Chaotic Dynamic Character of Human Chewing

Determined Using New Three-Dimensional Motion Capture Techniques

by

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Abstract

A need exists to determine the dynamic character of natural human chewing so human mandible or lower jaw biomechanics can be fully understood. No one has reported investigating the dynamic character of natural human chewing or a method to determine it. The dynamic character of natural human chewing not being known results in trial-and-error development of new therapies and products. Even more importantly, failure to understand the dynamic character of chewing results in flawed experimental design and data interpretation in studies of mandible motion. The objectives of this research were to develop a highly precise method to measure mandible motion during natural human chewing and to mathematically determine the dynamic character of natural human chewing. New techniques were employed with a high resolution motion capture system combined with a distortion minimizing attachment scheme for retroreflective markers to achieve precise measurements of mandible motion in three dimensions. Mathematical analysis of natural human chewing motion indicated that its dynamic character was chaotic. Studies involving mandible motion must take into account its chaotic dynamic character to advance knowledge of mandible biomechanics and achieve successful therapies and products.

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Chapter 1: Introduction

Human Mandible Biomechanical Mechanism and Dynamic Character

There is a need to determine the dynamic character of natural human chewing so the biomechanics of the human mandible or lower jaw can be fully understood. Natural chewing is unimpeded normal subconsciously controlled mastication. Dynamics is the study of motion of objects with the effects of forces acting upon an object and the mass of an object being taken into account. Studying the dynamics of an object increases understanding of how position, velocity, and acceleration of an object changes with time beyond just the shape of an object. No one to date has reported investigating the dynamic character of natural human chewing or a method to determine it. Knowledge of the dynamic character of natural chewing would facilitate the development of therapeutic procedures in dentistry, speech pathology, and reconstructive surgery. Knowledge of chewing dynamic character would also facilitate development of a wide variety of products including helmet chin straps and processed foods. Researchers and engineers not understanding the dynamic character of natural human chewing results in trial-and-error development of new therapies and products. Even more importantly, a lack of understanding of chewing dynamic character results in flawed experimental design and data interpretation in studies of mandible motion. The purpose of this research is to determine the dynamic character of natural human chewing. The objectives of this research are development of a highly precise method to measure mandible motion during natural human chewing and a mathematical determination of the dynamic character of natural human chewing.

To determine the dynamic character of natural human chewing one must know how the human jaws operate as a biomechanical system. The upper jaw or maxilla is fused to the skull providing a platform for the teeth of the maxilla to be met by the teeth of the moving lower jaw or mandible to produce the chewing function. The mandible is attached to the skull at the back of the mouth by the temporomandibular joints. The temporomandibular joints that attach the mandible to the skull can both act as hinges or as gliding joints for the mandible [1]. The articulations, or joints, of the mandible do not hold the mandible tightly to the skull. The connecting joint ligaments allow the mandible to move away from the skull. The joint ligaments and joint capsules guide the motion of the mandible while allowing greater motion between condyles, joint ends, and sockets than most other joints of the human body. The freedom of the mandible to move in multiple planes allows for some of the most complex movements of all the bones in the human body [2].

The loose joint connections of the temporomandibular joints mean the positioning of the mandible during chewing is mostly a function of the muscles of mastication [1]. The eight major muscles of mastication occur in four symmetric pairs on the left and right sides of the head. The muscles of mastication are the *masseter* at the rear of the cheek, the *temporalis* on the sides of the skull, and the *medial and lateral pterygoids* located between the rear of the mandible and the skull [1]. Muscles of mastication work in conjunction with other muscles of the head and neck to position the mandible to produce chewing motion.

The mandible in essence hangs from the skull in the loose temporomandibular joints and is suspended by the muscles of mastication. Being hung from the skull allows the mandible to slide right-to-left, front-to-back, and up and down. The mandible as a biomechanical mechanism can move linearly or translate along all three spatial axes designated X, Y, and Z. The hung position of the mandible allows it to rotate in three ways, lowering and raising the chin, moving the chin left and right, and twisting about the chin. The mandible is thus a mechanism able to rotate about the three spatial axes. The mechanics of the mandible can be described as moving with six degrees of freedom. Each degree of freedom is a separate translation or rotation of the mandible. The mandible, its muscles, and the temporomandibular joints are a complex biomechanical mechanism that is capable of linear and rotational motion.

The general categories of dynamic character for biomechanical systems as the human mandible are periodic, aperiodic, and chaotic. Mechanical systems with periodic dynamics repeat positions, velocities, and accelerations at regular intervals within fixed boundaries. Systems with aperiodic dynamics do not repeat and may or may not stay within certain bounds. Systems with chaotic dynamic character have positions, velocities, and accelerations that do not repeat at regular intervals but stay within complex boundaries called attractors.

The human mandible in the act of natural chewing has six degrees of freedom and exhibits complex and varied motion [2]. The more complex a mechanical system is the more likely it will have chaotic dynamic character. Given the complexity of the mandible and its associated structures as a biomechanical system and the observed complexity of natural chewing motion, the hypothesis of this research was that the dynamic character of natural human chewing is chaotic.

