, ranging from impaired masticatory function,² unhealthy diet,³ social disability,⁴ and

poor quality of life.⁵ Access to dental prostheses improves the quality of life for such patients.^{6,7} Approximately 30% of complete denture wearers experience dissatisfaction with their prostheses.^{8,9} The most common complaints made by such patients include difficulties with retention, stability, and comfort while eating,^{10,11} which can be traced in part to small denture movements in the mouth during chewing activities.^{12,13} Indeed,

survey studies reveal that most complete denture wearers eliminate or dramatically reduce consumption of hard foods (carrots, celery, nuts), sticky foods (toffee, dried fruit), and tough foods (beef, other tough meats) because of denture movements during chewing.¹⁴

Because of the negative impacts upon patient outcome associated with denture movements during chewing, improving the retention and stability of complete dentures is of considerable interest in prosthetic dentistry. One avenue of research has focused on the use of over-the-counter dental adhesives. Gnathodynamometry has historically been used to measure “macro” movements of the denture; that is, bite forces that cause denture dislodgement.^{15–18} Dental adhesives have been found to reduce macromovements of the denture and to improve retention, stability, overall function, and patient quality of life across studies.¹⁹ However, real-world complaints of patients dissatisfied with their complete dentures often derive from very small denture movements and shifts within the mouth (so-called “micromovements”). It is unclear whether denture adhesives have any effect upon reducing the frequency of denture micromovements during problematic activities such as chewing hard, sticky, or tough foods. Rendell *et al* reported the use of a multichannel magnetometer for measuring mandibular movement during chewing among denture wearers and dentate volunteers.²⁰ The subjects chewed standardized pieces of dried apricots and fresh white bread; separate trials were conducted for denture wearers with and without the use of denture adhesives. The mean chewing rate among the dentate volunteers was significantly faster than that of the denture wearers when not using adhesives. After denture adhesive was applied, the authors found statistically significant increases in the mean chewing rate for both foods among the denture wearers at 0, 2, and 4 hours post-application. These rates did not differ significantly from those seen among the dentate volunteers. Although the data support the idea that denture adhesives reduce denture micromovements during chewing, the study was limited to an analysis of a single point of movement on the denture, and only in a single, vertical plane. Therefore, the authors could not draw conclusions about three-dimensional (3D) movements of the denture.

Here we describe an exploratory study of 3D denture micromovements during chewing using a novel, customized experimental setup incorporating an electromagnetic articulograph (EMA) system (Wave; Northern Digital, Inc., Ontario, Canada) more commonly used in speech production research.²¹ The device is a non-line-of-sight positional capture system that includes a magnetic field generator (transmitter) and small sensors (receivers). As the transmitter generates an oscillating electromagnetic field with time-varying orientation, a signal of varying strength is induced in the sensors. The strength of the induced signal varies with the location and relative orientation of the receiver within the transmitted field such that the 3D sensor location can be determined from measurement of the signal strength.²¹ Historically, EMA systems have been used to track real-time, 3D orofacial movements in a variety of studies focused on disorders of speech (including speech analysis in denture wearers), as well as disorders of the vocal tract, swallowing, and mandibular function.^{22–26} Here, we describe the novel use of EMA technology during the chewing of

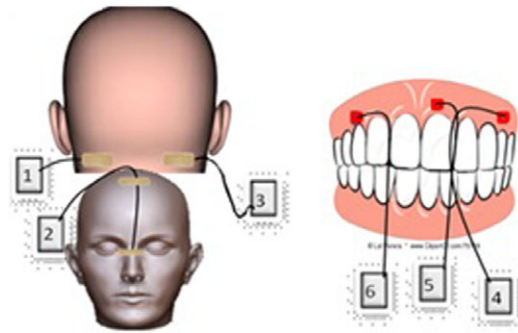


Figure 1 Placement of head sensors and sensors on acrylic dentures.

hard, sticky, and tough food items by denture wearers, with or without the use of denture adhesive, to determine the effects of the adhesive upon 3D denture micromovements.

