Research article

Coupling of motor oscillators – What really happens when you chew gum and walk?

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1. Introduction

The basis for the performance of a variety of voluntary actions involves controlled oscillatory activity of specific neuronal structures. Walking, tapping, chewing, and running are all examples of oscillatory motor behaviors which emerge from integrated cyclical neuronal activity. For many of these behaviors, the neural mechanisms underlying these actions involve complex neuronal clusters (i.e., central pattern generators, CPG’s) within the CNS with both somatosensory feedback and descending influences from higher regions moderating the resultant neuromotor outputs. Chewing and walking are primary neuromotor functions that individuals perform on an everyday basis with CPGs influencing much of the cyclic motor control of these activities. Although both actions can broadly be described as oscillatory, rhythmical motor tasks, they are, when undertaken independently, performed at different preferred frequencies involving different muscles/body segments with different overall goals. Colloquially, the inference has been that chewing would interfere with an individual’s gait, although the impact of chewing on walking performance has never been explicitly examined.

It has been established that both chewing and walking utilize central pattern generators to set the rhythmical characteristics of each task. It has been reported that the CPG’s for stepping are likely located in the spinal cord, whereas those involved in chewing can be found in the pons and medulla regions of the brainstem. Both of these CPGs can be modulated by descending inputs arising directly from cortical regions and/or sensory input. Previous research using animal models has reported that projections from the trigeminal system in the brainstem propagate to all levels of the spinal cord. Although similar axonal projections are not evident in humans, it has been reported that increasing the force of biting can lead to increases in neuromotor excitability, enhancing reflex responses in muscles of both the upper and lower limbs. Under these conditions, it is believed that the increased excitability of the α motor neuron pool observed during teeth clenching was generated through the corticospinal tract with the added inference that these projections could influence postural actions. Although individuals do not typically chew with maximal force, it seems plausible that the same neural mechanisms and pathways underlying the increased excitability during teeth clenching would be evident when chewing. Additionally, serotonin receptors have been associated with mediation of repetitive chewing activities in mammals, as well as influencing locomotor...
pattern generation in the spinal cord [30,33]. Consequently, there is some support to the idea that chewing may influence the pattern of lower limb muscle activity during purposeful actions such as walking.

A feature of many oscillatory behaviors with increasing age is a general decline in overall speed or rates, especially at faster frequencies. For example, increasing age is associated with declines in walking speed, reaction time, and finger tapping rates [1,5,7,21]. The fact that this process of slowing occurs across a range of movements has been described as a loss of the faster time scales of physiological processes [21,22]. The physiological basis for this neuromotor slowing has been linked to changes both at the peripheral (i.e., muscle atrophy, remodeling/loss of motor units [6,28]) and central level (i.e., loss of white and grey matter within the CNS, degeneration of neurotransmitter systems [31,41]). However, there has been little direct assessment of whether the motor processes involved in chewing are similarly affected by aging. One suggestion is that, in comparison to other motor tasks such as walking, chewing rates in older adults may be preserved given the increased neural input the masticatory muscles receive from both motor cortices, as well as its importance in nutrition and general survival [10,18,20].

This study was designed to assess the impact chewing at different frequencies had on walking performance for healthy young and older adults. It was predicted that an individual's stepping rate (and hence walking speed) would increase or decrease in line with the similar changes in chewing rates. It was also predicted that, while age-related differences would be seen in preferred walking speed, that no differences would be seen for chewing rates between the young and older individuals.

2. Methods

2.1. Participants

Fifteen healthy young adults (average age 23.2 ± 4.2 years) and fifteen healthy older participants (average age 66.5 ± 3.2 years) volunteered to participate in this study. All participants were recreationally active and reported no neurological disorders or neuromuscular injury that could influence performance. Demographic data relating to age, height, weight, and preferred chewing side were collected from each participant prior to data collection. Participants provided informed written consent prior to inclusion in the study and all procedures complied with the university IRB guidelines.

2.2. Experimental design

The following movement tasks were performed; a) chewing only and b) chewing while walking. Details regarding the specific tasks and conditions are as follows:

a) Chewing Only: This task was performed to assess each person's preferred chewing rate. Each person was required to perform this task under three chewing speed conditions: 1) preferred speed of chewing, 2) slow speed of chewing and, 3) fast speed of chewing. The preferred speed of chewing was self-selected [3]. The slow and fast speed conditions were set at 1 Hz and 2 Hz based upon previous research [27]. Individuals performed three 30 s trials for each chewing condition. Subjects were seated upright and supported in chair with their feet on the ground for all single-task chewing conditions. During the preferred chewing condition, subjects self-selected their preferred chewing speed. For the slow and fast chewing conditions, individuals initially practiced chewing at these specified rate while a metronome, set at either 1 Hz or 2 Hz, respectively, was played. After this practice period, the metronome was turned off. Participants then performed the specified chewing conditions with relevant data being recorded.

