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ORIGINAL ARTICLE

Effects of appetite, BMI, food form and flavor on mastication: almonds as a test food

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Objectives: To investigate the effects of appetitive sensations, body mass index (BMI) and physical/sensory properties of food (almonds) on masticatory indices and resultant pre-swallowing particle sizes.
Subjects/Methods: Twelve lean (BMI = 22.2 ± 0.3) and 12 obese (BMI = 34.3 ± 0.6) adults. After collecting appetitive ratings, electromyographic recordings were used to assess participants' microstructure of eating for five almond products (raw, dry unsalted roasted, natural sliced, roasted salted and honey roasted) under fasted and satiated conditions. Duplicate samples were masticated to the point of deglutition and then were expectorated and size sorted.
Results: No statistically significant effects of BMI were detected for any of the mastication measures. Maximum and mean bite forces were greater under the fasted condition. Sliced almonds required lower bite force than did the other almond varieties. The pre-swallowing particle sizes were significantly greater for the sliced almonds than all other varieties. Both the number of chews and mastication time were negatively correlated with particle size. There were no significant effects of almond form or flavor on particle size.
Conclusions: These results do not support differences in masticatory performance between lean and obese individuals, nor effects of sensory properties. Instead, the physical form of foods as well as an individuals' appetitive state may have a greater influence on masticatory behavior. The health implications of these observations warrant further investigation.
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Introduction

A primary function of mastication is to reduce the particle size of solid foods so they may be swallowed. Commonly, a wide distribution of particle sizes is produced (Lucas and Luke, 1983) and is governed by the size and weight of the ingested load (Lucas and Luke, 1984) as well as the particle size swallowing thresholds for specific food mixtures (Prinz and Lucas, 1995). Less widely documented are mastication's influences on nutrient bioaccessibility, satiety and cephalic phase responses.

The mechanical action of chewing breaks down food particles increasing the surface area available to enzymes. This, in turn, modulates the release of nutrients and other food constituents from the food matrix, which subsequently influence gut signaling, physical actions (for example, transit time) and ultimately digestive and absorptive processes. Numerous hormones are released in response to the presence of nutrients in the gastrointestinal tract. For example, lipid entering the duodenum and ileum increases plasma cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1), respectively, and the magnitude of these responses is directly related to the quantity of lipid present (Feinle *et al*., 2003, 2004; Feltrin *et al*., 2004). Higher plasma CCK levels are obtained with consumption of almond oil as compared to whole almonds suggesting that the form of an ingested food can influence the hormonal response (Burton-Freeman *et al*., 2004). This may relate to the bioaccessibility of the lipid which, in nuts, requires fracture of the parynchemal cell walls (Ellis *et al*., 2004). Through influencing hormonal responses, mastication may then have a bearing on satiety and body weight as higher CCK levels as well as GLP-1 are associated with greater subjective satiety ratings (Naslund *et al*., 1999; Burton-Freeman *et al*., 2002; le Roux *et al*., 2006).

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Additionally, the mechanical act of mastication may directly promote satiety. Oral feeding is more effective at inducing satiety than intragastric infusions, suggesting that oral stimulation optimizes the development of satiety (Jordan, 1969; Lavin *et al*., 2002). Studies in rats suggest that mastication activates histaminergic neurons in the paraventricular nucleus and ventromedial hypothalamus (Sakata *et al*., 2003). Activation of these neurons is linked with decreased food intake in rats, while antagonists augment intake (Sakata *et al*., 1988a, b; Fukagawa *et al*., 1989; Ookuma *et al*., 1989, 1993; Sakata, 1995).

Mastication is also an important cephalic phase stimulus. Chewing tasteless rubber promotes salivary flow (Richardson and Feldman, 1986) and may be required for the first-phase insulin response (Teff *et al*., 1995). Although the effect of cephalic phase responses on appetite and energy balance is yet to be elucidated, sensory stimulation is an effective stimulus for the release of numerous appetitive hormones such as CCK (Schafmayer *et al*., 1988; Wisen *et al*., 1992), ghrelin (Arosio *et al*., 2004), leptin (Sobhani *et al*., 2002) and insulin (Bruce *et al*., 1987; Teff *et al*., 1991; Teff and Engelman, 1996). Thus, mastication may influence appetite and feeding through this mechanism.

Almonds are an intriguing food model to study the appetitive effects of mastication, as there are seemingly conflicting issues related to their health impact. Regular almond consumption is associated with a reduction in several risk factors for cardiovascular disease (Jenkins *et al*., 2002; Sabate *et al*., 2003), but almonds are a high-fat, energy-dense food—characteristics often associated with positive energy balance (Schulz *et al*., 2002). However, accumulating evidence indicates that almond consumption does not promote positive energy balance (Fraser *et al*., 2002; Hollis and Mattes, in press). This has been attributed, in part, to limited bioaccessibility of lipid from almonds (Ellis *et al*., 2004). Conversely, this could also compromise the availability of lipid soluble cardiovascular protective compounds such as vitamin E (Spiller *et al*., 1998). Thus, further elucidation of the impact of mastication on almond ingestion is warranted.

