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Examining the Utility of a Bite-Count—Based Measure of Eating Activity in Free-Living Human Beings

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ABSTRACT

The obesity epidemic has triggered a need for novel methods for measuring eating activity in free-living settings. Here, we introduce a bite-count method that has the potential to be used in long-term investigations of eating activity. The purpose of our observational study was to describe the relationship between bite count and energy intake and determine whether there are sex and body mass index group differences in kilocalories per bite in free-living human beings. From October 2011 to February 2012, 77 participants used a wrist-worn device for 2 weeks to measure bite count during 2,975 eating activities. An automated self-administered 24-hour recall was completed daily to provide kilocalorie estimates for each eating activity. Pearson's correlation indicated a moderate, positive correlation between bite count and kilocalories (r=0.44; P<0.001) across all 2,975 eating activities. The average per-individual correlation was 0.53. A 2 (sex)×3 (body mass index group: normal, overweight, obese) analysis of variance indicated that men consumed 6 kcal more per bite than women on average. However, there were no body mass index group differences in kilocalories per bite. This was the longest study of a body-worn sensor for monitoring eating activity of free-living human beings to date, which highlights the strong potential for this method to be used in future, long-term investigations.
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OBESITY IS A SIGNIFICANT PUBLIC HEALTH PROBLEM affecting millions of adults worldwide.[1] The sharp rise in obesity in recent decades is partially due to an obesogenic environment that promotes energy imbalance: energy intake from eating and drinking is greater than energy expenditure from physical activity.[1] To fully understand the energy intake and expenditure patterns that contribute to weight change, energy intake and expenditure must be studied over long periods of time (weeks to months) outside of the laboratory in free-living settings. Years of research and practical use have demonstrated that long-term energy expenditure patterns can be approximated with accelerometry methods, despite difficulties in precisely equating measured activity with energy expenditure.[2] However, similarly accurate and practical methods for measuring long-term energy intake are still lacking.

Self-report tools for measuring energy intake in free-living include diet records, 24-hour recalls, food frequency questionnaires, and food photography methods.[3] These methods require time-consuming data entry, recording food types and portion sizes, and linking data with extensive dietary databases, limiting their use for long-term monitoring of intake except in the most well-funded, well-staffed studies.[4] Hence, whereas self-report tools are a viable solution for short-term monitoring of eating activity (days) or as periodic probes, they are less useful for continuous long-term monitoring of intake (weeks to months).

To reduce user burden and make long-term eating activity monitoring a more tenable proposition, new methods are being developed to measure the movements and sounds associated with eating and drinking, such as intake gestures, chews, and swallows.[5,6] Although these methods can detect eating activity using body-worn sensors in laboratory settings, they have not been used in free-living conditions for longer than a single meal.[7] Furthermore, the necessary body-worn sensors for these methods, including ear-pad microphones, upper back sensors, or sensors on the neck, are currently too obtrusive or uncomfortable for long-term use.[8]

In contrast with other body-worn sensors, a wrist-worn device that measures eating activity with a bite-count method has made unobtrusive, practical ambulatory monitoring of eating activity possible.[9,10] Unlike chewing, which involves repeated mastication of the same piece of food, a bite is defined as food placed into the mouth for consumption.[11] Prior research has demonstrated that a wrist-roll motion associated with taking a bite can be detected with a wrist-worn gyroscope and simple algorithm.[9] This method detects 94% of bites in controlled laboratory settings and 86% of bites in uncontrolled laboratory settings, with approximately one false positive per every five bites.[9] Here, the utility of this bite count based measure of eating activity is examined. This measure is relevant for dietetics practitioners seeking objective eating activity data from clients, patients, or research participants.

Previous laboratory studies of single-food meals have demonstrated a positive relationship between bite count and ad libitum energy intake, with men and individuals with higher body mass indexes (BMIs) consuming more kilocalories per bite (KPB).[12-14] However, in free-living conditions where foods consumed and eating environments are free to vary, it is unknown whether bite count and energy intake are related, or if average KPB varies by sex or BMI. Therefore, the purpose of our study was twofold: describe the relationship between bite count and energy intake for eating activities, and determine whether there are sex and BMI differences in KPB in free-living conditions.

