Age-related Difference in Oral Adaptation to Masticatory Perturbation

Chia-Shu Lin (winzlin@nycu.edu.tw)  
National Yang Ming Chiao Tung University  
https://orcid.org/0000-0002-6575-0887

Yi-Chen Chen  
National Yang Ming Chiao Tung University

Li-Jung Chao  
National Yang Ming Chiao Tung University

Wei-Chieh Kao  
National Yang Ming Chiao Tung University

Ta-Chung Chen  
Taipei Veterans General Hospital

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Abstract

Objectives: Mastication can be interfered with by intraoral perturbation (e.g., hard food). We developed the masticatory perturbation task (MPT) to assess the perturbation effect during mastication and quantify the degree of adaptation to masticatory perturbation in younger (YA) and older adults (OA).

Materials and Methods: 38 YA and 38 OA performed the MPT, which consists of three trials of assessment of masticatory performance (MP) without perturbation (i.e., the baseline condition), and three trials with perturbation (i.e., the perturbation condition). Perturbation was implemented by concurrently chewing testing food on the preferred side and a drinking straw on the non-preferred side. We estimated perturbation effect as $\Delta MP$ between the baseline vs. perturbation condition, and adaptation effect as $\Delta MP$ between the third vs. the first trial, for both age groups.

Results: We found significant perturbation effect, i.e., lower MP in the perturbation vs. the baseline condition, and adaptation effect, i.e., return of MP from the third trial to the first trial, in both groups. Moreover, the OA group showed a lower degree of adaptation compared to the YA group.

Discussion: The MPT is valid for assessing oral adaptation to masticatory perturbation

Conclusion: Increased age may be associated with lower degree of masticatory adaptation.

1. Introduction

Cumulating evidence has suggested a close association between the deterioration of oral health and declined oral function in older adults. Oral rehabilitation, such as installing a denture, plays a pivotal role in restoring and maintaining oral function when oral conditions are compromised (e.g., tooth loss). Longitudinal evidence suggests that when wearing a denture, patients would improve their eating ability and nutritional status after 3 to 6 months of adaptation (1, 2), especially for an improvement of eating hard food (1). Another multi-center study revealed that patients with dentures had difficulty in chewing masticate raw, hard, and fibrous food (3). Notably, not every patient would show such an improvement after adaptation, and a longer period of adaptation was not associated with the better improved function (4). Altogether, the evidence highlights that the gradual sensorimotor adaptation of oral condition is critical to improved oral functions under rehabilitation.

Assessment of masticatory performance (MP) has been developed to assess the individual ability to cut food and mix food particles into a bolus in a standardized testing condition (5). Lower MP of food mixing is associated with the intrinsic factor of oral conditions, including the number of teeth, maximal occlusal force, salivary flow rate, and tongue pressure (6-9). However, it is noteworthy that even under a suboptimal condition of oral health, individuals may still preserve some degree of masticatory function. For example, elderly people with no occlusal contact (i.e., Eichner index C) could still maintain approximately half of the food-cutting performance compared to those with occlusal contact (10). Such an adaptation is especially manifested when individuals perceive a perturbation during normal
mastication. For example, patients who just wore a new denture or appliance would feel difficulty in mastication, with lower MP. Nevertheless, after using it for a period, they have MP returned to the initial level (11, 12). Likewise, hard food may cause a sudden perturbation to mastication when individuals first encounter it but they get adapted to chewing it (13, 14). The ability for individuals to gradually adapt to their condition and maintain masticatory function is also pivotal to nutrient intake.

