Occlusal forces during chewing and swallowing as measured by sound transmission

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Historically, tooth forces during chewing have been measured directly in human subjects using force or pressure transducers located in complete dentures and in pontics of fixed partial dentures. The forces generated differ when comparing those in complete denture subjects to those with natural dentitions. The forces measured by transducers placed in pontics are dependent on the arbitrarily determined occlusion of the opposing tooth, which measures forces at one point only and not the total biting force across all the teeth. Integrated electromyograms (EMG) have been a popular method of studying occlusal forces. However, both amplitude and time relationships of integrated EMG are difficult to relate to occlusal force. This article describes an extraoral method for measuring total biting force during chewing in natural dentition subjects without occlusal disturbances.

The linear relationship between biting forces during isometric contractions and integrated EMG has been demonstrated by Garret et al.,[1] Ahlgren,[2] and Ahlgren and Owall.[3] However, the EMG recorded during chewing reflects both isotonic and isometric contractions of many muscles under changing conditions. A recent article by Kawazoe et al.[4] explored some of the complex relationships between amplitude of integrated EMG and magnitude of biting force.

Unilateral chewing is further complicated by the fact that the EMG activity of the masseter muscles is longer acting and less variable on the working side than on the nonworking side.[5]

The time relationships of rapid chewing movements are difficult to calibrate with the EMG amplitude of muscle contraction. The peak occlusal force occurs considerably later than the peak EMG activity, ranging from the 41 ms delay reported by Ahlgren and Owall[3] to the 73 ms delay reported by Hannam et al.[6]

To achieve accurate force data without disturbing the occlusion, an occlusal force measuring system based on sound transmission was developed as part of this project. Conant[7] introduced the technique of using sound waves to measure bite force. In the course of this experiment, we found refinements, including frequency selection for each particular patient, were necessary to make such a system practical.[8]

MATERIAL AND METHODS

Apparatus

Sinusoidal sound vibration at a specific frequency is introduced at the forehead with a piezoelectric crystal transducer. Sound vibration is transmitted to the chin through the teeth, temporomandibular joint (TMJ), and muscle pathways (Fig. 1). The greater the force between the mandible and the maxillae, the greater the amplitude of vibration received by an accelerometer positioned at the chin.

The specific frequency for each subject is selected for maximum transmission received at the chin while the subject clenches his teeth. Each subject usually displays one, two, or three amplitude peaks. If more than one amplitude peak is noted, the frequency selected is based on the most linear force-to-sound calibration. The frequencies used for the 20 normal subjects in this study are shown in Fig. 2 and range between 1,208 to 2,514 Hz.

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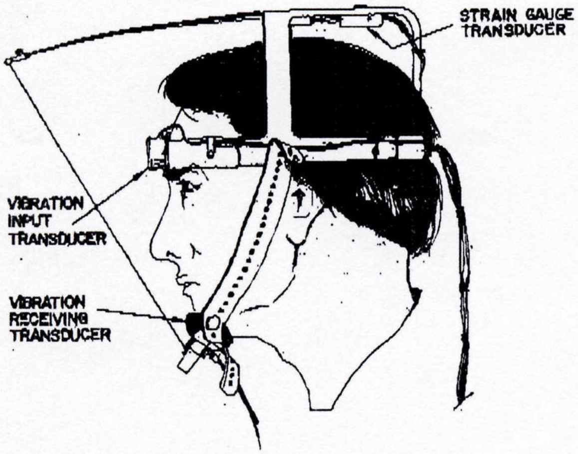

Fig. 1. Chewing force was measured using amplitude of sound vibration transmitted from forehead to chin. Vertical jaw movements were measured with strain gauge transducer mounted on head frame and tied to chin. No intraoral instrumentation was used.