It may be hypothesized that the health benefits of almond consumption will be altered by inter- and intra-individual differences in masticatory performance. Large ranges in the number of chews made before swallowing have been reported for carrots 9–65 chews, and Brazil nuts 14–44 chews (Lucas and Luke, 1986). There is also evidence of differences in particle sizes after a standardized number of chews, between 2.5 and 5.1 mm for carrots and 0.9–2.1 mm for Brazil nuts (Lucas and Luke, 1986). Other studies have reported differences in particle size distributions due to food type, yet indicate a lack of variability between and among individuals (Peyron *et al*., 2004). Intra-individual variability resulting in varied particle sizes may have implications for lipid bioaccessibility. If the degree of intra-individual variability is large enough, the subsequent influence on hormonal responses following almond consumption may alter both satiety responses and the health benefits of almonds.

Intra-individual differences in chewing behavior due to appetitive state or the palatability of the food may also influence lipid bioaccessibility. Increased deprivation time, resulting in increased hunger, leads to increased intake and meal duration (Bellisle *et al*., 1984) as well as an increase in initial ingestion rate (Spiegel, 2000). Additionally, the palatability of a food is important in dictating several aspects of chewing behavior. The preference for a food is positively correlated with eating rate (Hill and McCutcheon, 1984) and increased palatability is associated with reduced chewing per unit and increased meal size and duration (Bellisle and Le Magnen, 1981; Bellisle *et al*., 1984). Thus, a more palatable food or flavor can influence mastication and, potentially, lipid and nutrient bioaccessibility. Furthermore, this response may be heightened in the obese, where palatability may be more important in dictating eating behavior (Spiegel *et al*., 1989; Yeomans *et al*., 2004). This study explored the mastication of various flavors and forms of almonds in individuals in fasted and satiated states.

It is of particular interest to contrast the masticatory performance of individuals varying in body mass index (BMI). This characteristic has been associated with altered facets of the microstructure of eating that may lead to changes in putative satiety hormone release and attenuation of satiety cues. However, it is not well established that overeating in the obese can be ascribed to masticatory performance. Hill and McCutcheon (1984) reported an increase in eating rate, due to larger bite size, with increased body size and obesity. An increased eating rate could result in the obese swallowing larger particles resulting in decreased lipid bioavailability and a reduced impact on satiation from certain foods. A recent study noted weaker dietary compensation for peanuts in the obese as compared to their lean counterparts (Coelho *et al*., 2006). However, other studies have reported no effect of BMI on bite size, ingestion rate or meal size (Bellisle and Le Magnen, 1981; Spiegel *et al*., 1993). The present study additionally sought to contrast the masticatory function of lean and obese individuals. Exploring the role of mastication is especially relevant in a food model, such as almonds, with an approved health claim that may be influenced by the efficiency of their mastication.

Materials and methods

Participants

Twelve lean (BMI = 22.2 ± 0.3) and 12 obese (BMI = 34.3 ± 0.6) adults (25.2 ± 1.6 years) participated. Each BMI group consisted of six males and six females who were nonrestrained eaters (three-factor eating questionnaire restraint score $\leqslant$13) (Stunkard and Messick, 1985) with a full set of teeth, no nut allergies and who were regular breakfast consumers. All participants provided signed informed consent before study

initiation. This study protocol was approved by the Purdue University Institutional Review Board.

Protocol
The study followed a within-subject design with each participant returning for a fasted and satiated test session. Treatment order was counterbalanced. Participants were asked to follow an overnight fast of at least 8 h before each test session and reported to the laboratory 1 h after their habitual breakfast time. For the fasted session, a series of appetitive questions were immediately answered. For the satiated session, participants were first provided a meal consisting of instant plain oatmeal, flavored with vanilla and cinnamon, and a beverage of orange juice. Participants were instructed to consume the entire volume of orange juice and eat the oatmeal until they reached a level of 'comfortably full'. This was designated to participants as a 3 on a 9-point hedonic scale relating to fullness anchored by 1 = 'extremely' and 9 = 'not at all'. Appetitive questions were answered following consumption of the meal.

Appetitive ratings
Participants rated their hunger, fullness, desire to eat, desire to eat something sweet, desire to eat something salty, desire to eat something crunchy, prospective consumption and thirst using 100 mm visual analogue scales. Prospective consumption was assessed with the question, 'How much food could you eat right now' and was anchored with 'nothing at all' and 'the most that I have ever eaten'. All remaining questions were phrased as 'How strong is your feeling of hunger (fullness, desire to eat, and so on) right now' and anchored with 'not at all' and 'extremely'.