METHODS AND PROCEDURES

Participants and Recruitment

Participants were recruited from a mid-sized university and surrounding towns with e-mail, flyers, and website announcements. Participants received $50 and an eating activity summary for participating. The eligibility requirements included age 18 to 66 years, no eating disorder history, and daily access to an Internet-capable computer. Based on preliminary data, a large correlation (r=0.6) between bite count and kilocalories was expected.[9] Power analysis (α=.05, power=0.80) indicated that 28 meals per person were needed for within-individual correlations.[15] Participants were measured for 14 days to obtain 28 meals (assuming $\geq$2 meals per day), and the number of participants was maximized within study constraints to provide a large overall sample of eating activities. Recruitment aimed to sample equal numbers of men and women, and equal numbers of normal weight (BMI=18.5 to 24.9) and overweight/obese (BMI $\geq$25.0) participants. Ninety-four participants entered the study, 83 completed the study, four were excluded due to device battery problems, and two were excluded due to noncompliance with instructions, resulting in a final sample of 77 participants.

Materials

Bite-Counting Device. The bite counting device (Bite Counter, Bite Technologies) was a 64$\times$38$\times$25 mm black plastic rectangle weighing 75 g with an adjustable wrist band (Figure 1). The device operated as a digital watch when not in use during an eating activity. At the beginning of each eating activity, the user pressed a button to activate "bite-count" mode. The display indicated "on" in bite-count mode, such that no bite-count feedback was provided to the user. At the end of each eating activity, the user pressed a button to return to "time" mode. In addition, the device automatically returned to "time" mode after 1 hour of operating in "bite-count" mode. The device battery provided up to 14 hours of bite counting use and could be fully recharged in 3 hours. The device saved the date, time, duration, and bite count for each eating activity.

Automated Self-Administered 24-Hour Dietary Recall. Total kilocalories and grams of food consumed at each eating activity were obtained from version 1 of the National Cancer Institute's Internet-based automated self-administered 24-hour dietary recall (ASA24).[16] ASA24 uses a modified version of the interviewer-administered automated multiple pass method 24-hour recall. The automated multiple pass method accurately measures energy intake in free-living conditions,[17] but under-reporting energy intake with 24-hour recall methods is possible.[3] Despite this limitation, the ASA24 was a practical, low-cost, low—experimenter-burden tool for obtaining energy intake estimates for thousands of eating activities. In addition, in our study participants did not aim to record complete daily intake with the ASA24; their goal was to record eating activities that were also recorded with the bite counting device. In contrast to an in-person or telephone-administered 24-hour recall, the ASA24 was completed at participants' convenience from their computer. ASA24 staff provided a data file with total duration (minutes) to complete each recall.

Figure 1. The bite-counting device worn on the wrist in "time" mode.

Height, Weight, and BMI Measurements. Body weight and height were measured in street clothes without shoes using the Tanita WB-3000 Digital Beam Scale (Tanita Corp). Weight was measured to the nearest tenth of a pound, and height was measured to the nearest quarter inch. Pounds were converted to kilograms, inches were converted to meters, and BMI was calculated as weight in kilograms divided by height in meters squared.

Study Procedure

The Clemson University Institutional Review Board approved the study, and participants provided written informed consent. To determine eligibility, the participant completed an electronic demographics questionnaire. If the participant was eligible, he or she attended an individual orientation meeting.

Orientation. The experimenter explained the purpose of the study: to investigate whether a new device could estimate the amount of food eaten. Height and weight were measured. Each participant was given a wrist-worn device and written instructions. The experimenter demonstrated proper wearing and use. The participant was instructed to wear the device on the wrist of the hand that they normally ate with for the entire waking day, except when exercising, swimming, showering, or near water (eg, washing dishes) because the device is not waterproof. The participant was instructed to record all eating activities for which they could define a "start" time (before the first bite of food) and "stop" time (after the last bite of food). Participants did not record intake spread out over many hours that could not be easily defined with start and stop times (eg, grazing on pieces of candy all day). Hence, the study did not capture total daily intake with the bite-counting device, but only individual eating activities that had clear begin and end points.

The participant was given login information for the ASA24 website and written instructions for completing dietary recalls. The participant was instructed to record eating activities in ASA24 only if they had been recorded with the bite-counting device. The participant was also instructed to record beverages because the device is capable of detecting some drinking motions.[9] The participant completed a demonstration of the ASA24 program.

Data Collection. Participants recorded eating activities with the wrist-worn device and the ASA24 daily for 2 weeks. Participants received an e-mail message daily reminding them to use their wrist-worn device and to complete the ASA24 within 24 hours. After 1 week, the participant returned to the laboratory for device data downloading. The experimenter checked the data for errors and tested device operation. Further instructions and device replacement were provided as necessary. After the second week, the participant returned the device, and body weight was measured. The participant responded to a questionnaire asking, "In the past 2 weeks, how easy or difficult did you find it to complete the 24 hour dietary recall/use the bite counter?", with response options on a 7-point scale from 1=extremely easy to 7=extremely difficult, and "Which did you prefer using, the 24-hour dietary recall or the bite counter?"