The sine wave applied to the subject's forehead was generated by a Quan-Tech Wave Analyzer Model 2449 (Scientific-Atlantic, Inc., Randolph Township, N.J.), amplified by a Bogen amplifier Model C10 (Pioneer Electronics, Inc., Cleveland, Ohio), and introduced to the forehead by a piezoelectric crystal transducer of our own design (Fig. 3). This forehead transducer operated with a maximum input power of 55 milliwatts over its surface area of 10 cm^2. The sound was detected at the chin with a BBN Model No. 507 accelerometer (Bolt Beranek and Newman, Inc., Cambridge, Mass.). Unwanted sounds from such things as tooth contact and chewing were attenuated by a dual conversion hetrodyne type 100 Hz, 24 decibel per octave band pass filter incorporated in the Quan-Tech Wave Analyzer. For example, if the center frequency for a particular subject was 2,000 Hz, signals in the 1,950 to 2,050 Hz range would be unaltered. The voltage of signals with frequencies one octave away (975 or 4,100 Hz) would be attenuated to about one-sixteenth (24 decibels) of their original magnitude. Selection of band pass width was a compromise. Making the band pass narrower would further reduce unwanted signals; however, the overall response time of the system would be lengthened, which was an undesirable effect. The signals were demodulated and displayed on a strip chart recorder (Physiograph Model DMP-4B, Narco Biosystems, Inc., Houston, Tex.). Vertical jaw position and integrated EMG from the

Table I. Biting force during chewing*

	Sound transmission method	
Force	Average pounds† (kg)	Percentage of maximum bite force
Closing	18.2 (8.3)	11.2
At occlusion	58.7 (26.7)	36.2
Opening	12.5 (5.7)	7.7

*Number of patients = 20; average number of chews per patient = 266 for beef, bread, carrots, cheese, gum, and peanuts.
†Average maximum bite force = 162 pounds (74 kg).

masseter muscles were displayed on the second and third channels of the strip chart recorder.

The instrumentation was tested with an acrylic resin block substituted for the subject's head. For any one specific frequency, maximum error in linearity was found to be 0.31% and maximum error in reproducibility 1.56%. Output of the system for a range of frequencies using the acrylic resin block is shown in the curve in Fig. 2. This curve indicates that the sharp amplitude peaks (resonances) are a function of the patient and not inherent in the driving transducer.

Calibration was performed individually for each subject in a two-step procedure. In the first step (Fig. 3), biting force, as measured by an intraoral strain gauge gnathodynamometer,[9] was related to integrated EMG using two surface electrodes, one over each masseter muscle. A ground electrode was placed at the base of the neck. In the second step the integrated EMG was used, with nothing between the teeth, to calibrate the amplitude of vibration received at the chin. For ease in comparing the calibration curves to subjects, the amplitude of vibration received at the chin was adjusted (normalized) to read 100 units at 50 pounds of biting force. A linear calibration curve, which would appear as a straight line, was most nearly approached by subject JD. No subject produced a true linear relationship, (Fig. 4). Vibration showed a rapid increase for all 20 subjects initially, while at higher force levels the increase was less rapid. As a result, sensitivity and accuracy were greater for low biting force levels than for high biting force levels. Since each subject's calibration was unique, biting force recordings measured in the vibration units were converted to pounds using the particular subject's calibration.

The primary advantage of this system over gnathodynamometers was the ability to measure total