The concept of ‘masticatory adaptation’ has been highlighted in terms of the association between the deterioration of oral health and sustain of feeding behavior (13, 15-17). However, until now there has been no consensus about the definition of masticatory adaptation. It should be noted that the ‘adaptation’ is not simply a habituation (i.e., gradual loss of sensation) responding to prolonged stimuli (18). Instead, it is associated with one’s ability ‘to gradually modify our motor commands in order to compensate for changes in our body and in the environment’ (19). In other words, adaptation is associated with the complex processing of sensorimotor information adjusted for coping with environmental challenges, and therefore, in the current study, we considered ‘sensorimotor adaptation’ the better term to describe oral adaptation during mastication. At present, clinical research primarily focused on oral adaptation to dental treatment. For example, in the older patients wearing new dentures, their oral motor ability and tactile sensitivity was significantly associated with subjective adaptation to new dentures (20, 21). Aging also plays a key role in oral adaptation to masticatory perturbation. For example, older adults would adopt various approaches, as a measure of behavioral adaptation, to compensate for poor oral condition in order to eat food (16) or increase the number of chewing cycles during eating (13). Critically, the studies only assess individual subjective experience of adaptation (16, 20, 21). Until now, there has been no standardized approach to quantify the degree of individual adaptation to masticatory perturbation, and the association between aging and masticatory adaptation is not fully elucidated.

To develop a novel task for assessing oral adaptation to masticatory perturbation, we investigated the experimental paradigms of sensorimotor learning which have been widely used to assess individual differences in adaptation to environmental challenges. For example, in the force-field paradigm (Fig. 1A), the participant is first instructed to move a robotic device to reach a goal object without perturbation, as the baseline condition. Their performance (i.e., the trajectory of movement) is compared to the perturbation condition, in which the device is interfered with by an external force and they need to redirect the movement to reach the goal (Fig. 1A). Based on the design of force-field paradigm, we devised a masticatory perturbation task (MPT) for assessing the effect of the perturbation on mastication and to quantify oral adaptation to that perturbation. The baseline condition consists of a standardized gum-mixing assessment for MP (Fig. 1B). In the perturbation condition, the participant was asked to chew the gum at one side and a drinking straw at the other side at the same time, as an external interference to induce perturbation (Fig. 1B). Previous studies have shown that in healthy younger adults, the interference of an occlusal splint at the molar changed the MP of cutting food (22, 23). However, the studies only investigated the effect of perturbation and did not quantify the adaptation of masticatory perturbation. The MPT consisted of three trials without perturbation (i.e., B1, B2, and B3, the baseline condition), and three trials with perturbation (i.e., P1, P2, and P3, the perturbation condition) (Fig. 2A). The
trial-by-trial changes of MP in both baseline and perturbation conditions were investigated to understand if individuals gradually adapted to the perturbation, i.e., showing improvement in MP (Fig. 2A).

The current study aims to assess the effect of perturbation in the MPT and quantify oral adaptation to masticatory perturbation in both younger and older adults. Specifically, we tested the following three hypotheses:

1. Hypothesis 1: We hypothesized that the MPT induced a perturbation effect. Specifically, participants showed lower MP in the perturbation condition compared to the baseline condition (i.e., trial B1 vs. P1 and trial B3 vs. P3) (Fig. 2B).

2. Hypothesis 2: We hypothesized that participants showed adaptation to masticatory perturbation in the MPT. Specifically, participants showed higher MP for the third trial, compared to the first trial, in the perturbation condition (i.e., trial P3 vs. P1) (Fig. 2B).

3. Hypothesis 3: We hypothesized that age was associated with masticatory adaptation. We quantified the degree of oral adaptation to masticatory perturbation by comparing the baseline and perturbation conditions (i.e., trial P3 vs. B1) and hypothesized that the change between the conditions differed between younger and older adults (Fig. 2B).

4. Hypothesis 4: Finally, we hypothesized that masticatory adaptation is associated with oral conditions. Specifically, we hypothesized that individual age, the initial performance in the perturbation condition (i.e., trial P1), the number of missing teeth, the salivary flow rate, and tongue pressure, were associated with the degree of adaptation.

2. Methods

2.1. Participants

The current study is part of an integrative project on the association between aging, oral function, and brain function. The findings regarding brain features will be reported in another study. All the participants were recruited voluntarily from advertisements posted on bulletin boards at the university campus and local community. The inclusion criteria of study participants are: (a) being able to independently communicate with the researchers and completed written informed consent, and (b) aged between 20 to 85 years. The exclusion criteria are (a) having medical history of temporomandibular disorders (TMD) or showing symptoms of TMD, and (b) having acute dental and orofacial pain at the time of the study. All the participants have completed written informed consent before the study began. The study is supervised by the Institutional Review Board of the university.