Natural human chewing can reasonably be assumed to represent the dynamic character of motion of the human mandible. Natural human chewing activates all the muscles of mastication that control the position of the mandible [2]. Food being crushed in chewing produces passive resistant forces on the mandible [2]. Study findings of the dynamic character of chewing should have broad application in the study of the biomechanics of the human mandible.

Literature Review

Chaos in Human Motion Studies

Studies investigating possible chaotic dynamics of human motion have not investigated the motion of the mandible. Past studies have analyzed easier to record human motions and dynamics with more readily demonstrable chaotic characteristics. Two studied human motions are the dynamic balancing of a standing person [3] and bipedal walking [4]. The presence of chaotic dynamics has also been investigated in more subtle forms of motion by comparing several types of healthy and pathological motion in humans [5]. A study of signatures indicated the dynamics of hand motion was chaotic in character [6]. Reported studies indicated that chaotic dynamics exist for human motions both large and small. Observed chaotic effects of human motion have been found to be significant [5]. Past observed chaotic effects suggest that the possible chaotic dynamics of mandible motion could also be significant.

Yamada measured and performed an analysis of the dynamic character of swaying by humans maintaining upright posture while standing [3]. The location of the center-of-pressure, the point the force of the weight of the body passes through, on the plane where the feet were situated was recorded through time by Yamada. The location of the center-of-pressure for five subjects was recorded after the subjects were told to stand still. Subjects were then told to swing their arms as if they were running but not move their legs and the location of the center-of-pressure was again recorded. The time series of the radial distance from the center of the plane to the center-of-pressure was taken as an index for the swaying body. The trajectories of the radial distance to the center-of-pressure were studied using chaos analysis which produced phase-space dimensions and Lyapunov exponents of the dynamics for the center-of-pressure movement. The trajectories were plotted in phase-space and were found to form attractors which are enclosing shapes that contain non-repeating trajectories. The Lyapunov exponents for the center-of-pressure motions were found to be positive indicating chaotic character for the dynamics of swaying [3]. The Lyapunov exponents increased in value when the subjects were swinging their arms while standing. Yamada concluded the chaotic character of the postural swaying allowed irregular body movements and influences from outside the body to be incorporated into the sway maintaining upright posture. Yamada's work demonstrated that seemingly simple human motions have dynamics of chaotic character.

Using a mathematical model for human bipedal locomotion Kurz *et al.* demonstrated chaotic dynamics can arise from biomechanically simple models [4]. The legs were modeled as two massless rods connected at the hips by frictionless hinge joints. The weight of the body becomes a mass atop the legs. During movement, the leg in contact with the ground becomes the stance leg. The torso mass forms an inverted pendulum while the leg not in contact with the ground swings freely. When the free leg contacts the ground, it becomes the stance leg and the other leg swings. The ground was given a downward slope to provide the impetus for the motion. Simulations using the equations for the simple bipedal locomotion model produced results demonstrating attractors in phase-space and positive Lyapunov exponents indicating a chaotic dynamic character for the modeled human bipedal locomotion. The chaotic dynamic character of bipedal locomotion was determined even without including complex neural and muscular effects in the model. If chaotic dynamics can arise in very simple models of biomechanical mechanisms, it is probable that the complex mechanism of the mandible would exhibit motion with chaotic dynamic character.

Stergiou and Decker investigated how variabilities in human movements are related to healthy and pathological states [5]. Healthy infants were determined to have an optimum state of variability as measured by maximum positive Lyapunov exponents in their leg motion and sitting sway. Infants with periodic or very chaotic motion dynamics were determined to be unstable in their leg motion and sitting sway. The variability in motion of human knees with anterior cruciate ligament (ACL) injuries, referred to by Stergiou as deficiencies, was determined to be lower than healthy knees as measured by Lyapunov exponents. After surgical ACL repair the variability in motion of the knees was determined to be greater than healthy knees by Lyapunov exponents. Compared to healthy knees ACL deficient knees have sub-optimum variability while ACL repaired knees had variability beyond the optimum level. Stergiou and Decker concluded that motion with chaotic dynamic character was not a source of error in biological systems but a necessary state of healthy movement [5]. Because motion with chaotic dynamic character defines healthy movement, determining if natural mandibular motion has chaotic dynamic character is essential for a full biomechanical understanding of mandibular movement.

Chaotic character was found in the dynamics of writing signatures by Rashidi *et al.* [6]. Pen tip position through time was recorded for 40 subjects performing 20 signatures each. Positive Lyapunov exponents were found for dynamics of pen tip location through time for both the X and Y directions and corresponding velocities. Full mathematical analysis provided conclusive evidence that the act of writing a signature was a process with dynamics with chaotic character. Rashidi's study of signatures indicates that even human motions considered to be small, regular, and precise have dynamics with chaotic character. Rashidi's study of signatures suggests that mandibular motion dynamics is probably chaotic in character.