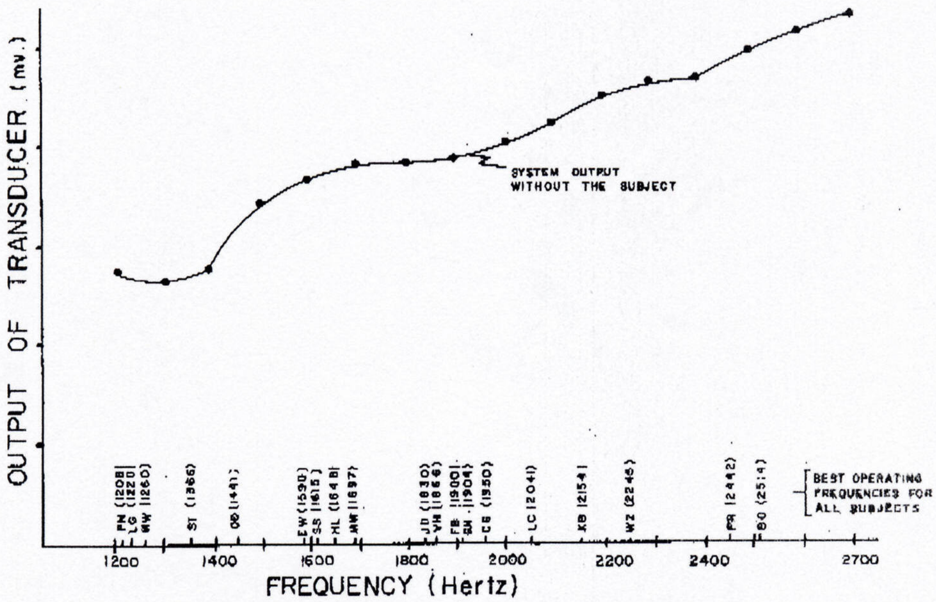

Fig. 2. Amplitude of sound transmission, as function of frequency, is shown when acrylic resin block was substituted for patient's head *(curve in upper portion)*. The peak frequencies (resonant) for 20 normal subjects ranged between 1,208 and 2,514 Hz *(along horizontal axis)*.

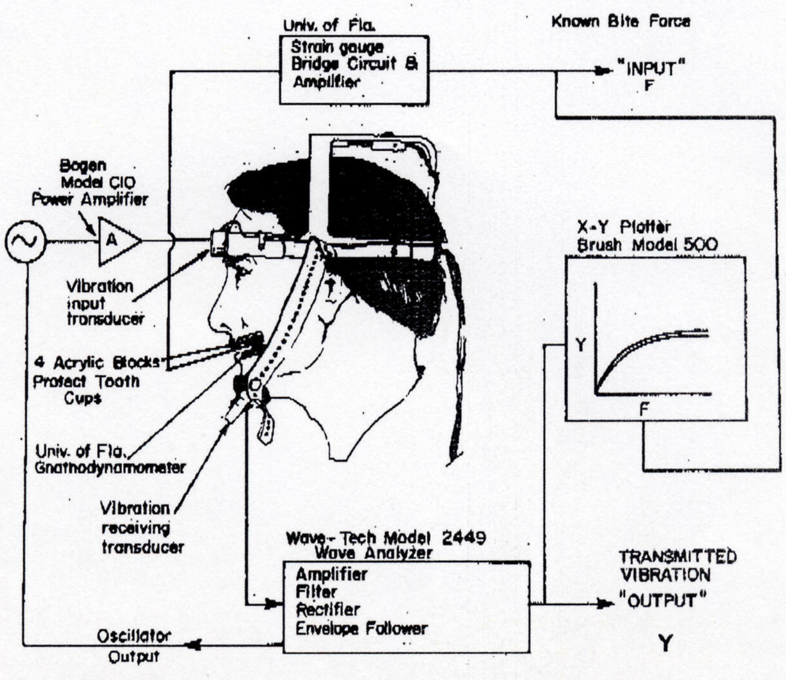

Fig. 3. Sound transmission system for measuring chewing force shown schematically during first step of calibration procedure. Amplitude of sound transmission is plotted in respect to biting force measured with intraoral gnathodynamometer. Following calibration, gnathodynamometer is removed, and no instrumentation is used intraorally during data recording.