Materials and methods

Subjects and consent

Ten pre-screened denture wearers with fair- or poor-fitting dentures were enrolled between March 26, 2013 and May 14, 2013 at The Procter & Gamble Company (Mason, OH). Eligible subjects were ≥ 18 years of age; had a complete maxillary denture and partial or natural teeth on the opposing dentition (mandibular); had a Kapur scale score²⁷ of ≤ 4 ; were regular users of adhesive (≥ 3 times per week); agreed not to use any adhesive on study visit days; and were in good general health as determined by the investigators. Subjects were excluded if they had a pacemaker; had implants or prostheses in the head region that might affect an electromagnetic field; had a complete mandibular denture or a poor-fitting mandibular partial denture; were pregnant or might be pregnant; or were participating in any other oral or dental product studies. At each visit, continuance criteria, including no to minimal use of denture adhesive on the day of the visit as well as all other exclusion criteria, were assessed for each subject.

The study was approved by the Goodwyn Institutional Review Board (protocol #2013021). All enrolled subjects gave written, informed consent for participation in this study.

Measurement of denture movement

Denture micromovement was measured using a novel method incorporating the EMA speech research system (Wave).²¹ All enrolled subjects had a replica of their complete maxillary denture made in a dental laboratory. The replica was constructed of typical denture acrylic, but coloring was not added so that the denture would remain clear for ease of placing sensors. Three-dimensional denture position was captured via three Wave system sensors embedded into each subject's replica denture. Three sensors were also placed as references on the subject's head, at the nasion and the left and right mastoid process, to record head movement so that denture movements relative to the head could be isolated and calculated (Fig 1 and Video S1). Wave system sensors were assigned exclusively to each subject during the study. If a sensor broke or failed during the study, it was replaced with another sensor assigned to that subject. The

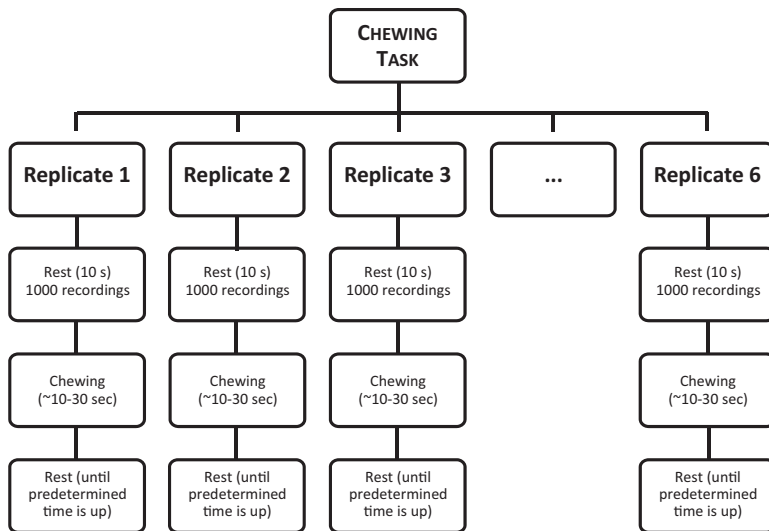


Figure 2 Chewing task procedure.

head sensors were cleaned with alcohol prior to each use. Between visits, the replica denture was cleaned, dried, and stored in a denture storage container, and the head sensors were stored separately in a zip-top bag, both labelled with subject's initials and subject number.

Investigational product

The denture adhesive under investigation in this study was Fixodent® Original Denture Adhesive (The Procter & Gamble Company, Cincinnati, OH).

Study design

This study had two treatments (presence or absence of adhesive), and chewing was evaluated for three food types (hard, sticky, tough), which were assessed in a six-period (visit), cross-over design. Each of the six study visits occurred on a different day and involved measurement of the denture micromovement during several different chewing activities with or without use of denture adhesive. Subjects were asked to come to each visit with no adhesive applied to their original denture. If this was not possible, then they were asked to come with very little adhesive such that removing their original denture would not be difficult. During the study visit, each subject was asked to perform a series of chewing activities while the Wave system recorded the position of the sensors on the subject's head and in the replica denture in the subject's mouth. There was a minimum overnight wash-out period between each visit. Standardized amounts of three types of food items were used in the study to represent hard (carrots), sticky (raisins), and tough food (smoked meat stick product, SlimJim, ConAgra Foods, Inc., Omaha, NE).