Kinematic Studies of Mandible Motion

Mandibular motion has been studied from a kinematic perspective. Kinematics is the study of the geometrically possible motion of objects without the effects of force and mass being taken into account. Kinematic studies of motion of an object or of parts of a human body concern only the geometric patterns and limits of the motion not the forces acting upon the object. Kinematic motion studies investigate how the position, velocity, and acceleration of the object change with the passage of time.

Kinematic studies of the mandible have been of interest to dentists since the late nineteenth century. A goal of dentistry is to improve effectiveness of oral treatments and dental appliances. Dr. Walker of Pass Christian, Mississippi described two methods for measuring the kinematic motion of the mandible in 1896 [7]. The first method was his reproduction of a Harvard University method using fixtures to connect the upper and lower teeth to white beads that were outside the mouth and attached to the teeth by rods. The mandible was moved while a long exposure photograph was taken of the beads. The white beads traced the motion of the mandible on a photographic plate. The second method developed by Walker relied on a brass clinometer that mounted to the head. The clinometer measured the angle of the mandible and the position of the mandible condyles. Walker used his clinometer measurements to improve the function of dentures he made for his patients [7].

Research into kinematics of the mandible continued into the twentieth century using a variety of methods [8]. These studies focused on the patterns and extent of mandibular motion from an anatomical and physiological view point. The idea of the mandible as a biomechanical mechanism in motion does not appear to have been part of the researchers' experimental concept. Researchers applied direct graphing methods to create tracings of mandible motion. Photographic, cinematographic, and radiographic methods were also used to record the motion of the mandible [9]. Research findings however did not agree on the limits and patterns of mandible motion [8]. Disagreements in study results left many unanswered questions about the physiological characteristics of mandible motion.

A notable researcher who addressed questions about mandible motion physiology was Dr. Ulf Posselt of Department of Prosthetics, Royal Dental School, Stockholm, Sweden. He conducted research at the State Dental School of Malmö, Sweden in the early nineteen fifties [8]. Posselt wanted to measure the movement capacity of the mandible in the occlusal plane and the sagittal plane taking into account both movement range and direction [8]. The occlusal plane is a horizontal plane that passes through the teeth biting surfaces. The sagittal plane is a vertical plane that passes through the midline of the face dividing it into left and right halves. Posselt made maps of the limits of possible mandible motion often referred to as the envelope of motion for the mandible. Posselt mapped the motion of the human mandible by attaching a stylus to the mandible that traced on a slide. Posselt's method only traced the motion of the mandible on a two-dimensional plane. Three dimensional motions outside of the plane were not recorded. While not recording natural three dimensional mandible motion as was done in the current study, Posselt demonstrated that mandible motion could be measured through the lips.

Posselt created tracings of the motion of the mandible in the horizontal occlusal plane by mounting a device with an adjustable tracing stylus to the mandible and a wax coated slide to the maxilla or upper jaw on which the trace was recorded [8]. The stylus was held in place by a fitted plate that spanned across the inside bow of the teeth of the mandible. The wax-coated glass slide was held by a similar plate fitted inside the teeth of the maxilla across the roof of the mouth. The envelope of motion was recorded by having the subject close his mouth until the stylus and plate came into contact. The subject then moved his mandible to the motion limits in the horizontal plane. The tracing device allowed adjustment of the distance the mandible was opened during the motion tracing. Tracings of the limits of horizontal mandible motion from mandible closed to fully open were produced.

Posselt made tracings of the limits of mandible motion in the vertical sagittal plane using a stylus and wax coated plate placed outside the mouth [8]. The tracing plate hung from a rod attached to the maxilla. The tracing plate was sized to be larger than the area expected to be covered by motion of the mandible. A stylus was held by a rod attached to the mandible. The stylus pin was extended from the mandible rod to contact the tracing plate by a rubber band. The ends of the rubber band were fixed to the rod with the center of the band stretched over the blunt end of the stylus pin. Tension of the rubber band pressed the stylus against the tracing plate in the manner of an arrow in a drawn bow. Rods were mounted to the mandible and maxilla by vitallium splints molded to the teeth so that the upper and lower teeth were brought together without interference. Subjects were asked to move their mandible to the limits of its motion. Posselt studied the sagittal plane tracings of vertical mandible movement of 15 subjects.

Posselt demonstrated the accuracy of his tracing method by using X-ray measurements of mandible positions during tracing and cadaver dissections for direct measurement of bone position during tracing [8]. Tracings of mandible motion have become known as Posselt diagrams and are the basis for mapping human mandible movement. Posselt's method is limited to recording two-dimensional motion confined to a plane. Tracings from different horizontal planes can be stacked using the tracing from the vertical plane but true three-dimensional motion cannot be directly recorded. Posselt's method directly measured only one rotation of the mandible, the raising and lowering of the chin. Posselt's experimental procedures confined mandible motion to one plane and the requirement the stylus be kept in contact with the plate restricted the motion of the mandible so natural motion could not be recorded.