Statistical Analyses

Data Merging and Preparation. Eating activities from the bite counting device and the ASA24 were matched using date and time. A pilot study served as guidance for identifying bite-count values (<10 or >50 bites) and kilocalorie values (<50 or >1,000 kcal) that were potential errors, which were then carefully cross-checked. If a match was reasonable (eg, a low bite count of eight and eating a small snack like a candy bar), the data were retained. However, if a match was unreasonable (eg, a 60-minute duration record (likely an "auto-off") with 120 bites and eating a small snack) or nonexistent, the data were removed. If foods were reported but no kilocalorie information was provided, the ASA24 staff nutritionist provided kilocalorie information. Of 3,310 reported eating activities, 263 eating activities (7.9%) were eliminated because of unmatched data or errors, leaving 3,047 eating activities.

Data were prepared for statistical analysis following guidelines for cleaning grouped data.[18] Outliers were removed within participants if the standardized value (*z*-score) of the data point was greater than 3.29, if the data point was clearly separated from the rest of the distribution for the participant, or if the Mahalanobis distance value was >20.52.[18] Outlier removal reduced positive skewness and kurtosis. Seventy-two eating activities (2.2%) were identified as outliers and removed, leaving 2,975 matched eating activities for statistical analyses, with an average of 39 eating activities per participant.

Calculated Measures. Each participant's unique KPB was calculated as the sum of kilocalories divided by the sum of bite count for all eating activities for that participant. Thus, each participant had one average KPB value. Similarly, each participant's average energy density was calculated as the sum of kilocalories divided by the sum of grams for all eating activities for that participant.

Statistical Analyses. Pearson's correlations were calculated to describe the overall relationship between bite count and ASA24 estimated kilocalories for the 2,975 meals, and the relationships between bite count and ASA24 estimated kilocalories for each individual (77 unique correlations). A series of 2 (sex)×3 (BMI group: normal, overweight, obese) analyses of variance tested group differences in KPB, energy density, and body weight change (poststudy weight−prestudy weight). Dependent *t* tests examined differences in body weight from prestudy to poststudy, and in self-reported ease of use between the ASA24 and the bite counting device. Analyses were performed using SPSS software, version 19 (2010, IBM-SPSS Inc). *P* values <0.05 were considered statistically significant. Descriptive statistics are presented as mean±1 standard deviation.

RESULTS

The 77 participants were 32±12 years old, 171±10 cm tall, weighed 78±20 kg at orientation, and had a BMI of 26.7±5.9 at orientation. There was no significant body weight change from prestudy to poststudy ($t[75]=0.77$; $P>0.05$), and no significant differences in body weight change between BMI groups or sexes (all *P* values >0.05). The 2,975 eating activities were, on average, 39±26 bites, 487±351 kcal, 13±9 minutes in duration, and 3±1 bites per minute. Participants reported an average of 3±1 eating activities and 1,456±748 kcal/day.

There was a moderate positive correlation between bite count and ASA24 estimated kilocalories consumed at each eating activity ($r=0.44$; $P<0.001$) (Figure 2). Within-individual correlations between bite count and ASA24 estimated kilocalories ranged from −0.08 to 0.86, with 66 of the 77 correlations (86%) >0.40 (Figure 3). The average within-individual correlation was 0.53.

On average, men consumed six more KPB than women ($F[1,71]=14.38$; $P<0.001$; $\eta^2=0.17$) (Table). There were no significant differences in KPB between BMI groups ($F[2,71]=0.71$; $P>0.05$; $\eta^2=0.02$), and no significant interaction between sex and BMI ($F[2,71]=2.14$; $P>0.05$; $\eta^2=0.06$). In addition, there were no significant differences in average energy density by sex or BMI group (all *P* values >0.05). Participants spent 25±11 minutes completing each daily ASA24 dietary recall (an average of 5.46±2.51 total hours during the 2-week study). Because bite count was recorded by pressing a single button, participants spent just a few seconds per eating activity using the bite counting device. Participants rated the device as significantly easier to use (1.94±0.89) than the ASA24 (3.12±1.20)