Each subject was randomized to a treatment sequence provided by the study sponsor (e.g., ABBAB, ABBAAB, etc., where A = adhesive and B = no-adhesive control). Before the experiments commenced, the subject was asked to remove his or her original denture. A dental professional removed any residue of denture adhesive from the subject's mouth (if necessary) and performed oral soft and hard tissue examinations.

A standardized amount of the assigned treatment, if applicable, was then applied to the subject's replica denture, which contained the previously attached Wave sensors. The subject was then assisted in returning the replica denture to the mouth.

Prior to application of the head sensors, the subject's skin was cleaned with a disposable alcohol swab. Three head sensors were then attached to the subject's head and face using first-aid adhesive tape, with one sensor placed behind each ear (mastoid process) and one on the bridge of the nose (nasion). After approximately 1 hour had elapsed to allow the denture adhesive to set, the subject was asked to move into the electromagnetic field generated by the Wave system and was asked to perform voluntary chewing activities. General comments made by the subject were recorded throughout.

Chewing procedure

Chewing experiments were repeated six times for each food type for every subject at every visit, or until a sensor failed by being bitten (Fig 2). Each chewing session lasted approximately 45 seconds per each replicate. A timed computer presentation was used to ensure consistency across and within subjects and experiments. The procedure was as follows, although total timing was sometimes adjusted to allow for differences in subjects' required chew time. Subjects were asked to chew "until ready to swallow," and this was different across subjects and food types. First, the subject sat still for 10 seconds ("rest" position). Next, chewing began, and the subject was reminded to refrain from partially swallowing the food and to wait until the entire bolus was ready to swallow. When ready to swallow, the subject raised his or her hand, and the operator noted the time to the second. The subject swallowed the bolus and was allowed to continue to chew as needed. When swallowing was complete, the subject lowered his or her hand and the operator noted the time to the second. The subject then returned to a rest position for the remaining seconds of the test. During chewing experiments, subjects who preferred not to swallow the food were instructed to raise their hand when the bolus was

ready to swallow and were allowed to discard the food without swallowing. Subjects were also allowed to sip water *ad lib* during or between the chewing experiments to mimic their regular chewing/swallowing habits.

Safety assessments

An oral soft and hard tissue examination was conducted at each study visit before the chewing experiments were initiated. A visual examination of the oral cavity and perioral area was made by a dental professional using a standard dental light, dental mirror, and gauze. The structures examined included the gingiva (free and attached), hard and soft palate, oropharynx/uvula, buccal mucosa, tongue, floor of the mouth, labial mucosa, mucobuccal/mucolabial folds, lips, and perioral area. Assessment of the oral hard tissues was conducted via a visual examination of the dentition and restorations using a standard dental light, dental mirror, and air syringe. All abnormal findings were recorded and categorized by their location.

Efficacy assessments and statistical analysis

Sample size

Sample size calculations were not carried out for this study. The sample size of 10 was chosen based on logistical considerations.

Data capturing

The locations of the head sensors and the denture sensors were recorded during the chewing experiments by the Wave system at 100 samples per second; however, to compute a more accurate location of the “home” position, 500 samples from the “rest” position (seconds 3 to 8) were used. Approximately 2000 samples were used to track the location of each sensor during chewing and swallowing movements. The 3D (*x*, *y*, *z*) position of each sensor was recorded by the proprietary WaveFront software provided with the Wave system, in units relative to the global coordinate system created by the Wave field generator.

Smoothing

The (*x*, *y*, *z*) trajectories of each sensor were filtered using a local regression smoothing procedure²⁸ with a bandwidth of 40 consecutive samples (1.3% of a 30-second session).

Correction for head movement

After the data were smoothed, the movement of the head, as characterized by the rigid body determined by the position of the three head sensors, was removed from both the head sensors and the denture sensors using 3D rotation calculation to rotate the location of all 6 sensors such that the head sensors were in a reference plane. Removing the head movement from the movement of the denture sensors effectively preserves independent movement of the denture and presents those positions free of any general head movement that the subject may create.