Posselt's methods have been improved using mechanical and electronically instrumented pantographs. Pantographs mount to the head and track the motion of the mandible by means of a mechanical connection between the mandible and recording devices [10]. While producing three-dimensional position data of the mandible, the instrumentation interferes with mandible motion of natural chewing [9]. The mechanisms of pantographs limit the motion of the mandible. Pantographs are supported by soft tissues of the head which introduce errors into the measurements recorded during active chewing. Elimination of distortions in recordings of mandible motion arising from measuring instruments was an objective of the current study.

Problems of restricted mandible motion during measurement caused by direct connection of the mandible to the recording apparatus have been mitigated by researchers using magnetic tracking devices [11]. Magnetic positioning devices measure the position of magnets attached to the teeth with an array of sensors placed near the mandible [11]. The sensors were supported by a frame that rested on the head and face of the subject which removed restrictions to the motion of the mandible [11]. However, the magnetic positioning instrumentation was supported by soft tissues of the head which lead to the introduction of measurement errors during chewing.

Another disadvantage of magnetic positioning devices was insensitivity to motions of the mandible that rotate but do not displace the magnet relative to the sensors. Measurement of natural mandible motion requires isolation of the measurement instruments from soft tissue movement and sensitivity to mandible rotations.

Measurement problems introduced when the head is used to support measurement instruments can be eliminated by using motion capture technology. Motion capture technology uses retroreflective markers or small lights to mark body landmarks and moving body segments. The marker positions are recorded using video cameras. The use of small low mass markers on the body while collecting data with a remote camera reduces errors. A simple motion capture system of two markers and one camera for recording chewing motion in two-dimensions was investigated by Pinheiro, *et al.* [12]. Pinheiro placed one marker on the forehead as a head position reference marker and another marker on the mandible to observe motion. A rigid connection was used between the mandible marker and the mandible. Pinheiro's method was insensitive to rotations of the mandible since only one marker was placed on the mandible. Pinheiro's method was a motion capture version of Posselt's method as it recorded vertical motion in the sagittal plane. The head position reference marker was held in place on the forehead with a cloth band and was used to subtract the movement of the head relative to the camera from the motion of the mandible. The use of a headband to hold the head position reference marker was a source of error because it allowed soft tissue movement to confound the recorded position data. A more complex arrangement of markers and cameras must be used than what Pinheiro used to measure natural three-dimensional mandible motion.

Motion capture technology was used by Röhrle *et al.* to record three-dimensional chewing motion [13]. Röhrle used an array of video cameras to track reflective markers on a rod positioned horizontally in front of and across the face rigidly connected to the mandible by a short rod that extended out of the mouth. The markers were placed one at each end of the horizontal rod and one in the center. The ends of the horizontal rod were slightly bent back toward the face at the halfway points between the center and end markers. Three markers attached to the mandible made recording rotations of the mandible possible. Röhrle's placement of the cameras two meters away from the markers limited sensitivity of his method. Röhrle held the head position markers in place with a head band. Movement of the head band relative to the head during chewing was observed by the authors but the movement was considered to be small enough so it could be ignored when compared with mandible displacement. Camera placement using the current study's method overcomes the limited sensitivity reported by Röhrle. Hard mounting markers to the mandible and head would eliminate errors introduced by soft tissue movement.

Furtado, *et al.* set out to record three-dimensional motion of the mandible while overcoming the problems of measuring devices that interfere with the natural motion of the mandible [14]. Furtado used a motion capture system composed of three infrared cameras and nine very light weight retroreflective markers. A single marker was rigidly attached to the middle of the incisors of the mandible. One marker was attached by adhesive to the forehead to record overall head motion. The remaining six markers were placed three to a side along the inferior edge of the mandible or lower jaw line by adhesive. The first jaw-line marker was placed below the corner of the mouth. The second marker was placed on the angle of the posterior mandible where it begins to ascend. The third jaw-line marker was placed on the skull just above the mandible condyles. The placement of the jaw-line markers on soft tissues of the head limited method accuracy. The light weight retroreflective markers did not interfere with the chewing motion but the use of a single marker rigidly attached to the mandible made rotations of the mandible undetectable by Furtado's method. Furtado's method recorded the linear displacements of the incisors in three dimensions but was insensitive to mandible rotations.

Dynamic Studies of Mandible Motion

Anderson, *et al.* investigated the effect of food morsel or bolus hardness on chewing kinematics [15]. Bhatka, *et al.* investigated the effect of bolus (food morsel) size on chewing cycle kinematics [16]. Anderson and Bhatka used the same equipment, a motion capture system with three cameras that recorded the position of light-emitting diodes. Reference diodes were placed on an eyeglass frame worn by a subject. A single marker diode was taped to the subject's chin. A single chin diode marker rendered mandible rotations undetectable. The placement of the mandible maker on the soft tissue of the chin also introduced error into the mandible position data. Anderson's and Bhatka's kinematic analysis did not extend beyond accounting for subject and treatment differences. Their motion capture system suffered from both mandible rotation insensitivity and soft tissue movement errors. Anderson's and Bhatka's motion analysis did not include any consideration of the dynamic character of the motion.