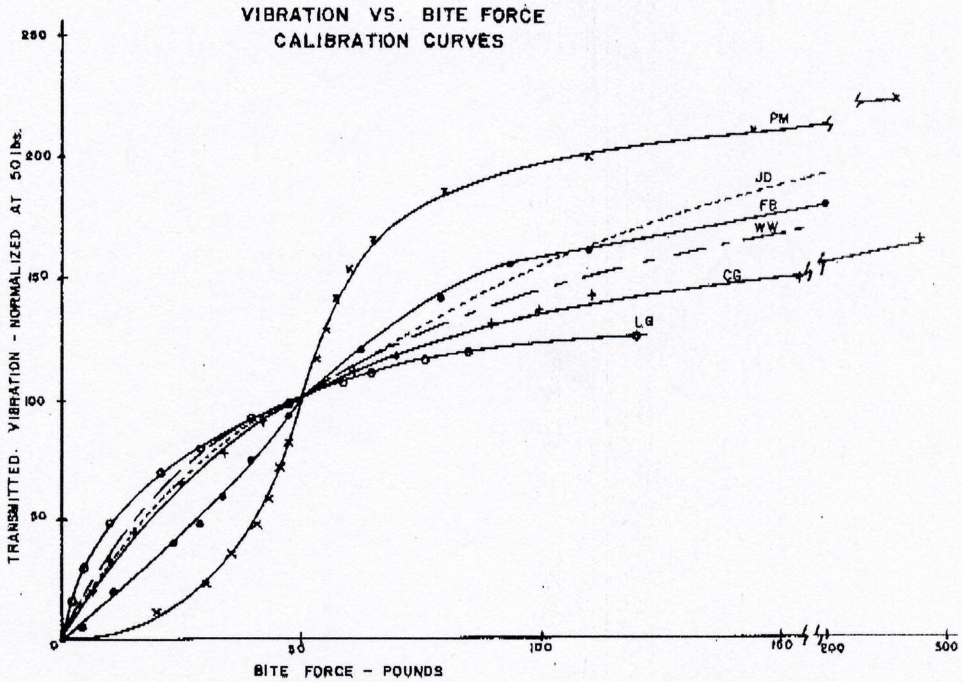

Fig. 4. Amplitude of sound vibration transmitted to chin from forehead showed rapid initial increase followed by more gradual increase at higher force levels. Calibration curve for subject PM was unusual. Five other calibration curves were more representative of 20 subjects in study.

forces without intraoral devices. The disadvantage was somewhat lower amplitude precision. The maximum error of the system was 25% for some subjects at the higher biting force levels. Future improvements in vibration transducer placement and design will improve the precision of this method. In this study, relatively large sample groups were used to minimize the effect of possible errors which could have occurred at the higher biting forces.

The great advantage of this system over integrated EMG was the accurate time relationship between occlusal force and transmitted vibration. The timing was accurate to within 15 ms. A 90% full-scale vibration reading was reached within 15 ms following initiation and termination of a step input of force. A semiconductor strain element system for measuring vertical jaw movements was combined with the transmission system so that opening, closing, and occlusal phases of chewing could be determined accurately (Fig. 1).

SUBJECTS

Twenty subjects with good occlusion were selected for this study. They ranged from 17 to 55 years of age and included 13 men and 7 women. Criteria for having good occlusion included: (1) 28 to 32 teeth present in good arch alignment, (2) no abnormal tooth abrasion or mobility, (3) no teeth in crossbite, (4) posterior teeth intercuspated according to Angle's Class I occlusion, (5) normal gingival tissues, (6) lack of muscle pain and other dysfunction symptoms, (7) no balancing interferences, and (8) anterior guidance in right and left lateral and protrusive movements.

Data were collected for the right and left sides during unilateral chewing of cheese, raisins, bread, beef, peanuts, carrots, and gum cut into bite-sized portions. An average number of 266 chews were analyzed for each subject. The only instruction given the subject was designation of the side on which to chew.

FINDINGS

Clenching

The maximum biting force during clenching for these 20 subjects as measured with an intraoral strain gauge gnathodynamometer averaged 162 pounds (74 kg) and ranged from 55 to 280 pounds (25 to 127 kg). There appeared to be no correlation of biting force either to sex or age. The weakest biting force (55 pounds) occurred in a 20-year-old, tall, healthy