2.2. Study design

The current study is a cross-sectional investigation of the effect of an experimental intervention (i.e., masticatory perturbation) on MP, as the primary outcome. MP was assessed using the variogram (VARG)-
based approach (24), which quantifies the degree of food mixing. A lower VARG score denotes better 
MP (24). In addition, the clinical variables associated with MP, including the number of missing teeth, the 
salivary flow rate, and tongue pressure were assessed, respectively using the previously published 
methods (6, 8, 9). In order to investigate the association between masticatory adaptation and age, the 
participants were separated into two age groups: the younger adults (YA) who were aged less than 50 
years and the older adults (OA) who were aged over 50 years.

Masticatory perturbation test (MPT)

The MPT was designed to quantify the degree of oral adaptation to masticatory perturbation. The task 
consists of six sequential trials (Fig. 2A):

1. The first three trials (i.e., the baseline condition) were a standard assessment of food-mixing ability 
using a piece of fruit-chew (“Hi-Chew”, Taiwan Morinaga Co. Ltd.). We used the fruit-chew that 
consists of a white and a red portion with grape flavor. The participants were instructed to chew the 
piece of fruit-chew with 20 strokes and expectorated it into a plastic bag. The duration of chewing 20 
strokes was assessed as the masticatory duration (MD). The participants were asked to chew the 
fruit-chew as naturally as they eat them elsewhere. They were free to choose any side to chew and 
adjust their own speed to chew it.

2. After the baseline condition, the participants identified their preferred side of mastication during the 
baseline condition. They were shown a drinking straw made of bamboo fiber (“Bamboo Straws”, 
BAMBOO Taiwan) and instructed to place the straw in the mouth so that the straw was occluded 
between the upper and lower molars of the non-preferred side of mastication (Fig. 1B). It is 
noteworthy that we chose the straw because of its fibrous component, which may cause more 
difficulty in eating, according to previous findings (3). The participants were instructed that in the 
following trials, a drinking straw would be occluded at the same time when the chewing task was 
performed.

3. Subsequently, in the last three trials (i.e., the perturbation condition), the participants repeated the 
same assessment of mixing ability by focusing on chewing the fruit-chew at the preferred side and 
occluding the straw at the non-preferred side concurrently. In both conditions, the participants 
expectorated the fruit-chew into a plastic bag after 20 strokes of chewing, and the chewed fruit-chew 
was analyzed according to the pipeline published previously (24). Each trial was separated for a 
period of approximately ten seconds to avoid excessive fatigue.

2.4. Assessment of clinical variables

In addition to MP and MD, the following clinical variables were collected in this study:

(A) Number of missing teeth (NMT): we quantified the NMT according to the methods published in 
previous research (24). Notably, we counted implant-supported prostheses and fixed crowns/bridges as 
part of the remained teeth because these prostheses contribute to sensory feedback of mastication. 
Removable dentures and residual roots were counted as missing teeth.
(B) Salivary flow rate (SFR): we quantified the SFR under a stimulated condition, using the methods published in previous research (25). The participants were asked to chew an odorless gum for three minutes and all the saliva produced during this period was collected.

(C) Maximal tongue pressure (TP): we quantified the TP using the Iowa Oral Performance Instrument (IOPI Medical LCC, Redmond, WA, USA).

(D) Physical fitness: we assessed the hand-grip force (HGF) using a handgrip dynamometer according to the methods published in previous research (26). Body mass index (BMI) was calculated according to individual weight and height.

(E) Difficulty of nutrient intake: the difficulty in nutrient intake was assessed using the food intake questionnaire (FIQ), a self-reported assessment of the experience of chewing difficulty for 23 common food in Taiwan (27).