Anderson used gum with durometer readings of 440g and 670g using a type D penetrator pin [15]. Durometer hardness is the force in terms of gram weight resisting the durometer hardness tester pin penetration into the gum. Each piece of gum had a fixed mass of 2.5g and standardized size of 900 mm^3 after being forced into a purpose built mold [15]. The chewing motions of 26 subjects were recorded for the two hardness levels of gum. Anderson determined that duration of chewing did not change with increased gum hardness. Amount of mandible motion was determined to increase when the harder gum was chewed, but the shape of the motion did not change. Velocity of the mandible increased in all but the occlusal phase when the harder gum was chewed. While Anderson investigated the dynamics of the mandible in chewing his analysis did not include an analysis of the character of the dynamics.

Bhatka recorded the motion of the chin for 38 subjects while they chewed gum pieces with equal material properties and masses of 1g, 2g, 4g, and 8g [16]. Bhatka observed that the envelope of motion for the mandible increased with increasing mass of the gum piece. Shape of the mandible motion was maintained with the motion increasing in all three dimensions proportionally with increasing mass of the piece of gum. The duration of the chewing cycles did not change with a change in the mass of the piece of gum. Dynamic character determination of mandible motion was not part of Bhatka's study.

Wintergerst, *et al.* investigated the effect of bolus size and hardness on the variability of chewing cycle kinematics using a statistical analysis of the data collected by Anderson [15] and Bhatka [16][17]. The within-subject variability of chewing kinematics was determined to increase with bolus hardness and bolus size. Wintergerst speculated that placing the marker on the soft tissue of the chin could be a possible source of within-subject variability. The lowest within-subject variability was observed for a bolus weight of 2g. Wintergrest did not consider the source of the within-subject variability was an indication that chewing could exhibit chaotic dynamic characteristics. Changes in variability with changes in experimental conditions is indicative of dynamics with chaotic character which supports the hypothesis of the current study.

The effect on chewing cycles for chewing isolated to one side of the mouth was investigated by Crane, *et al.* [18]. Mandible motion in chewing was recorded using three retroreflective markers placed on an eyeglasses frame and three markers attached to an orthodontic bracket glued to the lower left canine tooth. Crane determined the duration of the phases of the chewing cycle had greater variance than the overall cycle duration. Crane concluded that human chewing is a more complex process than previously thought. While realizing that chewing was more complex, Crane did not consider that the complexity could be due to dynamics with chaotic character.

Computer Modeling of the Mandible

Peck and Hannam developed a complex computer model to investigate motion dynamics of the mandible using the anatomy of the head, neck, and mandible [19]. The model was developed to compensate for the limited experimental findings on the biomechanics of the mandible. The model was intended to overcome the difficulties of direct experimental measurement of the physical and physiological variables associated with mastication. The bones, joints, ligaments, and musculature of the human mandible were modeled using linear and nonlinear equations solved by numerical integration. The model simulated the dynamics of the mandible based on the assumptions used to develop the model. Peck and Hannam used their model to investigate the loading of the mandible joint during chewing, tensions in the muscles, mandible movement constraints, and the effect of motor activation strategies on mandible motion [19]. They did not use experimental measurements to confirm the accuracy of their complex model. They also did not state whether or not chaotic dynamics was included in their model. Their work did indicate computer modeling could be successfully applied as a tool in understanding mandible motion but actual recorded natural chewing motion needs be used to substantiate computer model simulation of mandible motion.

The scientific literature on mandible kinematics and dynamics supports the current study's hypothesis by documenting the complexity of mandible motion and observed variability in mandible motion between people. The literature did not provide conclusive confirmation of chaotic dynamics in mandible motion but suggests it. Mandible motion literature did demonstrate the need for an improved measurement method for mandible motion to test the current hypothesis. The complexities that make the motion of the mandible worthy of study make studying the mandible difficult. Testing the hypothesis that the mandible has natural chewing dynamics of a chaotic character requires overcoming the measurement difficulties encountered in previous mandible motion studies.

Chapter 2: Methods and Materials

Problems of Mandible Motion Measurement

The complex motion of the human mandible in natural chewing makes its measurement challenging. The greatest challenge in measuring the motion of the human mandible in natural chewing is getting observational access to the mandible without distorting its natural motion. The mandible is completely covered with soft tissue without any areas of relatively hard or low movement soft tissue as found when investigating motion of the limbs at the wrists, ankles, and sides of the knee. Measuring devices for chewing must either pass through the lips, be placed inside the mouth, or noninvasively penetrate soft tissues to contact or image the bone beneath. Passing devices through the lips or placing measuring devices inside the mouth can easily disrupt the natural motion of chewing. Radiographs, X-ray computed tomography (CT scan), and magnetic resonance imaging (MRI) can noninvasively penetrate soft tissue but accurately recording three-dimensional motion is difficult using radiographs and is not currently possible with CT scan or MRI.