Masticatory performance
Electromyographic recordings (BioPac Systems Inc., Goleta, CA, USA) were used to assess the participants' microstructure of eating, including measurements on number of chews, bite strength (as measured in mV (Mioche *et al*., 2004)), time spent chewing and chewing rate. At the first test session, a carrot was used to determine the dominant chewing side of the participants' mouth. The temporalus and masseter muscles on the dominant chewing side of each participant were then identified by palpation, and bipolar surface electrodes were placed approximately 3 cm apart along each muscle. A third electrode was also placed on the inside of their wrist. A series of five almond varieties were presented in duplicate, in a counterbalanced order. Participants chewed each almond individually until they would normally swallow. They then expectorated the almonds into a series of sieves and rinsed their mouths three times with 20 ml aliquots of deionized water, expectorating after each rinse into the same set of sieves. The palatability of the almonds was recorded on a 9-point hedonic scale following presentation of the second sample.

Almond samples
Five almond forms were used: Butte variety raw, dry unsalted roasted, Blue Diamond (Sacramento, CA, USA) Roasted Salted, Blue Diamond Honey Roasted and natural sliced. All almond samples were individually weighed and only almonds with weights between 1.00 and 1.05 g were used. Breaking force for each of the almonds was determined using a texture analyzer with a knife probe. A mean value was determined from analyzing five nuts of each type. The sliced almonds were analyzed by stacking the 1.00 g sample.

Almond particle size assessment
For particle size measurements, the almonds were separated by a mechanical sieving process. The expectorated samples were collected through a series of five sieves yielding the following particle size ranges: >3.35, 3.35–2.00, 1.99–1.00, 0.99–0.5, 0.49–0.25 and <0.25 mm. The expectorated samples were washed with 250 ml deionized water poured through the stack of five sieves and then dried at 54°C for 6 h. This time and temperature combination has previously been shown to eliminate all water in similarly sized almond samples (Ow *et al*., 1998). The dried fractions are expressed as percentages of the original almond weight.

Statistical analysis
Statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS), version 12.0. The criterion for statistical significance was $P<0.05$, two-tailed. All data are expressed as mean ± s.e. Appetitive ratings, palatability ratings, masticatory performance and particle sizes were analyzed by repeated measures analysis of variance followed (when appropriate) by paired *t*-tests. *P*-values were adjusted to control for multiple testing. Relationships between masticatory performance, particle size and BMI were determined by correlation analyses. Stepwise regression analyses were performed with particle size as the dependent variable and masticatory performance as well as palatability as the independent variables. Chewing rates (number of chews per s) for the first and last five chews for each chewing sequence were compared using paired samples *t*-tests applying Bonferroni's correction to determine if chewing rate differed throughout the chewing sequence.

Results

Appetitive ratings
Hunger ratings were significantly greater ($F(1,20) = 117.4$, $P<0.001$) and fullness ratings were significantly lower ($F(1,19) = 88.3$, $P<0.001$) during the fasted session compared

to the satiated session. Additionally, the desire to eat ($F(1,19) = 131.2$, $P < 0.001$), desire to eat something sweet ($F(1,19) = 5.3$, $P = 0.032$), desire to eat something salty ($F(1,19) = 9.0$, $P = 0.007$) and the desire to eat something crunchy ($F(1,20) = 8.4$, $P = 0.009$) were all significantly greater during the fasted session. Prospective consumption ratings were also higher at the fasted session ($F(1,19) = 103.7$, $P < 0.001$) as was thirst ($F(1,20) = 6.7$, $P = 0.018$). No statistically significant BMI effects were detected for any of the appetitive measures. As a result, data from all participants were pooled.

Palatability

Preferences for each of the almonds did not differ between test sessions and were all rated as palatable. Presentation of the almond varieties was counterbalanced and there was no time effect on palatability. Additionally, only two samples of each almond variety were masticated at each test session. Therefore, neither fatigue nor sensory-specific satiety appeared to influence the palatability ratings and, consequently, mastication. Palatability ratings for all of the almonds did not differ by BMI group. The palatability of the roasted salted and honey roasted almonds were significantly greater than the other almond forms ($F(4,92) = 21.0$, $P < 0.001$). However, no significant correlations between palatability and either masticatory performance or pre-swallowing particle size were observed.

Masticatory performance

There were no differences in chewing rates for the first and last five chews of each chewing sequence suggesting a constant chewing rate. The coefficients of variation for mean bite force for each almond form indicated that bite force was consistent throughout the chewing sequence (Table 1). Greater maximum ($F(1,23) = 7.6$, $P = 0.011$) and mean ($F(1,23) = 5.2$, $P = 0.032$) (Figure 1) bite forces were observed under the fasted condition. Additionally, there were significant effects of almond form on all mastication parameters: maximum force ($F(4,92) = 9.0$, $P < 0.001$), mean force ($F(4,92) = 3.5$, $P = 0.010$), number of chews ($F(4,92) = 14.1$, $P < 0.001$), time spent chewing ($F(4,92) = 17.8$, $P < 0.001$) and chewing rate ($F(4,92) = 3.2$, $P = 0.016$) (Figure 1).