Denture home position

An estimate of the coordinates for each subject’s denture “home” position was computed by taking the median, for each denture sensor, of the 500 samples recorded during seconds 3

to 8 of the rest periods for each activity, across all replicates. The Distance from Home (DfH) measure was computed at each sample of activity as the Euclidean distance in (*x*, *y*, *z*) from the current to corresponding home position for each sensor.

Denture level location

A rotation was applied to the denture sensors to bring them into a horizontal position so that the denture movements could then be properly quantified (e.g., up/down, or side-to-side movements). This also standardized the denture orientation across subjects and corrected for any differences in subject posture or palate angle. This rotation was determined from the median of the “home” positions of the denture.

Variables

The data for each activity, sensor, and replicate were summarized separately for each subject at every visit. Once the “home” coordinates were defined (as the median denture rest positions), the Euclidean Distances from Home (DfH) were calculated for each sample of the activity, starting with the 13th second up until the second when swallowing began. The DfH at each moment represents the denture movement for that 1/100th of a second of the activity. The DfH data were then summarized over the activity duration with endpoints computed for each sensor, replicate, and visit for each study subject. These endpoints included the mean Euclidean DfH, the maximum Euclidean DfH, and the Total Euclidean distance traveled, all summarized by a median over the series of replicates for a given activity. Further, we analyzed several threshold endpoints, including the percent of moments with the Euclidean DfH greater than or equal to specific thresholds of 1.5 mm, 2.0 mm, and 2.5 mm, again all when the median was taken over the replicates.

Treatment comparisons

Treatments were compared for each food separately using a mixed model ANOVA for a crossover design with repeated measures (sensors) within visits. The model included terms for subject (random effect), treatment, period (visit), sensor, treatment by period and treatment by sensor interactions, carryover effects, and the variable of interest as the response. The analysis focused on the three denture sensors, which served as repeated measures within periods. Equal correlation was modeled between the sensors. If the carryover term was not significant at the 0.1 level ($p < 0.1$), then the final model did not include the carryover term. Interaction terms, mainly the treatment by sensor interaction, were retained if their significance was approximately $p = 0.1$ level or below.

Results

Subject demographics

Ten subjects (seven female) were enrolled and included in the statistical analyses. The mean subject age was 60.9 ± 10.4 years, ranging from 45 to 75 years. Six of the subjects were Caucasian, and four were black.

Table 1 Efficacy endpoints for the hard food (carrot) chewing exercises. Data were calculated with the median taken over the replicates

Endpoint	Treatment	Adjusted mean (SE)	Adhesive comparison (% difference)	<i>p</i> Value (no adhesive vs. adhesive)
Mean DfH (mm)	Adhesive	0.819 (0.0809)	$\Delta = -0.299$ (26.8%)	<i>p</i> < 0.001
	No adhesive	1.117 (0.0801)		
Maximum DfH (mm)	Adhesive	1.790 (0.1902)	$\Delta = -1.023$ (36.4%)	<i>p</i> < 0.001
	No adhesive	2.813 (0.1877)		
Total distance traveled (mm)	Adhesive	65.521 (9.7588)	$\Delta = -34.228$ (34.3%)	<i>p</i> = 0.001
	No adhesive	99.749 (9.5909)		
Proportion of DfH \geq 1.5 mm	Adhesive	0.089 (0.0438)	$\Delta = -0.143$ (61.6%)	<i>p</i> < 0.001
	No adhesive	0.232 (0.0433)		
Proportion of DfH \geq 2 mm	Adhesive	0.034 (0.0190)	$\Delta = -0.049$ (59.0%)	<i>p</i> = 0.005
	No adhesive	0.083 (0.0187)		
Proportion of DfH \geq 2.5 mm	Adhesive	0.010 (0.0075)	$\Delta = -0.019$ (65.5%)	<i>p</i> = 0.019
	No adhesive	0.029 (0.0074)		

Table 2 Efficacy endpoints for the sticky food (raisin) chewing exercises. Data were calculated with the median taken over the replicates