Improved Measurement of Mandible Motion

Development of a method to measure the three dimensional motion of the human mandible was the first objective of the current study. The author previously successfully applied motion capture techniques to the study of large motions of the arms. The author designed marker placement schemes, became adept in the operation of the motion capture system, and developed data extraction C++ code to compute velocities for an investigation into the effects of wrist and forearm training on baseball bat swing speed [20]. The bat velocity motion capture methodology was refined in a second study where the relation between subject anthropometric and physiological variables and bat swing speed was investigated [21]. The author applied the previous study techniques of motion capture to recording mandible motion.

Full natural three-dimensional motion of the mandible was measured by developing new techniques for video motion capture. Video motion capture technology was developed to record motions of the human limbs and body. Motions of the limbs are readily observable and recordable by cameras while motion of the mandible is partially hidden from view. The novel method developed during this study overcame existing limitations by moving three-dimensional motion of the mandible outside of the mouth making it recordable by cameras without motion distortion. Precision of one tenth of a millimeter was achieved in recording mandible motion with the new techniques.

Using the new techniques to measure the natural three-dimensional motion of the human mandible allowed the dynamics of mandible motion to be analyzed as a biomechanical mechanism. Mathematical determination of the dynamic character of natural human chewing was the second objective of this study. Taking into account the work of previous researchers, an experimental method utilizing motion capture was devised so that full three-dimensional recording of the motion of the mandible during natural chewing could be recorded. Natural chewing is unimpeded normal subconsciously controlled mastication. Mandible marking apparatus could not interfere with either natural closing of the mandible or motion of the tongue. Elimination of error introduced by placing reference motion capture markers on soft tissue of the head was a major element in the design of the experimental methodology of this study. Motion capture technology overcomes the problems of measuring instruments attached to soft tissues of the head that cause motion distortion.

The chewing motion of a person was captured by video cameras recording the position of retroreflective markers placed on the person. The markers are small and very light weight so chewing motion was not impeded. The motion capture system computed the spatial coordinates of the retroreflective markers for each frame of video. Known positions of the markers relative to the body were used in a computer model to position the model body to fit the recorded locations of the markers. The very precise natural chewing motion data was then subjected to mathematical analysis to determine the character of the dynamics of chewing.

Motion Capture System Operating Principle

The motion of the mandible in chewing was recorded using a Motion Reality Inc. motion capture system. Motion capture is a photo-electronic method that allows highly precise measurements of human movement without effecting natural motion. An array of digital video cameras is used to record three-dimensional positions of retroreflective markers within a defined volume of space. The space in the recording fields of the cameras is termed the capture volume. The number and placement of cameras in an array can be varied to adapt the system to the characteristics of the motion to be captured. Motion is recorded by measuring the location in space of the markers for each frame of recorded video. Position measurement of markers in space was accomplished using two computers. The first computer processed the video images to isolate the markers from the rest of the image by employing the high brightness contrast of the markers to the rest of the image. The video image pixel positions of the isolated markers were then transmitted to a second computer for processing into marker locations in space. The computed marker spatial locations were then used to generate the motion of the object being studied.

An example capture volume with one marker and a four camera array is depicted in Fig. 1. The retroreflective marker appears as a bright point or star in the recording fields of the cameras. The location of the center of the star on the pixel grid of the photo-sensors of each camera is recorded by the system (Fig. 1). The positions of the cameras about the capture volume produce a unique line of sight to the marker within the volume for each camera. The lines of sight to the marker are computed to minimize the total error in the calculated point of intersection of the sight lines. The marker pixel position data from all the cameras is used at the start of the error minimization calculations. Camera data can be excluded from the calculations if it is the source of most of the calculated error. The three-dimensional coordinates of the marker are produced when the line-of-sight intersection error has been minimized. The three-dimensional location coordinates recorded for a marker are those for the center point of the marker.