(F) Oral adaptation to masticatory perturbation: To quantify the degree of adaptation, we calculated the index Adapt% by comparing the MP of the last trial (i.e., P3 of the perturbation condition) and the first trial (i.e., B1 of the baseline condition) in the MPT. The index Adapt% was calculated using the following formula:

\[
Adapt(\%) = \frac{\text{VARG}_{P3} - \text{VARG}_{B1}}{\text{VARG}_{B1}}
\]

The discrepancy would reflect if the perturbation effect gradually diminished due to adaptation. A smaller discrepancy (i.e., a lower Adapt%) suggests that after three trials of the perturbation condition, the final MP (i.e., trial P3) returned back to the initial performance (i.e., trial B1 in the baseline condition). In contrast, a larger discrepancy at trial P3 compared to trial B1 suggests that the effect of perturbation remained strong after three trials of perturbation and did not return to the initial level (B1). Likewise, the index Adapt% was also calculated for masticatory duration using the following formula:

\[
Adapt(\%) = \frac{\text{Duration}_{P3} - \text{Duration}_{B1}}{\text{Duration}_{B1}}
\]

2.5. Statistical analysis

We first performed descriptive analyses for the demographic and clinical variables as well as the results of the MPT. The normality of the data was assessed using the Shapiro-Wilk test. Comparison between the YA and the OA groups was performed using the independent t-test and Wilcoxon signed-rank test, depending on the normality of data distribution. To further quantify the association between MP and
individual condition of physical fitness and food intake, analyses of bivariate correlation were conducted between the results of the MPT and the HGF, the BMI, and the score of the FIQ, using Pearson's correlation coefficient (\( r \)) and Spearman's correlation coefficient (\( \rho \)), depending on the normality of data distribution.

For Hypothesis 1, we compared the VARG score from the first and third trials, respectively, between the baseline and the perturbation conditions (i.e., trial B1 vs. P1 and trial B3 vs. P3) (Figure 2B). Because the VARG scores were non-normally distributed (see Table 2), the non-parametric Wilcoxon signed-rank test was performed. Additionally, the comparison between the MD was performed between the two conditions. For Hypothesis 2, we compared the VARG score between the first and the last trials, respectively for the baseline and the perturbation conditions, using Wilcoxon signed-rank test. For Hypothesis 3, the index of masticatory adaptation (Adapt\%) was compared using the Mann-Whitney U test between the YA and OA groups. For Hypothesis 4, multiple linear regression models were set to test if the following factors of oral conditions: individual age, the initial MP in the perturbation condition (i.e., the VARG score of P1, VARG\(_{P1}\)), the NMT, the SFR, and the TP, as the predictors, was associated with the degree of adaptation (i.e., Adapt\%), as the dependent variable. The presence of multi-collinearity was assessed if the variance inflation factor (VIF) was larger than 2. All the statistical tests were conducted using IBM SPSS version 24, with the significance level alpha=0.05.

3. Results

3.1. Descriptive analyses of demographic and clinical variables

The results of demographic and clinical variables were summarized in Table 1. In total 76 participants (mean age = 48.6 years, 43 female and 33 male), were included in the study, including 38 participants in the YA group (mean age = 28.1 years, 19 female and 19 male) and 38 participants in the OA group (mean age = 69.2 years, 24 female and 14 male). The association between sex and group was not statistically significant (chi-square test with continuity correction, \( P = 0.36 \)). Compared to the YA group, the OA group showed a significantly higher NMT, lower SFR, lower TP, and lower HGF (Table 1). In contrast, the BMI and difficulty in food intake (i.e., the FIQ score) was not significantly differed between the groups (Table 1).
Table 1
Results of descriptive analyses of demographic and clinical variables