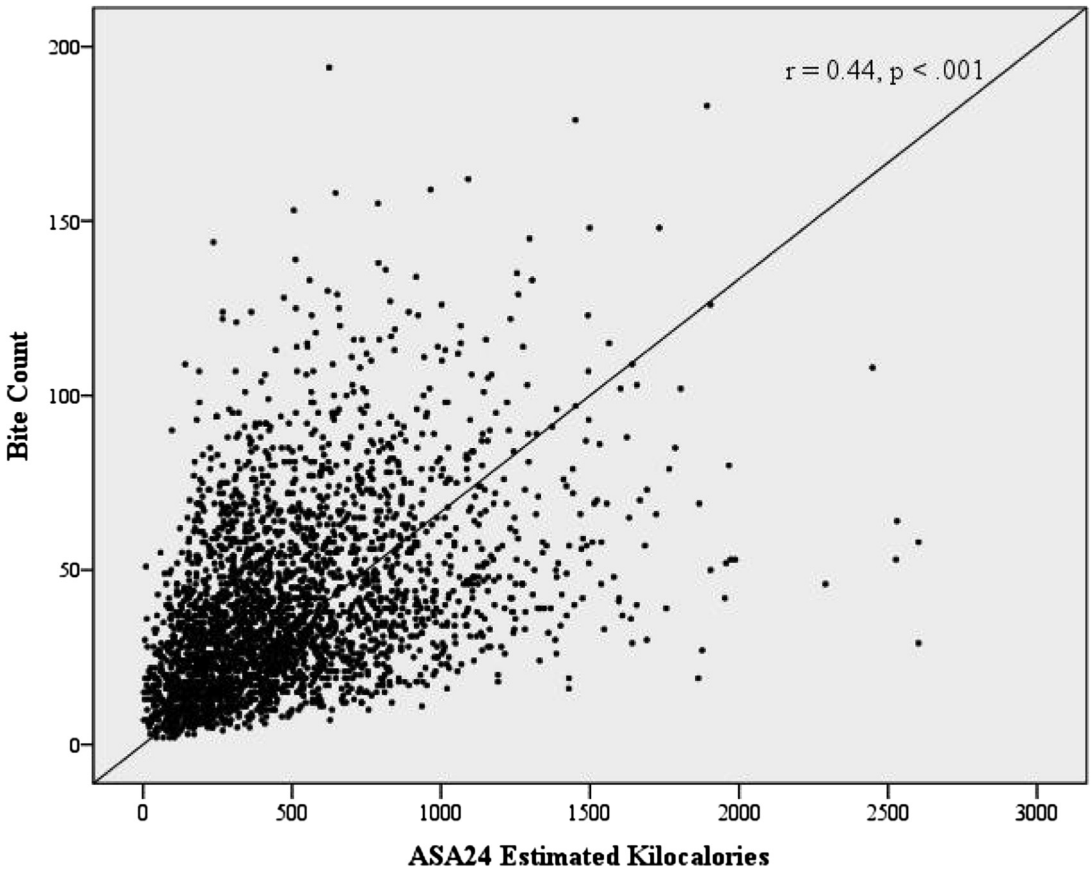

Figure 2. Scatterplot of the relationship between bite count and automated self-administered 24-hour dietary recall (ASA24) estimated kilocalories across all 2,975 eating activities (r=0.44; P<0.001).

(t[76]=8.72; P<0.001). When asked which tool they preferred, 57 of 77 participants indicated that they preferred the bite counting device over the ASA24.

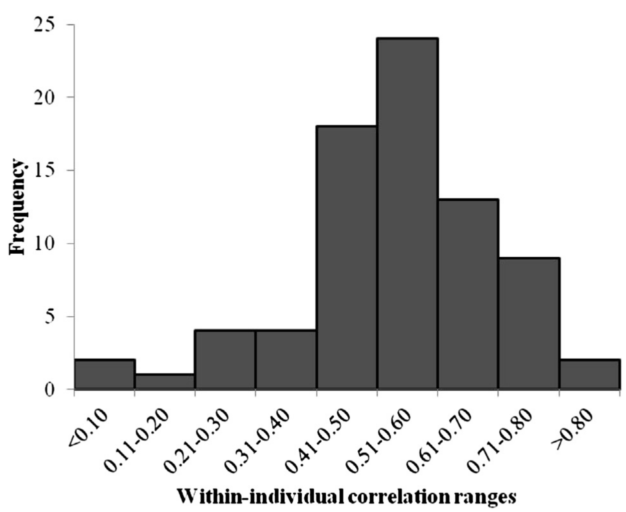

Figure 3. Histogram of within-individual correlations between bite count and automated self-administered 24-hour dietary recall estimated kilocalories. Sixty-six of 77 correlations (86%) are >0.40, and the average correlation is 0.53.