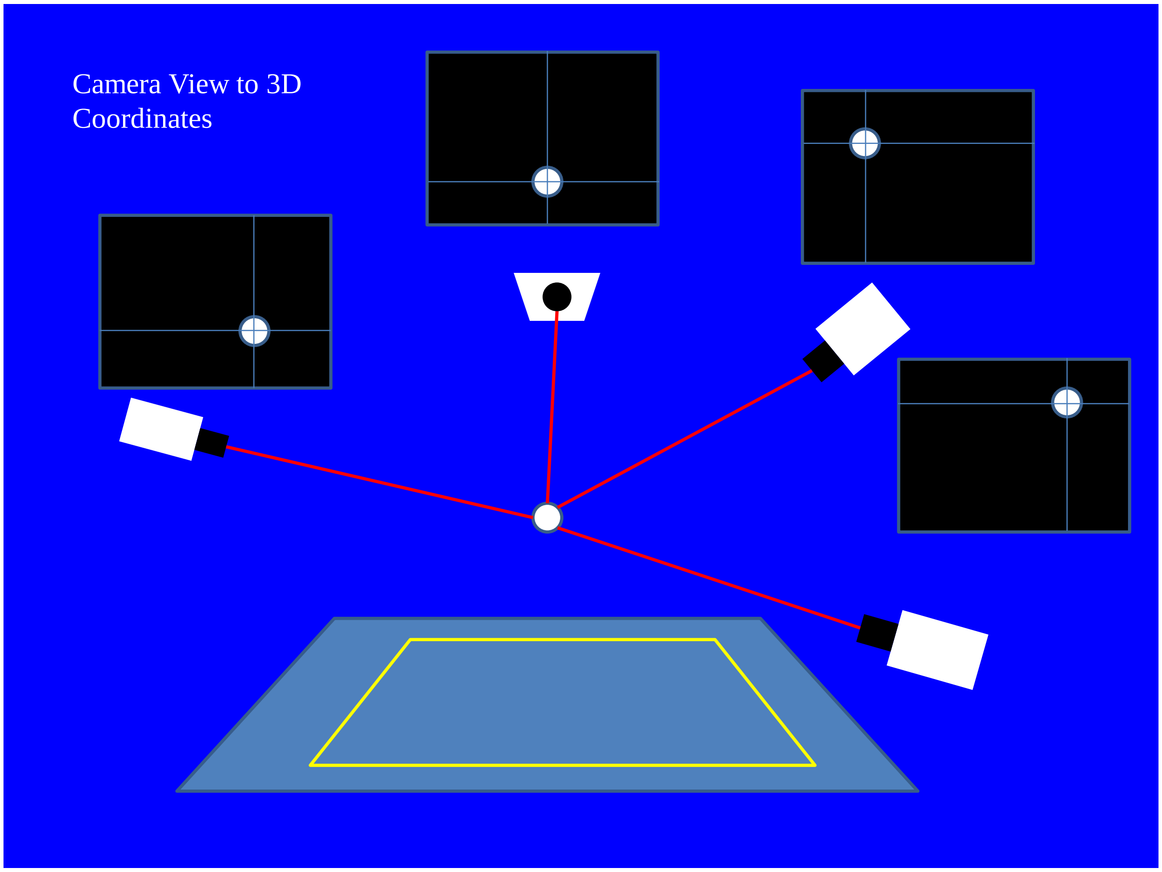


Figure 1. Motion Capture System with four camera array and single retroreflective marker with camera views and lines-of-sight intersection at single marker.

The motion capture system computes the three-dimensional coordinates of a marker within the capture volume by comparing the pixel positions of the marker using a direct linear transformation equation with eleven terms as well as one radial distortion term [23]. The constants of the recorded marker-pixel-position to marker-spatial-location transformation equation are produced from a calibration scheme using two types of recorded calibration points within the capture volume. The first type of calibration points used had predefined locations in the capture volume coordinate system. These predefined calibration points were termed known calibration points. The calibration scheme used for this study had nine known calibration points. Eight of the known points set out the corners of a cube with sides 152.4mm (6in) long with the ninth point set in the center of the top plane of the cube. The numbering of the known calibration points defined the origin and direction of coordinate axes of the capture volume. The points were numbered so the X and Z axes defined a horizontal plane in the capture volume and the Y-axis defined the vertical dimension.

The second type of calibration points used had no predefined locations in the capture volume and were termed unknown points. These unknown points were used to expand calibration to the entire capture volume. Unknown points were created by moving a single marker inside the capture volume as the system recorded the pixel position of the marker in each camera recording field at intervals of a few seconds. Several hundred unknown points are recorded to fill the capture volume with calibration points recorded by all the cameras.

The motion capture system uses the known and unknown calibration points to compute the coefficients of the transformation equation that converts the camera pixel positions of a marker into three-dimensional spatial coordinates. The calibration calculation minimizes the error between the transformation equation calculated locations and defined locations of the known calibration points. The unknown calibration points are used to minimize the sight line intersection location error throughout the entire capture volume. The calibration calculation was completed when the overall error from both the known and unknown calibration points was minimized. The calculated error was the root-mean-square difference between the measured coordinates and the transformation equation computed coordinates for the calibration markers. The calibration routine eliminates unknown calibration points with large position errors in the course of the calculation. The transformation equation error was reported when the calibration calculations were completed.

Defining the Mandible in the Motion Capture System

Preparations for capturing the motion of an object began with the definition of the motion problem being entered into the motion capture system. The problem definition established the allowed degrees of freedom, specification of the markers on the object, and an object scaling definition. The degrees of freedom of the object listed the allowed motion of the object and were referred to as system variables. The marker specification listed the number and location of markers on the object. The scaling definition allowed automatic adjustment of the generic model to specific objects captured by the system.