<table>
<thead>
<tr>
<th>All participants</th>
<th>Age (year)</th>
<th>NMT</th>
<th>SFR (ml/min)</th>
<th>TP (Kpa)</th>
<th>HGF (Kg)</th>
<th>BMI</th>
<th>FIQ</th>
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<td>76</td>
<td>76</td>
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<td>0.7</td>
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<td>14.3</td>
<td>16.9</td>
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<table>
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<th>SFR (ml/min)</th>
<th>TP (Kpa)</th>
<th>HGF (Kg)</th>
<th>BMI</th>
<th>FIQ</th>
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<td>37</td>
<td>38</td>
<td>38</td>
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<td>2.8</td>
<td>60.4</td>
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<tr>
<td>IQR</td>
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<th>Older adults</th>
<th>Age (year)</th>
<th>NMT</th>
<th>SFR (ml/min)</th>
<th>TP (Kpa)</th>
<th>HGF (Kg)</th>
<th>BMI</th>
<th>FIQ</th>
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<td>49.8</td>
<td>27.2</td>
<td>23.2</td>
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</table>

\(^a\) The comparison of sSFR, TF, HGF, and BMI was performed using independent t-test. The comparison of other variables was performed using Mann-Whitney U test. All the values denote the two-tailed p value.

BMI, body mass index; FIQ, food intake questionnaire; IQR, interquartile range; NMT, number of missing teeth; SFR, salivary flow rate; STD, standard deviation; TP, tongue pressure
3.2. Descriptive analyses of the results of the MPT

The results of the MPT were summarized in Table 2. For MP, we summarized the mean VARG across three trials, respectively, for the baseline and the perturbation conditions. The OA group showed a higher mean VARG (baseline: 85.3; perturbation: 94.5) compared to the YA group VARG (baseline: 81.0; perturbation: 87.8), though the difference was not statistically significant ($P = 0.06$ for both conditions) (Table 2). For the MD, we summarized the mean duration across three trials, respectively, for the baseline and the perturbation conditions. The YA group showed a higher masticatory duration in both conditions compared to the OA group, though the difference was not statistically significant (Table 2). The index of adaptation (Adapt%) presented a large inter-individual variation for MP (from $-31$–$60\%$) as well as the MD (from $-38$–$53\%$) across all participants.

Table 2. Results of descriptive analyses of the masticatory perturbation task
### All participants

<table>
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<tr>
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<th>Masticatory performance (VARG)</th>
<th>Masticatory duration (sec)</th>
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<td>Mean</td>
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<td>89.6</td>
</tr>
<tr>
<td>IQR</td>
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<td>20.1</td>
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<tr>
<td>Minimum</td>
<td>64.5</td>
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<tr>
<td>Maximum</td>
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### Younger adults

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<td>Mean</td>
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<td>Median</td>
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### Older adults

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<tr>
<td>Mean</td>
<td>85.3</td>
<td>94.5</td>
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3.3. Results of Hypotheses 1

For Hypothesis 1, the Wilcoxon signed-rank test revealed that the VARG score from the perturbation condition was significantly higher than that in the baseline condition in trial P1 vs. B1 ($Z = -5.1$, two-tailed $P < 0.001$) as well as trial P3 vs. B3 ($Z = -3.8$, two-tailed $P < 0.001$) (Fig. 33A). The findings supported Hypothesis 1 about the perturbation effect of the MPT.

In addition, the effect was found in both YA and OA groups. In the YA group, the VARG score from the perturbation condition was significantly higher than that in the baseline condition in trial P1 vs. B1 ($Z = -2.8$, two-tailed $P = 0.005$) as well as trial P3 vs. B3 ($Z = -2.3$, two-tailed $P = 0.023$). In the OA group, the VARG score from the perturbation condition was significantly higher than that in the baseline condition in trial P1 vs. B1 ($Z = -4.3$, two-tailed $P < 0.001$) as well as trial P3 vs. B3 ($Z = -3.1$, two-tailed $P = 0.002$) (Fig. 3A).

Furthermore, the Wilcoxon test revealed that the MD from the perturbation condition was significantly higher than that in the baseline condition in trial P1 vs. B1 ($Z = -2.0$, two-tailed $P = 0.044$) as well as trial P3 vs. B3 ($Z = -3.1$, two-tailed $P = 0.002$) (Fig. 3B). Notably, an increased MD was only found in the YA group in trial P3 vs. B3 ($Z = -3.5$, two-tailed $P < 0.001$) but not in the OA group (Fig. 3B).