DISCUSSION

The global obesity crisis has triggered a need for novel eating activity monitoring techniques that are practical for long-term use in free-living settings. In our study, 77 participants used a simple ambulatory device to record eating activities for 2 weeks in completely uncontrolled, free-living conditions, resulting in a data set of 2,975 useable eating activities. This was the longest study of a body-worn sensor for monitoring eating activity of free-living human beings to date, which highlights the strong potential for this method to be used in future, long-term investigations.

Our study found that bites and kilocalories were positively correlated across all 2,975 eating activities, despite the kilocalories in a bite of food naturally varying due to different foods consumed and bite sizes. The within-individual correlations indicated that bite count may be an excellent indicator of energy intake for certain individuals, whereas this relationship may not hold for others. It is speculated that some individuals may eat in a way that allows bite count to be more accurately detected, but identifying the extent to which individual differences could influence the relationship between bites and kilocalories is a direction for future research. Further, this was the first study using the bite-count measure in free-living human beings, and the training at study orientation was limited, possibly resulting in low correlations between bite count and energy intake for some individuals. Future work should investigate whether

Table. Kilocalories per bite compared between sex and body mass index (BMI) groups in a study to describe the relationship between bite count and energy intake

	Normal weight	Overweight	Obese	All BMI groups
	←mean±standard deviation→			
Men	19±7 (n=18)	14±5 (n=9)	18±5 (n=11)	17±7* (n=38)
Women	11±4 (n=20)	12±4 (n=11)	12±4 (n=8)	11±4* (n=39)
Both sexes	14±7 (n=38)	13±4 (n=20)	15±7 (n=19)	14±6 (n=77)

*$P<0.001$.

improved device training alone could improve the within-individual correlations.

This study also showed that it is possible to examine important eating behaviors in free-living human beings with a simple bite-counting device. Men ate an average of 17 KPB whereas women ate an average of 11 KPB, a finding similar to sex differences observed in single-food laboratory studies.[12-14] Furthermore, men did not eat a more energy dense diet than women, suggesting that men ate more KPB due a difference in the amount of food per bite. Obese and overweight individuals did not eat more KPB than normal-weight individuals, a finding that did not coincide with BMI differences reported in single-food laboratory studies.[12-14] It is possible that these BMI results do not match laboratory findings because participants may have altered their usual intake. However, there were no differences in energy density between BMI groups, and body weights did not change. Taken together, these findings suggest that sex may be a robust contributor to KPB across laboratory and free-living conditions, whereas an individual's BMI may only predict KPB in tightly controlled laboratory studies. Further study of BMI group differences in KPB with a larger sample of overweight and obese individuals is needed to confirm these results.

An objective of future research with the bite-count method is to develop an energy intake prediction equation using individual features, such as sex, to convert bite count to kilocalories. It is expected that the correlation of 0.44 between bite count and kilocalories found in this study will improve with the development of a prediction equation accounting for individual differences in KPB, better device training, and by correlating bite count with known energy intake values (such as through direct observation of food intake in cafeteria settings).

A limitation of the bite-count method is that it is not completely automated: the user presses a button to turn the bite-count feature on and off. If an individual forgets to record eating activities, this could result in underestimation of total daily energy intake, with a cumulative long-term effect similar to underreporting with self-report methods.[19] In addition, it is difficult to capture extended grazing activities and some liquid intake with the bite-count method, which may result in underestimation of total daily energy intake. Conversely, if an individual forgets to turn the device off, other activities may trigger false bite counts, resulting in possible overestimation of intake.[9] Research efforts are underway to develop a method for automatically detecting eating activities, expanding the potential for this practical method to be used as an objective and unbiased measure of eating activity over the long term.[20] Despite needing to turn the device on and off, participants preferred the easier-to-use bite-counting device over the ASA24 program and spent substantially less time recording their eating activities with the device.

CONCLUSIONS

Our study demonstrated that bite count and energy intake were positively correlated, with an average per-individual correlation of 0.53, and that the bite-count method can be used to objectively monitor eating activity in free-living human beings for whom foods and eating environments are completely uncontrolled. Future investigations could potentially use the bite-count method over the long term, thereby improving understanding of how eating activity characteristics are related to obesity.

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STATEMENT OF POTENTIAL CONFLICT OF INTEREST

E. R. Muth and A. W. Hoover have formed Bite Technologies, a company to market and sell a bite-counting device. Clemson University has filed a US patent for intellectual property known as “The Weight Watch,” serial no. 61/144,203 with a filing date of January 13, 2009. Bite Technologies has licensed the method from Clemson University and has been funded by South Carolina Launch, a state organization that incubates startup companies associated with university intellectual property. All authors receive royalty payments from bite-counting device sales.

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