Table 1 Coefficients of variation for mean bite force by almond form and treatment

Almond form	*Fasted session*	*Satiated session*
Raw	56.53	52.19
Salted	55.02	53.79
Roasted	48.54	60.91
Sliced	57.56	59.23
Honey roasted	52.93	59.51

Post hoc tests revealed sliced and roasted almonds elicited a significantly lower maximum force and mean force than did the other almond varieties. The number of chews was significantly greater for both the sliced and raw almonds as compared with the roasted, salted roasted and honey roasted varieties. Time spent chewing was significantly higher for both the sliced and raw almonds than the other varieties. Maximum force and mean force were correlated ($r^2 = 0.970$, $P < 0.001$) as were the number of chews and time spent chewing ($r^2 = 0.880$, $P < 0.001$). No statistically significant BMI effects were observed for any of the mastication measures.

Almond breaking force

The raw almonds required the highest initial force to break the nut (7441.5 ± 332.3 g) followed by honey roasted (5980.58 ± 172.5 g), roasted (5003.5 ± 208.7 g), salted (4939.7 ± 266.9 g) and sliced (1349.4 ± 110.6 g).

Almond particle size assessment

The total percent recovery of the dried, expectorated almond samples was $43.8 \pm 11.3\%$. This is in close agreement with previously reported recoveries using similar techniques (Peyron *et al*., 2004). When the water used to rinse the sieves was also collected and dried, 95–97% of the original almond weight was recovered. As a result, analyses assumed the difference between the original almond weight and the almond weight recovered on the sieves could be attributed to almond particles smaller than 0.25 mm.

There were no significant feeding (fasted vs satiated) or BMI effects for percent recovery. As a result, subsequent analyses were based on pooled data. The fractions by almond form are shown in Table 2. The percent of sliced almonds with particles greater than 0.25 mm was significantly greater than all other forms, and honey roasted almonds had the smallest proportion of particles of this size range ($F(4,92) = 17.8$, $P < 0.001$). Sliced raw and roasted almonds had a significantly greater proportion of particles larger than 3.35 mm ($F(4,92) = 8.6$, $P < 0.001$). Sliced almonds had a significantly lower percent recovery of particles less than 0.25 mm ($F(4,92) = 17.5$, $P < 0.001$) than all other almond forms and honey roasted had the highest recovery of that particle size.

Raw, roasted, sliced and honey roasted total percent recoveries negatively correlated with hunger ratings ($r^2 = -0.59$, $P = 0.002$; $r^2 = -0.51$, $P = 0.011$; $r^2 = -0.52$, $P = 0.009$; $r^2 = -0.64$, $P = 0.001$, respectively) under the satiated condition only. The number of chews ($r^2 = -0.27$, $P < 0.001$) and chewing time ($r^2 = -0.34$, $P < 0.001$) were negatively correlated with the total percent of almond recovered in the sieves (>0.25 mm). Regression analyses revealed that oral processing time was the best predictor of almond particle size, although there was no significant predictor for sliced almonds in both sessions, as well as for