Endpoint	Treatment	Adjusted mean (SE)	Adhesive comparison (% difference)	<i>p</i> Value (no adhesive vs. adhesive)
Mean DfH (mm)	Adhesive	0.835 (0.1049)	$\Delta = -0.363$ (30.3%)	<i>p</i> < 0.001
	No adhesive	1.198 (0.1038)		
Maximum DfH (mm)	Adhesive	1.752 (0.2195)	$\Delta = -0.740$ (29.7%)	<i>p</i> < 0.001
	No adhesive	2.492 (0.2170)		
Total distance traveled (mm)	Adhesive	31.565 (6.3147)	$\Delta = -12.622$ (28.6%)	<i>p</i> = 0.003
	No adhesive	44.186 (6.2717)		
Proportion of DfH \geq 1.5 mm	Adhesive	0.113 (0.0488)	$\Delta = -0.145$ (56.2%)	<i>p</i> = 0.004
	No adhesive	0.258 (0.0482)		
Proportion of DfH \geq 2 mm	Adhesive	0.052 (0.0287)	$\Delta = -0.070$ (57.4%)	<i>p</i> = 0.016
	No adhesive	0.122 (0.0283)		
Proportion of DfH \geq 2.5 mm	Adhesive	0.023 (0.0161)	$\Delta = -0.036$ (61.0%)	<i>p</i> = 0.031
	No adhesive	0.059 (0.0159)		

Hard food (carrot) experiments

For the distance endpoints, there was a statistically significant advantage for the adhesive treatment over the no-adhesive control (Table 1). For example, with adhesive treatment, the mean DfH of dentures during chewing was reduced by 26.8%, the maximum DfH of dentures during chewing was reduced by 36.4%, and the total distance travelled by dentures during chewing was reduced by 34.3%, when compared with no-adhesive control treatment ($p \leq 0.001$ for all comparisons). Adhesive treatment also compared favorably against no-adhesive treatment for all thresholds, even for the most stringent measurement of percent of samples for which the DfH \geq 1.5 mm (Table 1). Dentures in the adhesive treatment condition had a DfH \geq 1.5 mm during 8.9% of samples, as opposed to during 23.2% of samples in the no-adhesive control condition, a 61.6% reduction in denture micromovements with adhesive ($p < 0.001$).

Sticky food (raisin) experiments

We observed similar results during the raisin experiments as during the carrot experiments. The adhesive treatment conferred a statistically significant advantage over no-adhesive

control treatment for all distance endpoints (Table 2). With adhesive treatment, the mean DfH was reduced by 30.3% ($p < 0.001$), the maximum DfH was reduced by 29.7% ($p < 0.001$), and the total distance travelled by dentures during chewing was reduced by 28.6% ($p = 0.003$) when compared with no-adhesive control treatment. For the threshold endpoints, dentures in the adhesive treatment condition had a DfH \geq 1.5 mm during 11.3% of moments, as opposed to during 25.8% of moments in the no-adhesive control condition, a 56.2% reduction in denture micromovements with adhesive ($p < 0.001$). Similar results were seen for the percent of moments with DfH \geq 2.0 mm and DfH \geq 2.5 mm threshold endpoints as well.

Tough food (processed meat stick) experiments

As with the raisin and carrot experiments, we found that adhesive treatment was superior to no-adhesive treatment for all distance endpoints in the tough food chewing experiments (Table 3). With adhesive treatment, the mean DfH was reduced by 31.0%, the maximum DfH was reduced by 28.8%, and the total distance travelled by dentures during chewing was reduced by 31.7% when compared with no-adhesive control treatment ($p < 0.001$ for all comparisons). For the threshold endpoints,

Table 3 Efficacy endpoints for the tough food (processed meat stick) chewing exercises. Data were calculated with the median taken over the replicates