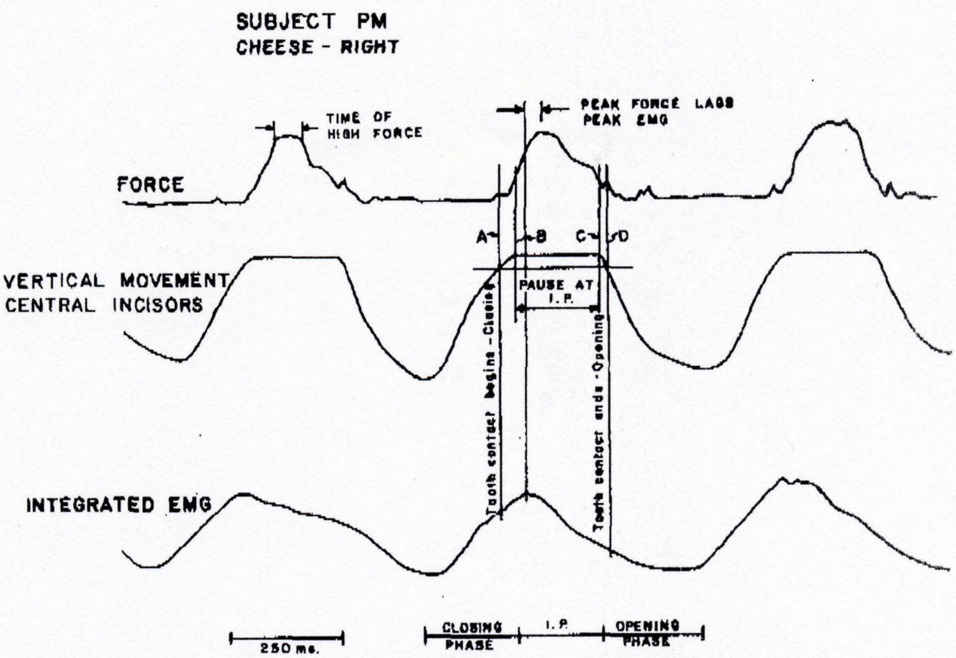

Fig. 5. Typical chart-recorder graph made during chewing. Occlusal force *(top)*, vertical jaw position *(middle)*, and masseter muscle integrated EMG activity *(bottom)*. Peak force lagged behind peak EMG activity. Chewing force was greatest during phase of occlusal contact when jaw was motionless at intercuspal position.

man. On palpation, his masseter muscles were very small. His 17-year-old sister had a maximum biting force of 200 pounds.

Chewing

A comparison of the simultaneous tracings produced by the occlusal force, the vertical motion of the central incisors, and the masseter muscle integrated EMG during typical chewing is shown in Fig. 5. The force generated during chewing was greatest during the phase when the jaw was motionless at the intercuspal position. The force during the closing phase of chewing was less, and the least force occurred during the opening phase. Most chews exhibited a period of high force during the occlusal phase. Typically, there was a considerable time delay between the peak integrated EMG activity and the peak biting force. The mean delay time was 43 ms (SD = 29 ms) for 1,410 chews recorded by 12 subjects, which was averaged over the seven different types of foods.

The forces generated during the phase with the teeth in maximum intercuspation for 20 subjects were surprisingly high, averaging 58.7 pounds (26.7 kg) which was 36.2% of the average maximum biting force. Chewing forces generated during the closing phase toward maximum intercuspation averaged 18.2 pounds (8.3 kg) compared with 12.5 pounds (5.7 kg) during the opening phase away from maximum intercuspation (Table I).

Table II. Time measurements in chewing*

Time	Sound transmission method	
	Average (ms)	SD (ms)
Chew	672	122
Occlusal phase	194	38
High force during occlusal phase	115	35

*Number of patients = 20; average number of chews per patient = 266 for beef, bread, carrot, cheese, gum, and peanuts.

For the 20 subjects, the total time of chewing averaged 672 ms. The time of the occlusal phase averaged 194 ms. The high force produced during occlusal contact persisted for an average of 115 ms, or 59% of the total 194 ms (Table II).

Swallowing during chewing. The jaw closed to the intercuspal position in nearly all of the swallows during chewing for the 20 subjects with good occlusion. During swallowing, the jaw remained closed for

Table III. Occlusal force during swallowing*

	Sound transmission method		
	Time closed (ms)	Time high force (ms)	Max force closed (pounds)
Average	683	522	66.5
SD	249	279	55

*Number of patients = 20; total number of swallows = 368 and average number of swallows = 18.4 per patient.

an average of 683 ms, which was considerably longer than the 194 ms of occlusal contacts during chewing (Table III). A high force persisted for an average of 522 ms of the total 683 ms closed in the intercuspal position. The occlusal force produced during swallowing averaged 66.5 pounds (30.2 kg) (Table III) which was higher than the force recorded during chewing (Table II).

DISCUSSION

Occlusal forces during chewing were found to be surprisingly high (58.7 pounds, 26.7 kg), during the relatively long 194 ms phase of occlusal contact and low during both the closing phase (18.2 pounds, 8.3 kg) and the opening phase (12.5 pounds, 5.7 kg). Swallowing occurred primarily in the intercuspal position, yielding a force of 66.5 pounds (30.2 kg), which was higher than the chewing forces. Swallowing force persisted for 552 ms at the intercuspal position. The force values recorded for the opening and closing phases may be slightly greater than actual values due to chewing noises that passed through the filter. Noise occurring only in the narrow 100 Hz band pass would not be attenuated. All other sounds would be greatly attenuated at 24 decibels per octave.