b) Gait and Chewing: For the gait-chewing task, four conditions were performed. All walking was performed at the individual's preferred speed. Individuals performed three walking trials for each condition. All walking trials were performed in a straight line over a distance of 25 ft. The conditions were: 1) walking at a persons preferred speed without chewing, 2) walking while the individual chewed at their preferred rate, 3) walking while chewing at a slow rate (1 Hz), 4) walking while chewing at a faster rate (2 Hz). For conditions 1 and 2, individuals self-selected their preferred walking speeds and (for condition 2 only), their preferred chewing rates. For the fast and slow chewing conditions, individuals initially practiced chewing at these specified rate while a metronome (set at either 1 Hz or 2 Hz) was played. After this practice period, the metronome was turned off. Participants then performed the specified conditions with relevant chewing and gait data being recorded. All walking trials were performed with the metronome turned off.

For all chewing conditions, participants were provided with one piece of Trident® spearmint gum and were given up to one minute to chew and soften the gum, as well as establish a comfortable chewing pattern before data collection commenced. Individuals were asked about the preferred side for chewing and asked to chew on that side for the duration of the study [11,39]. Participants were able to exchange the gum bolus between each trial; however, bolus size was kept consistent across all trials. Individuals removed the gum during the no-chewing conditions.

2.3. Data collection and processing

All data processing and analyses were performed using custom software developed in Matlab (Mathworks R14). EMG activity was recorded from the masseter muscle the Delsys Trigono system (Delsys, Boston, MA) at a sample rate of 2000 Hz. Prior to data analysis, EMG data were down sampled to 1000 Hz, rectified, then filtered using a second-order low-pass Butterworth filter (cut-off frequency 400 Hz). In addition, a linear envelope of the EMG signal was attained using a low pass filter set at 20 Hz.

Assessment of each person’s gait was collected using three Delsys triaxial accelerometers. These sensors were positioned on the head, lower back (L3 spinous process), and lower leg (distal Achilles tendon) during the walking trials as per our previous research [2]. Gait-related acceleration data was collected at 148 Hz using the Delsys Trigono system (Delsys, Boston, MA), down sampled to 100 Hz and filtered using a second-order low-pass Butterworth filter with a cutoff frequency of 40 Hz. The following analyses were subsequently performed on the EMG and acceleration data:

2.3.1. Chewing

For all conditions, an indication of each individual’s chewing rates were derived from a surface EMG sensor placed over the belly of the masseter muscle on the individual’s preferred chewing side. A measure of the overall chewing frequency (rate) for each chewing condition was attained by determining the number of contractions (based upon the EMG signal) for the masseter muscle over the period for each trial. Selection of a muscle contraction was based upon a peak picking algorithm which identified the maximum peak within a pre-specified time window. The accuracy of the peak-picking algorithm was verified by visual inspection of 25% of the trials in each condition. The average (mean) responses and the intra-individual variability (IV) were calculated for the chewing rates.

2.3.2. Gait

Consistent with the chewing measures, measures of the number of steps (step rate) were attained for each trial within each condition from the accelerometer data. Selection of each step were based upon a peak picking algorithm which identified the maximum peak within a pre-specified time window. The accuracy of the peak-picking algorithm was
verified by visual inspection of 25% of the trials in each condition. Average and IIV values were calculated for step rates for comparison.

In addition, a 20-foot Zeno pressure sensitive walkway (Prototronics, Havertown, PA, sample rate: 120 Hz) was used to provide additional spatio-temporal gait measures. Average (mean) and IIV measures were calculated for the following spatio-temporal gait variables: step length (cm), step time (sec), and gait velocity (cm/sec). All gait-related IIV calculations were based upon the between-trial standard deviation (SD) for each individual. This data was processed using the Prototronics PKMAS software (ProtoKinetics LLC).

2.4. Statistics

For all tasks, a repeated measures, mixed generalized linear model (GLM) was used to assess differences between the two age groups and as a function of the specific conditions. Significant interaction effects were explored using planned contrasts (one-way ANOVA’s) within the mixed model design. All tests were performed using SAS statistical software (SAS Institute Inc., Cary, NC) with a significance level of $p < 0.05$.