3.4. Results of Hypotheses 2
For Hypothesis 2, the Wilcoxon signed-rank test revealed that the VARG score from the first trial was significantly higher than that from the third trial in the perturbation condition (trial P1 vs. P3, Z = -3.7, two-tailed \( P < 0.001 \)). Consistently, there was a trend of statistical significance of higher VARG score from the first trial compared to that from the third trial in the baseline condition (trial B1 vs. B3, Z = -2.0, two-tailed \( P = 0.046 \)) (Fig. 3A). The findings supported Hypothesis 2 about the adaptation to masticatory perturbation.

In addition, the effect was found in both YA and OA groups. In the YA group, the VARG score was higher in the first compared to the third trial in the perturbation condition (trial P1 vs. P3, Z = -2.9, two-tailed \( P = 0.003 \)) as well as the baseline condition (trial B1 vs. B3, Z = -3.1, two-tailed \( P = 0.002 \)) (Fig. 3A). In the OA group, a higher VARG was only found in the perturbation condition (trial P1 vs. P3, Z = -2.2, two-tailed \( P = 0.025 \)).

Furthermore, the Wilcoxon signed-rank test revealed that the MD from the first trial was significantly higher than that from the third trials in the perturbation condition (trial P1 vs. P3, Z = -4.4, two-tailed \( P < 0.001 \)) as well as the baseline condition (trial B1 vs. B3, Z = -5.0, two-tailed \( P < 0.001 \)) (Fig. 3B). The effect was found in both YA and OA groups (Fig. 3B).

### 3.5. Results of Hypotheses 3

For Hypothesis 3, the Mann-Whitney U test revealed that the Adapt\% was significantly lower in the YA group (mean = 1.2%, median = -0.7%) compared to the OA group (mean = 10.5%, median = 11.2%) (Z = -2.5, two-tailed \( P = 0.014 \)) (Table 2). The findings supported Hypothesis 3 that age is associated with the adaptation to masticatory perturbation. Notably, additional analyses revealed that the difference between VARG\(_{B1}\) and VARG\(_{P3}\) was not statistically significant in the YA group (Z = 0.0, two-tailed \( P = 0.99 \)). In contrast, the score VARG\(_{P3}\) was significantly higher than the score VARG\(_{B1}\) in the OA group (Z = -3.2, two-tailed \( P = 0.001 \)). The findings suggested that adaptation (i.e., changes in MP) occurred in the YA but not the OA group.

### 3.6. Results of Hypotheses 4

For Hypothesis 4, we first examined the bivariate correlation between Adapt\%, age, VARG\(_{P1}\), the NMT, the SFR, and the TP. The results showed that all factors were significantly correlated with Adapt\%, except for SFR (\( \rho = -0.18, P = 0.14 \)). Therefore, in the following linear regression model, only four predictors (i.e., age, VARG\(_{P1}\), the NMT, and the TP) were included. The model revealed that VARG\(_{P1}\) (\( \beta = 0.35, P = 0.004 \)) was significantly associated with Adapt\%, with a lower degree of collinearity (VIF < 2). In contrast, age, the NMT, and the TP were not significantly associated with Adapt\%. The findings partially supported Hypothesis 4 that one of the factors of oral condition, i.e., the initial MP in the perturbation condition, was associated with individual differences in adaptation to masticatory perturbation.

### 4. Discussion

### 4.1. Summary of the major findings
In this study, we designed and conducted a novel task for assessing individual adaptation to masticatory perturbation. Our findings showed (a) the perturbation effect, i.e., lower MP in the perturbation condition (i.e., gum chewing with occluding a drinking straw) compared to the baseline condition (i.e., gum chewing only) (Fig. 3A), and (b) an adaptation effect, i.e., the return of MP from the third trial to the first trial in the perturbation condition. Notably, these effects were found in both YA and OA groups (Fig. 3A). Finally, we found that (c) the OA group showed a lower degree of adaptation to masticatory perturbation (i.e., higher Adapt%) compared to the YA group (Table 2), and better MP in the perturbation condition was associated with better adaptation.