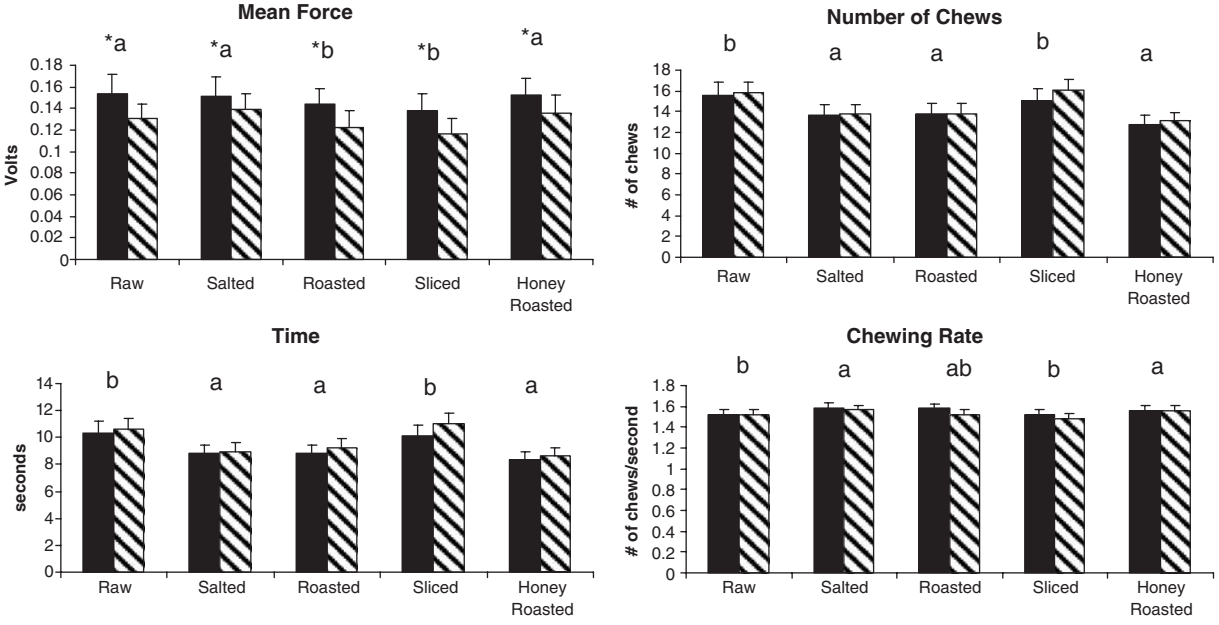

Figure 1 Mean bite force, number of chews to deglutition, time to deglutition and chewing rate (number of chews/s) by almond form and test session (fasted: black bars; satiated: striped bars) measured by electromyographic recordings. Values are means ± s.e. of the mean, $n = 24$. Letters denote significant differences between almond forms ($P < 0.05$). *Denotes significant differences between fasted and satiated sessions.

Table 2 Particle size distribution by almond form/weight (%)[a,b]

	> 3.35 mm	*2.00–3.35 mm*	*1.00–2.00 mm*	*0.50–1.00 mm*	*0.25–0.50 mm*	*< 0.25 mm*
Raw	3.76 ± 0.92a	8.62 ± 1.03a	15.37 ± 0.82a	11.24 ± 0.44a	4.88 ± 0.29a	56.13 ± 2.19a
Roasted	2.81 ± 0.61a	7.52 ± 0.83c	14.84 ± 0.89a	12.62 ± 0.66b	7.26 ± 0.32b	54.95 ± 2.04a
Salted	2.20 ± 0.68b	6.38 ± 0.84b	14.46 ± 0.96a	14.27 ± 1.52b	6.97 ± 0.40bc	56.01 ± 2.60a
Honey roasted	1.90 ± 0.60b	5.93 ± 0.80b	12.65 ± 1.05b	10.90 ± 0.63a	6.48 ± 0.57c	62.13 ± 2.17b
Sliced	5.22 ± 1.26a	10.55 ± 1.20d	18.89 ± 0.85c	9.69 ± 0.59c	3.68 ± 0.29d	51.98 ± 2.09c

[a]Values represent the percentage of the initial sample weight before mastication.
[b]The difference between the original almond weight and the almond weight recovered on all sieves was attributed to almond particles < 0.25 mm.
Values are mean ± s.e. of the mean; $n = 24$.
Letters that are different within the same column denote significant differences between almonds at $P < 0.05$.

Table 3 Regression analyses of variables contributing to particle size by almond form and treatment[a]

Almond form	*Independent variable*	β-*Coefficient,* P-*value*
Fasted session		
Raw	Mastication time	−0.596, 0.002
Roasted	Mastication time	−0.534, 0.007
Salted	Mastication time	−0.503, 0.012
Honey roasted	Mastication time	−0.601, 0.001
	Palatability	−0.350, 0.032
Satiated session		
Raw	Mastication time	−0.518, 0.009
Salted	Mastication time	−0.593, 0.003

[a]Almond forms not listed revealed no significant relationships for any tested variables.

salted and honey roasted almonds in the satiated session (Table 3).

Discussion

Oral processing of foods is modulated by characteristics of the consumer and properties of the foods ingested. Recent evidence of the health benefits associated with nut consumption (Jenkins *et al*., 2002; Sabate *et al*., 2003) coupled with findings of limited bioaccessibility of lipid from almonds (Ellis *et al*., 2004) prompted this study investigating the roles of appetitive state, BMI, physical form, and sensory properties of almonds on mastication and resultant differences in pre-swallowing particle sizes. The results of

the present study indicate that each of the assessed almond attributes influenced masticatory function, but the physical form of the almonds had the greatest influence on particle size at swallowing.

No statistically significant effect of BMI on any of the masticatory parameters was detected. Although the sample size was limited, possibly precluding identification of significant effects, the results are similar to other studies where bite-sized solid food units as well as single or mixed flavor meals were consumed (Bellisle and Le Magnen, 1981; Spiegel *et al*., 1993). Conversely, Hill and McCutcheon (1984) report a positive association between eating rate and body size and obesity. However, in that study, the increased eating rate was accomplished by taking larger bites, whereas in the current study, bite size was consistent. Other work noted varying bite size and eating rate did not result in differences in total intake, nor were there differences between lean and obese participants (Spiegel *et al*., 1993; Spiegel, 2000). The obese may consciously control eating attributes, such as meal size and duration, but there is less basis to assume they would consistently modify masticatory behavior. Thus, the preponderance of evidence indicates the masticatory behavior of lean and obese individuals is comparable. Consequently, within the limits of this study's statistical power, the obese would not be expected to experience differential hormonal responses nor diminished satiety cues following the consumption of almonds as compared to their lean counterparts.