3. Results

3.1. Chewing only conditions

Overall, participants were able to accurately follow instructions regarding the different frequency of chewing when seated. A significant main effect for condition was seen for the average chewing rate ($F_{(2,56)} = 1316.79; p < 0.001$) with planned contrasts revealed differences between all three conditions (all $p's < 0.001$). A significant age group effect was also observed for the IIV of the chewing rates ($F_{(1,26)} = 5.40; p = 0.032$) with the older adults exhibiting greater variability compared to the young adults. No interaction effects were found. Fig. 1 illustrates the pattern of activity for the masseter muscle (both mean and intra-individual variability, IIV) for the two age groups and across the three conditions are also shown.

3.2. Chewing: walking and seated comparisons

Inferential analysis was performed to assess whether the average chewing rates were different between the seated (chewing only) and walking/chewing conditions. Comparisons were made between similar conditions only (i.e. slow-slow, fast-fast, or preferred-preferred). The results revealed no significant differences between similar chewing conditions (all $p's > 0.50$).

3.3. Walking and chewing

3.3.1. Chewing rates

An example of the EMG and acceleration signals for both chewing and walking during each of the three chewing-walking conditions (i.e., slow, preferred and fast) are shown in Fig. 2. For chewing rates, a significant condition effect was found for both the average ($F_{2,56} = 860.27; p < 0.001$) and IIV ($F_{2,56} = 4.25; p = 0.007$) measures. Planned contrasts revealed significant differences between all conditions ($p's < 0.001$) with the mean and IIV values being lower during the slow chewing condition and increasing across the preferred and fast chewing conditions respectively. No differences were found for the chewing rates between the two age groups.

3.3.2. Walking (stepping) rates

For the gait-acceleration data, the overall number of steps and the timing between individual steps (i.e. inter-step intervals) were determined for further analysis. A significant condition effect was found for average ($F_{3,81} = 241.6; p < 0.001$) and variability ($F_{3,81} = 3.17; p = 0.023$) of the step rate measures. For the average measures, planned contrasts revealed the differences were between all conditions (all $p's < 0.001$) except the preferred gait/no chewing and the fast chewing conditions. For the IIV of step rate, differences were seen between the slow chew/walking and both the fast chew/walking and preferred walking/no chew conditions (all $p's < 0.001$). No interaction effects or differences between the two age groups were observed for these measures. Fig. 3 illustrates the pattern of change in the chewing and gait responses (both mean and IIV) for the young and older groups across the experimental conditions.

3.3.3. Walkway assessment of gait

In addition to the gait analysis performed above, further gait assessments were attained from the pressure sensitive walkway. The summarized changes in step time, step length and gait velocity between the two groups and across conditions are shown in Fig. 4. These results revealed significant age by condition interaction effects for gait velocity ($F_{3,84} = 9.93; p < 0.001$), step time ($F_{3,84} = 21.62; p < 0.001$), and step length ($F_{3,84} = 38.23; p < 0.001$). For the velocity measures, planned contrasts revealed differences between the slow chewing and all other conditions ($p's < 0.05$). Generally, the older adults walked at a slower velocity compared to the young adults. Similarly, for the step time and step length measures, differences were observed between the same chewing conditions ($p's < 0.01$) with the exception of the fast chewing/walking and the no-chewing/preferred conditions. Step lengths were greatest during the fast chewing/walking conditions and decreased during the slow chewing/walking condition. Similarly, step times were longer during the slow chewing/walking conditions and shorter during the fast chewing/walking condition ($p's < 0.01$). Across all conditions, the older adults exhibited significantly decreased step lengths and increased step times compared to the young adults ($p's < 0.01$).

4. Discussion

The aim of this study was to examine the effect chewing at various rates has on walking performance for healthy young and older adults. The results revealed that step rates (and hence walking speed) was strongly influenced by chewing rate, with both the young and older adults walking either faster or slower depending on the specified chewing rates. Interestingly, while the older adults tended to walk slower (i.e. slower velocity) compared to the younger adults, there were no differences in the average chewing rates as a function of age. This finding suggests that despite the widespread slowing of motor function seen with aging, mastication itself does not appear as affected by aging.

4.1. Impact of chewing on gait

A prominent finding from the study was that changes in the rate of mastication had a significant impact on stepping rates (and, consequently, gait velocity) for both the young and older adults. When individuals chewed at a faster or slower pace, their step rate changed in a similar, systematic fashion. As highlighted in Fig. 3, an individual’s step rate during walking was tightly linked to the rate at which they were chewing. While there would seem to be no doubt that the rhythmical action of chewing had a strong driving influence on an individual’s gait, the question of importance lies in the physiological basis for chewing driving a person’s gait. One possible explanation is that the greater neural input related to mastication (in comparison to the neural drive for muscles involved in walking) may effectively lead to coupling of step rate with chewing rates. Previous research has demonstrated that mastication is a complex motor process, arising from the combination of neuro-oscillatory output from central pattern generators (CPG) within the brainstem. In particular, activity in the pons and medulla regions appear to be fundamental to the generation and control of chewing actions [12,15,26]. However, these CPG’s do not operate in
isolation, with their resultant neural output being moderated both by descending signals from higher motor centers and sensory feedback from receptors within the face and mouth [15,16,37]. Furthermore, those specific muscles involved in chewing (i.e. masseter) receive bilateral neural signals from both motor cortices [24,25]. In contrast, the CPGs involved for gait are, for humans, less well developed [15,17], with the lower limb muscles central to walking only receiving input from a single, contralateral hemisphere.