The force values recorded during the occlusal and swallowing phases would have a negligible effect from chewing noises. The mandible is motionless during these phases, and therefore generation of unwanted sounds is minimal.

The intercuspal position is of prime importance during chewing. It is in this position that the forces generated are the highest and longest acting. Also, steep anterior tooth guidance appears to have a lower risk of excessive tooth forces than was previously thought because the forces produced in eccentric contacts during the closing and opening phases are fairly low and short acting. Teeth are usually positioned in opposing dental arches in a manner that permits the intercuspal position forces to be directed along the long axis of their roots. Periodontal ligament support is optimal at this time, and tipping forces are minimized.

This study measured total occlusion force which was greater than the forces measured by transducers placed in tooth supported restorations. DeBoever et al.[10] studied chewing with a force transducer in a posterior pontic of a fixed partial denture. In three subjects, they found the mean forces to be 2.44, 2.03, and 4.26 pounds. Maximum forces seldom exceeded 15 pounds. In a single molar tooth transducer, Anderson and Picton[11] showed chewing forces of the normal dentition to range from 18 to 31 pounds (8 to 14 kg). In a single tooth transducer, Graf et al.[12] reported axial load peaks of 9 pounds (4 kg).

Most studies agree that the forces generated in the occlusal phase were greater than those occurring during the closing or opening phases. This was also true for the denture wearers[13] as well as for subjects with natural dentitions.[3]

Integrated EMG activity was useful in this study for bite force calibration in the static isometric mode. However, during chewing it was evident that peak occlusal force occurred well after peak EMG activity. For that reason, EMG activity by itself is difficult to correlate with force during chewing. The mean time delay between peak EMG and peak force of 43 ms in this study corresponded closely to the 41 ms reported by Ahlgren and Owall[3] and was less than the 73 ms reported by Hannam et al.[6]

Forces during swallowing

The forces produced during swallowing (66.5 pounds; SD, 55 pounds) were greater than those occurring during chewing (58.7 pounds, SD 45.6 pounds). The swallowing force, on the average, was 41% of the subject's maximum biting force. The phase of occlusal contact during swallowing was considerably longer and more variable (683 ms; SD, 249 ms) than the phase of occlusal contact during chewing (194 ms; SD, 38 ms). Duration of forces produced during swallowing averaged 522 of the total 683 ms, or about 76% of the occlusal phase. Apparently a bracing action of the teeth is important for swallowing in the 20 subjects of this study.

It seems unusual that forces in swallowing would be greater than forces during chewing. Most swallows occurred in the intercuspal position, which is consistent with the findings of Pameijer et al.,[14] who reported that 162 of 182 swallows had tooth contact in the intercuspal position.

The sound transmission method for measuring interjaw force, which was developed as a part of this project, proved to be practical for research purposes. It seems likely that future improvements in transducer design could improve its accuracy at the higher force levels and that combining this system with jaw movement and EMG data would continue to yield important findings concerning chewing function. For future studies, it would be of interest, for example, to compare (1) high biting strength with low biting strength subjects, (2) subjects with good occlusion to those with malocclusion, (3) bruxers with normal subjects, (4) children with adults, and (5) subjects with and without abnormal swallowing habits.

CONCLUSIONS

Forces during the phase of occlusal contact during chewing and swallowing are surprisingly high (36.2% and 41%), about 40% of the subject's maximum biting force. Previous studies using transducers in fixed partial dentures measured only a portion of the total force and have given the impression that chewing forces are much less than the data reported in this study. The importance of occlusal stability in the intercuspal position is of utmost clinical significance.

Steep anterior guidance does not appear to expose the teeth to extreme lateral forces. The gliding contacts of the teeth while entering and leaving the intercuspal position have been shown to be of short duration and low magnitude when compared with the forces generated in the intercuspal position.

During chewing, the peak occlusal force occurred well after the peak EMG activity. EMG activity by itself does not directly correlate with the force generated during chewing.

The sound transmission method for measuring interjaw force during chewing, which was developed as part of this project, proved to be practical for research purposes. No intraoral devices are required, and the time relationship to force is accurate to within 15 ms.

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