The appetitive state of the participants influenced their bite force (that is greater force when fasted), but this did not translate into statistically significant differences in pre-swallowing particle size. Appetitive state also did not affect the other measured masticatory indices. The effects of hunger on the microstructure of eating have been investigated previously. In one study, increased deprivation time, resulting in increased hunger, led to both increased food intake and meal duration, but there was no influence on eating rate (Bellisle *et al*., 1984). Other work noted increased hunger led to an increased initial eating rate, but this effect was diminished after 10 min of eating (Spiegel *et al*., 1989). However, in this latter study, eating rate was defined by the number of solid food units consumed per time rather than chews per unit of time, and thus was not an actual measure of mastication rate. Additionally, a constant chewing rate was observed for each almond sample in the current study. Even so, the enhanced bite force under the fasted condition did not lead to a difference in pre-swallowing almond particle size. Consequently, a difference in post-ingestive outcomes due to the effects of appetitive state on mechanical degradation of almonds would not be expected.

The honey roasted and salted almonds received the highest hedonic ratings. However, palatability did not influence the measured mastication parameters or final particle size. This is in contrast to several previous studies that have reported accelerated eating rates with more palatable foods (Bellisle and Le Magnen, 1981; Bellisle *et al*., 1984; Hill and McCutcheon, 1984). Again, these measures of eating rate were determined as a volume of food per time and did not specifically measure a rate of mastication. Other analyses of the microstructure of eating revealed only an inverse association between palatability and chewing time per food unit (Bellisle *et al*., 1984). Thus, it appears that while the palatability of a food may alter facets of eating, it does not markedly alter masticatory performance.

Nut shape exerted the strongest effect on mastication and particle size. The sliced almonds elicited lower maximum and mean bite forces and greater time and number of chews to deglutition. Differences in jaw movements and length of feeding sequences (bite to swallow) for foods of varying forms and textures have been reported. Generally, they indicate longer mastication times with harder textured foods (Lucas and Luke, 1986; Hiiemae *et al*., 1996; Hiiemae and Palmer, 1999). Sliced almonds required the longest processing time, but lowest bite force, and they had the lowest instrumentally measured breaking force. This implies that a harder texture was not responsible for a longer mastication time. Instead, the sliced almonds may require a longer mastication time due to an increased surface area requiring additional time to wet the particles with saliva to form a cohesive bolus and facilitate swallowing. Saliva's role has been proposed as especially critical for swallowing smaller mouthfuls (Lucas and Luke, 1984). Additionally, a difference in the rate of breakdown and deformability of the sliced almonds as compared to the whole almonds may contribute to the observed differences in masticatory performance.

Particle size distributions before swallowing for varying foods typically fall in a similar range, both across and between individuals, yet are characteristic to an individual (Lucas and Luke, 1984, 1986; Peyron *et al*., 2004). However, when an artificial test food is chewed a fixed number of times, large differences in median particle size are observed (Fontijn-Tekamp *et al*., 2004). The literature suggests that particle size is an unreliable criterion for swallowing, in part, because it varies based on the amount of food in the mouth (Lucas and Luke, 1984, 1986; Hiiemae and Palmer, 1999). Instead, it appears that the importance of particle size in swallowing is dependent on food type or form. This is consistent with the differences in particle sizes of sliced vs whole almonds that were observed. The sliced almonds yielded a significantly larger percent recovery indicating a larger particle size. Regression analyses indicated that the variable that contributed the most to particle size was mastication time. Previous work suggests that median particle size decreases with the number of chewing strokes (Lucas and Luke, 1986). Interestingly, the sliced almonds required increased mastication time, yet yielded the largest particle sizes implying a diminished efficiency in the rate of breakdown of the particles. The lower bite strength used to masticate the sliced almonds may contribute to this discrepancy. Additionally, the honey roasted variety yielded a significantly lower percent recovery implying smaller

particle sizes; however, this difference could not be attributed to any differences in masticatory behavior.

The results of this study do not support differences in masticatory function between lean and obese individuals. The shape, texture and sensory properties of almonds, as well as participants' appetitive state exerted greater influences on masticatory behavior. Whether this, in turn, influences physiological responses (for example, digestion, endocrine secretion, gastrointestinal (GI) transit and appetite) to foods and energy balance, as well as how other populations and food items may differ, warrants further study.

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References

Arosio M, Ronchi CL, Beck-Peccoz P, Gebbia C, Giavoli C, Cappiello V *et al*. (2004). Effects of modified sham feeding on ghrelin levels in healthy human subjects. *J Clin Endocrinol Metab* **89**, 5101–5104.

Bellisle F, Le Magnen J (1981). The structure of meals in humans: eating and drinking patterns in lean and obese subjects. *Physiol Behav* **27**, 649–658.

Bellisle F, Lucas F, Amrani R, Le Magnen J (1984). Deprivation, palatability and the micro-structure of meals in human subjects. *Appetite* **5**, 85–94.