Endpoint	Treatment	Adjusted mean (SE)	Adhesive comparison (% difference)	<i>p</i> Value (no adhesive vs. adhesive)
Mean DfH (mm)	Adhesive	0.845 (0.0893)	$\Delta = -0.380$ (31.0%)	<i>p</i> < 0.001
	No adhesive	1.225 (0.0882)		
Maximum DfH (mm)	Adhesive	1.817 (0.1933)	$\Delta = -0.736$ (28.8%)	<i>p</i> < 0.001
	No adhesive	2.553 (0.1910)		
Total distance traveled (mm)	Adhesive	45.783 (7.8568)	$\Delta = -21.210$ (31.7%)	<i>p</i> < 0.001
	No adhesive	66.992 (7.7936)		
Proportion of DfH ≥ 1.5 mm	Adhesive	0.083 (0.0420)	$\Delta = -0.194$ (70.0%)	<i>p</i> < 0.001
	No adhesive	0.277 (0.0414)		
Proportion of DfH ≥ 2 mm	Adhesive	0.037 (0.0271)	$\Delta = -0.093$ (71.5%)	<i>p</i> = 0.002
	No adhesive	0.130 (0.0267)		
Proportion of DfH ≥ 2.5 mm	Adhesive	0.018 (0.0144)	$\Delta = -0.036$ (66.7%)	<i>p</i> = 0.024
	No adhesive	0.054 (0.0142)		

the use of adhesive during chewing experiments with the processed meat stick had an even greater effect on reducing denture micromovements than those seen in the experiments with carrot and raisin. Dentures in the adhesive treatment condition had a DfH ≥ 1.5 mm during 8.3% of moments, as opposed to during 27.7% of moments in the no-adhesive control condition, a 70% reduction in denture micromovements with adhesive (*p* < 0.001) (see Video S2). Again, similar results were seen for the percent of moments with DfH ≥ 2.0 mm and DfH ≥ 2.5 mm threshold endpoints.

Safety

There were three non-serious, mild adverse events (AEs) experienced by two study subjects. All AEs resolved by the end of the study.

Discussion

Complete denture wearers are often subject to poor nutritional status, poor general health, social anxiety, and depression.^{3,29-31} Denture movements during speaking and chewing have been found to be a contributing factor to these negative outcomes, and improved satisfaction with denture fit and chewing and speaking performance is associated with a higher quality of life for complete denture wearers.³² Here, we have demonstrated that the use of denture adhesive is associated with statistically significant reductions in the nature and extent of denture micromovements in experimental chewing situations when compared to a no-adhesive control. For all three food items tested, including carrot (hard food), raisin (sticky food), and processed meat stick (tough food), the use of denture adhesive was associated with a reduction in the magnitude of denture micromovements by approximately one-third. An even greater effect was seen when considering the percentage of the time that dentures were shifted away from the “home” position during chewing. Even at the smallest threshold, the percent of moments in which the DfH ≥ 1.5 mm, the use of denture adhesive was associated with statistically significant reductions of between 56% and 70%.

In addition, we were able to demonstrate that the use of denture adhesive was well tolerated.

One of the strengths of the current study was the use of the EMA system (Wave Speech Research System) as part of a novel method to capture denture micromovements in all three dimensions during chewing. Earlier studies using gnathodynamometry have been limited to measuring only bite forces that cause denture dislodgement, rather than measuring micromovements. The EMA approach used in this study provides many advantages over earlier technology for studying denture movements. First, the system is objective and unbiased, as it does not rely upon self-reports of denture movements by study subjects, a particular advantage given that the reliability of patient self-report in many areas of oral health outcomes has been the subject of much debate.³³⁻³⁵ Second, the method was able to dramatically limit or eliminate confounding head movements through the use of reference sensors on the mastoid processes and nasion, allowing us to focus on independent movements of the denture during chewing.

One perceived weakness of the study might be the small sample size of 10 subjects. Though the sample is small, the use of the crossover design adds power by increasing the number of observations. In addition, we replicated each chewing experiment six times for each food type for each subject. The sample size was sufficient to consistently statistically differentiate adhesive from no-adhesive control in this design.

Conclusion

In this study, a novel method incorporating an electromagnetic articulograph (Wave Speech Research System) was able to differentiate between adhesive treatment and no-adhesive control treatment for denture micromovements during different chewing challenges with hard, sticky, and tough foods. The use of adhesive was associated with statistically significant reductions in denture micromovements for all three foods as measured with both distance and thresholds. Based on the results from this study, the novel method incorporating the Wave system should prove useful in future studies to study denture movement during a variety of speaking and chewing activities

and under a variety of different experimental conditions, with the ultimate goal of reducing or eliminating denture movements to improve quality of life for denture wearers.

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