Obviously, entrainment between these two motor processes would likely require some neural connections between the respective CPG’s. Previous research using animal models have reported projections from the spinal trigeminal nucleus to the cervical, thoracic, and lumbar-sacral levels of the spinal cord [29] although it should be pointed out that similar projections have not been reported for humans. For humans, a more likely pathway could be the corticospinal tract as it has been reported that forceful (voluntary) clenching of the teeth can lead to increased excitability of the α motor neuron pool for muscles of both the upper and lower limbs [4,34]. This increased excitability observed during teeth clenching, which was propagated through the corticospinal tract, was also reflected by enhanced reflex responses within the soleus (lower limb) and first dorsal interosseous (upper limb) muscles. Consequently, it may be that there is increased neural drive related to chewing in comparison to that seen for gait, thus leading to a coupling of a person’s step rate to chewing rates when the two tasks are performed simultaneously. The inference from this is that the descending drive for mastication may not only lead to excitation of the α motor neuron pool for muscles of both the upper and lower limbs, but may actually entrain the muscle activity of the legs during walking. Irrespective of the underlying physiological mechanism, the results show that changes in chewing speed tends to drive stepping rates (and hence gait speed) in both young and older adults.

4.2. Age-related impact on chewing

Under the chewing only conditions, there were no differences in the average chewing rates for the young and older adults. The lack of any
Fig. 2. Representative EMG (right) and acceleration (left) signals illustrating rate of chewing (EMG) and walking (acceleration) patterns for the slow, preferred and fast chewing conditions. EMG and acceleration traces are shown for a single older individual.

Fig. 3. Graphs depicting changes in average and IIV of chewing rates and step intervals for the two age groups as a function of the different conditions are shown. For all graphs, error bars represent one SE of the mean.
age-related differences in chewing rates is of interest given the general pattern of movement slowing commonly reported for other voluntary actions [21,22,36]. For example, increasing age has been linked with declines in gait speed, slower rate of finger tapping, and increased reaction time [1,9,38]. Indeed, in the current study, the older adults exhibited significantly slower walking speeds during both the chewing and non-chewing conditions, affirming the general view that gait speed declines with increasing age. The lack of any age-related differences in chewing rates across the various speed conditions may indicate that the control mechanisms underlying chewing are less affected by normal aging compared to the neuromotor processes responsible for lower limb movements.

Interestingly, the preservation of similar rates of chewing for the young and older adults did not extend to the pattern of intra-individual variability during chewing. For these measures, the chewing responses of the older adults were characterized by increased within-subject variability compared to the young participants. This increased variability provides evidence to support the view that changes in IIV measures may be a more sensitive biomarker of age-related decline compared to average values [14,23,32].

Despite our finding of strong coupling between chewing and walking, there are still limitations within the current design which need to be considered. While the selection of the slow and fast chew speeds were determined a priori based on previous research, a more balanced approach whereby the fast and slow chewing speeds were specifically determined as a ratio of the person’s actual preferred chewing rate may provide more insight as to the underlying chewing dynamics. Additionally, the use of the metronome to assist setting the desired fast and slow rates for designate the chewing rates may have indirectly influenced the gait timing. Although the metronome was not played during the walking trials, the possibility of a carry-over effect from previously using the metronome for setting the chewing speeds cannot be discounted.

5. Conclusions

The main findings of this study were that the rate at which a person chewed had a strong driving influence on the stepping rate (and hence walking speed) for both young and older healthy adults. One suggestion for this coupling is that, when performed simultaneously, the neural drive related to chewing entrains the muscles involved in the basic gait action of stepping. The coupling of stepping with chewing rates for both the young and older adults was observed despite overall age-related differences in walking speed. On this point, while the older adults

Fig. 4. Graphs depicting changes in gait velocity (bottom), step time (middle) and step length (top) for the two age groups as a function of the different conditions. For all graphs, error bars represent one SE of the mean.
tended to walk slower compared to the young adults, there were no differences in the average chewing rates as a function of age. This finding suggests that despite the widespread slowing of motor function seen with aging, mastication itself does not appear to be similarly affected by increasing age.

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References