Bruce DG, Storlien LH, Furler SM, Chisholm DJ (1987). Cephalic phase metabolic responses in normal weight adults. *Metabolism* **36**, 721–725.

Burton-Freeman B, Davis PA, Schneeman BO (2002). Plasma cholecystokinin is associated with subjective measures of satiety in women. *Am J Clin Nutr* **76**, 659–667.

Burton-Freeman B, Davis PA, Schneeman BO (2004). Interaction of fat availability and sex on postprandial satiety and cholecystokinin after mixed-food meals. *Am J Clin Nutr* **80**, 1207–1214.

Coelho SB, de Sales RL, Iyer SS, Bressan J, Costa NM, Lokko P *et al*. (2006). Effects of peanut oil load on energy expenditure, body composition, lipid profile, and appetite in lean and overweight adults. *Nutrition* **22**, 585–592.

Ellis PR, Kendall CW, Ren Y, Parker C, Pacy JF, Waldron KW *et al*. (2004). Role of cell walls in the bioaccessibility of lipids in almond seeds. *Am J Clin Nutr* **80**, 604–613.

Feinle C, O'Donovan D, Doran S, Andrews JM, Wishart J, Chapman I *et al*. (2003). Effects of fat digestion on appetite, APD motility, and gut hormones in response to duodenal fat infusion in humans. *Am J Physiol Gastrointest Liver Physiol* **284**, G798–G807.

Feltrin KL, Little TJ, Meyer JH, Horowitz M, Smout AJ, Wishart J *et al*. (2004). Effects of intraduodenal fatty acids on appetite, antropyloroduodenal motility, and plasma CCK and GLP-1 in humans vary with their chain length. *Am J Physiol Regul Integr Comp Physiol* **287**, R524–R533.

Fontijn-Tekamp FA, van der Bilt A, Abbink JH, Bosman F (2004). Swallowing threshold and masticatory performance in dentate adults. *Physiol Behav* **83**, 431–436.

Fraser GE, Bennett HW, Jaceldo KB, Sabate J (2002). Effect on body weight of a free 76 kilojoule (320 calorie) daily supplement of almonds for six months. *J Am Coll Nutr* **21**, 275–283.

Fukagawa K, Sakata T, Shiraishi T, Yoshimatsu H, Fujimoto K, Ookuma K *et al*. (1989). Neuronal histamine modulates feeding behavior through H1-receptor in rat hypothalamus. *Am J Physiol* **256**, R605–R611.

Hiiemae K, Heath MR, Heath G, Kazazoglu E, Murray J, Sapper D *et al*. (1996). Natural bites, food consistency and feeding behaviour in man. *Arch Oral Biol* **41**, 175–189.

Hiiemae KM, Palmer JB (1999). Food transport and bolus formation during complete feeding sequences on foods of different initial consistency (see comment). *Dysphagia* **14**, 31–42.

Hill SW, McCutcheon NB (1984). Contributions of obesity, gender, hunger, food preference, and body size to bite size, bite speed, and rate of eating. *Appetite* **5**, 73–83.

Hollis JH, Mattes RD: Does adding a high fat, high energy density food to one's diet necessarily promote weight gain. *Br J Nutr* (in press).

Jenkins DJ, Kendall CW, Marchie A, Parker TL, Connelly PW, Qian W *et al*. (2002). Dose response of almonds on coronary heart disease risk factors: blood lipids, oxidized low-density lipoproteins, lipoprotein(a), homocysteine, and pulmonary nitric oxide: a randomized, controlled, crossover trial. *Circulation* **106**, 1327–1332.

Jordan HA (1969). Voluntary intragastric feeding: oral and gastric contributions to food intake and hunger in man. *J Comp Physiol Psychol* **68**, 498–506.

Lavin JH, French SJ, Read NW (2002). Comparison of oral and gastric administration of sucrose and maltose on gastric emptying rate and appetite. *Int J Obes Relat Metab Disord* **26**, 80–86.

le Roux CW, Batterham RL, Aylwin SJ, Patterson M, Borg CM, Wynne KJ *et al*. (2006). Attenuated peptide YY release in obese subjects is associated with reduced satiety. *Endocrinology* **147**, 3–8.

Lucas PW, Luke DA (1983). Methods for analysing the breakdown of food in human mastication. *Arch Oral Biol* **28**, 813–819.

Lucas PW, Luke DA (1984). Optimum mouthful for food comminution in human mastication. *Arch Oral Biol* **29**, 205–210.

Lucas PW, Luke DA (1986). Is food particle size a criterion for the initiation of swallowing? *J Oral Rehabil* **13**, 127–136.

Mioche L, Bourdiol P, Monier S, Martin JF, Cormier D (2004). Changes in jaw muscles activity with age: effects on food bolus properties. *Physiol Behav* **82**, 621–627.