4.2. Oral adaptation to masticatory perturbation

The importance of masticatory function has been highlighted in recent years because of its critical role in nutrient intake in older adults (28). At present, various approaches have been developed to assess MP, defined as ‘a measure of the comminution of food attainable under standardized testing conditions’ (29). The findings demonstrated that individual difference in MP was associated with their oral conditions, such as the number of remained teeth, saliva secretion, and tongue and biting forces (6–9). Following the findings, dentists focused on restoring these oral conditions (e.g., missing teeth) to improve individual MP (30). While most of the studies treated MP as an ability to eat, the nature of mastication as an adaptive oral process was largely ignored. Adaptation of mastication is associated with the ability ‘to make an acceptable food bolus or whether the food texture has to be changed’ (15). Our findings revealed that such an adaptation occurred between trials of assessment. As shown in Fig. 3A, changes in MP were significant between three trials of consecutive mastication. The findings highlight that MP is not a fixed value invariant to oral condition. In contrast, even within the same standardized testing condition, MP may fluctuate trial by trial. Critically, the findings correspond to neuroimaging findings of human mastication that showed mastication is associated with complex sensorimotor processing (31), rather than merely a fixed pattern of jaw movement.

An important finding revealed here is that adaptation occurred when normal mastication was interfered with by perturbation. If MP was determined only by the intrinsic factors of oral conditions (e.g., the number of remained teeth), adaptation should be observed only when individuals receive prosthetic treatment. Therefore, to explain the trial-by-trial adaptation of perturbation, one may consider the functional changes that gain a compensating effect on mastication. Older adults may increase the number of chewing cycles before swallowing in order to compensate for more missing teeth (13, 15). Consistently, we found that in the perturbation condition, participants spent more time (i.e., a larger MD) compared to the baseline condition, especially in the YA group (Fig. 3B). The finding suggested that functional adaptation (e.g., increasing time for chewing) may play a key role in the oral adaptation to perturbation.

4.3. Age-related difference and factors associated with masticatory adaptation
In comparison to our previous studies, we did not find a statistically significant decrease in MP in the OA group compared to the YA group. The lack of significance may be associated with better physical/mental fitness and oral health for the older participants (see more discussion in 4.5). Nevertheless, even with similar baseline MP, the OA group showed worse adaptation to perturbation (i.e., a higher Adapt%), compared to the YA group. Such an age-related difference cannot be fully explained by the intrinsic factors of oral condition, such as the NMT or the TP, because they were not statistically associated with Adapt% in our analyses of multiple linear regression.

It should be noted that adaptation is complex sensorimotor processing and individual ability of sensorimotor learning may play a key role. For example, individuals with better adaptation may be more attentive to the intraoral condition (e.g., to perceive the hardness of food) or changing sides for chewing (16). In other words, the age-related difference may reflect the ability of sensorimotor learning between YA and OA groups. A recent study of oral motor training suggested that older and younger adults differed in their performance of training (32). Compared to the older participants, the younger participants showed more improvement in task efficiency (32). Notably, in older adults, sensorimotor learning is associated with their general cognitive functions (e.g., attention control) (17, 33). Therefore, the age-related difference in masticatory adaptation may also relate to different cognitive functions between age groups.