Naslund E, Barkeling B, King N, Gutniak M, Blundell JE, Holst JJ *et al*. (1999). Energy intake and appetite are suppressed by glucagon-like peptide-1 (GLP-1) in obese men. *Int J Obes Relat Metab Disord* **23**, 304–311.

Ookuma K, Sakata T, Fukagawa K, Yoshimatsu H, Kurokawa M, Machidori H *et al*. (1993). Neuronal histamine in the hypothalamus suppresses food intake in rats. *Brain Res* **628**, 235–242.

Ookuma K, Yoshimatsu H, Sakata T, Fujimoto K, Fukagawa F (1989). Hypothalamic sites of neuronal histamine action on food intake by rats. *Brain Res* **490**, 268–275.

Ow RK, Carlsson GE, Karlsson S (1998). Relationship of masticatory mandibular movements to masticatory performance of dentate adults: a method study. *J Oral Rehabil* **25**, 821–829.

Peyron MA, Mishellany A, Woda A (2004). Particle size distribution of food boluses after mastication of six natural foods. *J Dent Res* **83**, 578–582.

Prinz JF, Lucas PW (1995). Swallow thresholds in human mastication. *Arch Oral Biol* **40**, 401–403.

Richardson CT, Feldman M (1986). Salivary response to food in humans and its effect on gastric acid secretion. *Am J Physiol* **250**, G85–G91.

Sabate J, Haddad E, Tanzman JS, Jambazian P, Rajaram S (2003). Serum lipid response to the graduated enrichment of a step I diet with almonds: a randomized feeding trial. *Am J Clin Nutr* **77**, 1379–1384.

Sakata T (1995). Histamine receptor and its regulation of energy metabolism. *Obes Res* **3** (Suppl 4), 541S–548S.

Sakata T, Fukagawa K, Fujimoto K, Yoshimatsu H, Shiraishi T, Wada H (1988a). Feeding induced by blockade of histamine H1-receptor in rat brain. *Experientia* **44**, 216–218.

Sakata T, Ookuma K, Fukagawa K, Fujimoto K, Yoshimatsu H, Shiraishi T *et al*. (1988b). Blockade of the histamine H1-receptor in the rat ventromedial hypothalamus and feeding elicitation. *Brain Res* **441**, 403–407.

Sakata T, Yoshimatsu H, Masaki T, Tsuda K (2003). Anti-obesity actions of mastication driven by histamine neurons in rats. *Exp Biol Med (Maywood)* **228**, 1106–1110.

Schafmayer A, Nustede R, Pompino A, Kohler H (1988). Vagal influence on cholecystokinin and neurotensin release in conscious dogs. *Scand J Gastroenterol* **23**, 315–320.

Schulz M, Kroke A, Liese AD, Hoffmann K, Bergmann MM, Boeing H (2002). Food groups as predictors for short-term weight changes in men and women of the EPIC-Potsdam cohort. *J Nutr* **132**, 1335–1340.

Sobhani I, Buyse M, Goiot H, Weber N, Laigneau JP, Henin D *et al*. (2002). Vagal stimulation rapidly increases leptin secretion in human stomach. *Gastroenterology* **122**, 259–263.

Spiegel TA (2000). Rate of intake, bites, and chews-the interpretation of lean–obese differences. *Neurosci Biobehav Rev* **24**, 229–237.

Spiegel TA, Kaplan JM, Tomassini A, Stellar E (1993). Bite size, ingestion rate, and meal size in lean and obese women. *Appetite* **21**, 131–145.

Spiegel TA, Shrager EE, Stellar E (1989). Responses of lean and obese subjects to preloads, deprivation, and palatability. *Appetite* **13**, 45–69.

Spiller GA, Jenkins DA, Bosello O, Gates JE, Cragen LN, Bruce B (1998). Nuts and plasma lipids: an almond-based diet lowers LDL-C while preserving HDL-C. *J Am Coll Nutr* **17**, 285–290.

Stunkard AJ, Messick S (1985). The three-factor eating questionnaire to measure dietary restraint, disinhibition and hunger. *J Psychosom Res* **29**, 71–83.

Teff KL, Devine J, Engelman K (1995). Sweet taste: effect on cephalic phase insulin release in men. *Physiol Behav* **57**, 1089–1095.

Teff KL, Engelman K (1996). Palatability and dietary restraint: effect on cephalic phase insulin release in women. *Physiol Behav* **60**, 567–573.

Teff KL, Mattes RD, Engelman K (1991). Cephalic phase insulin release in normal weight males: verification and reliability. *Am J Physiol* **261**, E430–E436.

Wisen O, Bjorvell H, Cantor P, Johansson C, Theodorsson E (1992). Plasma concentrations of regulatory peptides in obesity following modified sham feeding (MSF) and a liquid test meal. *Regul Pept* **39**, 43–54.

Yeomans MR, Blundell JE, Leshem M (2004). Palatability: response to nutritional need or need-free stimulation of appetite? *Br J Nutr* **92** (Suppl 1), S3–S14.