4.4. Limitation of the study and further considerations

As shown in Table 1, the mean TP (54.5 Kpa) reported here is similar to the findings from a previous study with the same age and ethnic group (34). In the OA group, the mean SFR (2.1 ml/min), mean HGF (27.2 kg), and mean BMI (23.2) were similar to the mean SFR (2.0 ml/min), mean HGF (26.2 kg), and mean BMI (23.5) reported in previous studies on healthy elderly people (25). However, the OA group here still preserves good BMI and physical strength. It should be noted that participants of the OA group were recruited from the local community voluntarily. Therefore, the participants may over-present the older people who are more physically and mentally active in society activity. In other words, the OA group may under-present older adults with poorer physical and mental fitness. Secondly, a critical element of the MPT is the choice of materials for inducing perturbation. Previous studies adopted an occlusal splint to induce probation during mastication (22, 23, 35). The current study adopted a more natural object (i.e., a drinking straw and fruit chews) to induce perturbation, which reduced pain or discomfort during chewing and mimicked the fibrous components and flavor of real food. Therefore, the perturbation and adaptation effects observed here may not be generalized to the effects from other kinds of food/objects. Thirdly, we here considered the adaptation as the result of complex sensorimotor processing. It would be difficult to delineate the sensory and motor components of adaptation merely based on the MPT. An individual with a better Adapt% may be benefited from precise sensory feedback (e.g., sensing the hardness of the straw) or improved motor skills (e.g., swift tongue movement). Further investigation is required to elucidate the interplay between these components.

5. Conclusion
Our findings demonstrated the MPT as a valid test for assessing oral adaptation to masticatory perturbation and revealed the association between age and masticatory adaptation.

**Declarations**

**A. Author Contributions**

Y-C Chen, L-J Chao, and W-J Kao: Contributed to data acquisition. T-C Chen: Contributed to interpretation, and critically revised the manuscript. C-S Lin: Contributed to conception, design, data acquisition and analysis, interpretation, drafted and critically revised the manuscript.

**B. Ethics Approval and Consent to Participate**

The study is approved and supervised by the Institutional Review Board of National Yang-Ming University (YM109057F). Before the study started, all the participants completed the written informed consent.

**C. Funding**

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**D. Conflict of Interests**

The authors have reported no potential conflicts.

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**References**


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Figures

A Force-field task (for limb movement)

Without perturbation (baseline)

Goal

Trajectory

Hand

With perturbation (+external force)

Early adaptation

Late adaptation

Force

B Masticatory perturbation task (for mastication)

Without perturbation (baseline)

Masticatory performance

Gum

Teeth

With perturbation (+external object)

Early adaptation

Late adaptation

Drinking straw

Figure 1
The concept of assessing sensorimotor adaptation. (A) In the force-field paradigm, participants are instructed to move a robotic device to reach a goal object. The trajectory of the movement, which is usually a smooth one in the baseline condition, is recorded. In the condition with perturbation, an external force is applied on the robotic device so that for the first few trials, participants may not reach the goal as smoothly as in the baseline condition. Notably, when participants adapt to the perturbation (i.e., being resistant to the external force), the trajectory to reach the goal is developed as the baseline condition. (B) In the masticatory perturbation task, participants are asked to chew a piece of gum for assessing mixing ability in the baseline condition. In the perturbation condition, they are asked to chew the gum on one side and a drinking straw on the other side concurrently, with the latter as an external interference to induce perturbation.
The design of the masticatory perturbation task (MPT). (A) The MPT consists of six assessments of the performance of mixing food. Masticatory performance (MP) is assessed using the variogram-based approach and indexed by the VARG score (a lower score denotes higher MP). The first three trials are MP assessment without perturbation (i.e., B1, B2, and B3, the baseline condition), followed by three trials of MP assessment with perturbation (i.e., P1, P2, and P3, the perturbation condition). (B) Hypothesis 1
focuses on the perturbation effect of the MPT, i.e., lower MP (i.e., higher VARG score) in the perturbation condition compared to the baseline condition. Hypothesis 2 focuses on the adaptation effect of the MPT, i.e., higher MP (i.e., lower VARG score) in the third trial compared to the first trial of the perturbation condition. Hypothesis 3 focuses on the age-related difference in the degree of oral adaptation, as indexed by Adapt%.

Figure 3

Results of the major hypotheses. (A) For masticatory performance, all participants and both age groups showed a significant perturbation effect and adaptation effect. (B) For the masticatory duration, all participants and both age groups showed a significant adaptation effect. The younger adults but not the older adults showed a perturbation effect.