The motion capture system object model was used to record the motion of the object. The locations of markers placed on an object or body under study were defined in the model. The positions of the retroreflective markers attached to a body were specified in body defined coordinate systems. Body coordinate systems had their origins attached to the body. Body coordinate systems moved within the capture volume and relative to each other as permitted by the defined degrees of freedom for the bodies. The graphic image of a body was called a skin. The graphic skin was used for creation of display animation and did not play a role in the capturing of the motion. The model used for human chewing motion was composed of two rigid bodies. The first rigid body in the model was the upper jaw or maxilla. The second rigid body in the model was the lower jaw or mandible. The maxilla was defined as the root body from which the motion of the mandible was measured. The anatomical location of the origin of the body coordinate axes for the maxilla and mandible was located at the center point between the two rearmost molars on a plane with the chewing surface of the molars. The X axis points toward the left molar from the origin. The Y axis points up toward the roof of the mouth perpendicular to the occlusal plane. The Z axis points out toward the incisors from the origin (Fig. 2).

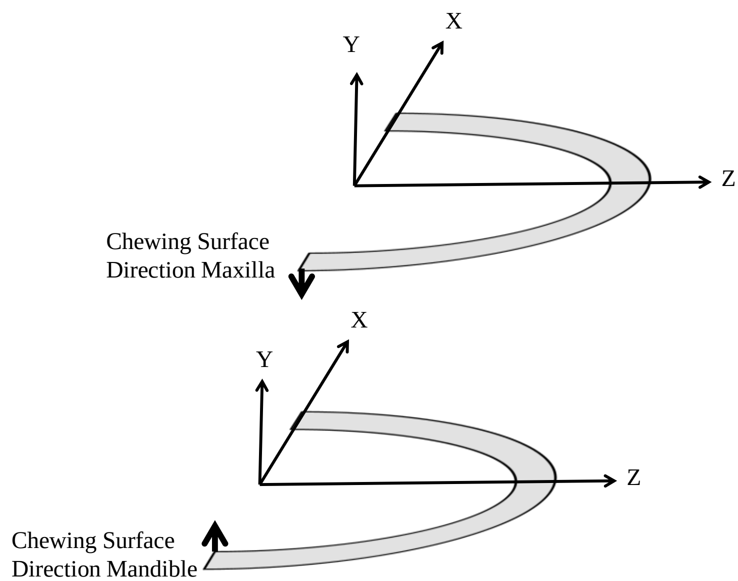


Figure 2. Body coordinate axes for the maxilla and mandible. The gray arcs are the chewing surface of the teeth.

The maxilla and mandible were each defined as having six degrees of freedom in the model. The degrees of freedom were three linear translations and three rotations. The linear translations were of the body coordinate system origins. The rotations were Euler angle rotations about the body coordinate axes [24]. In an Euler angle rotation, the orientation of the coordinate axes was changed by rotating about one axis by a given angle. The order of the rotations was important as each subsequent rotation was made about the new orientation of the coordinate axes. The order of Euler angle rotations was defined in the problem definition.

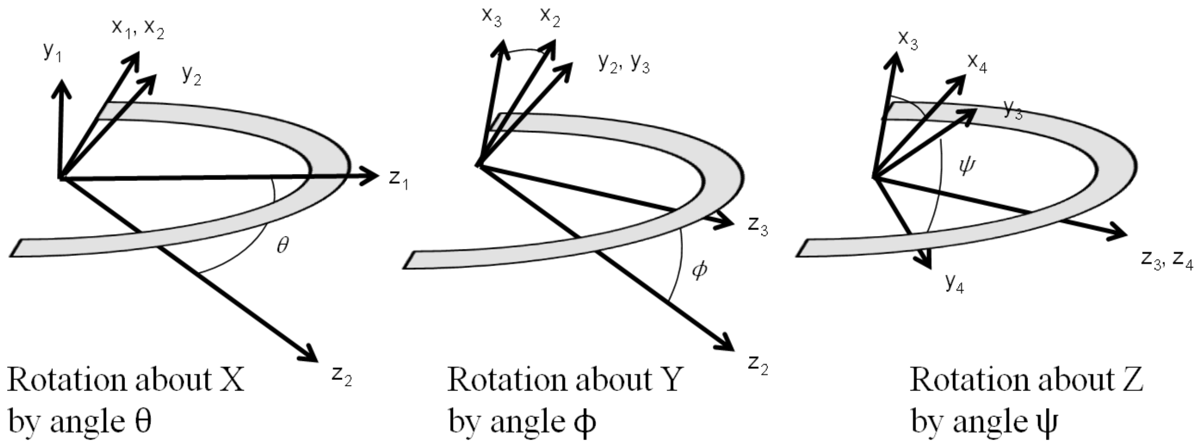


Figure 3. Euler angle rotations defining coordinate axes orientation change.

Figure 3 depicts an example of Euler angle defined coordinate axes orientation change. The first rotation is about the X axis by angle θ taking the axes from orientation 1 to 2. The second rotation is about the Y axis by angle ϕ taking the axes from orientation 2 to 3. The third rotation is about the Z axis by angle ψ taking the axes from orientation 3 to 4. The importance of the order of the rotations is seen in Fig. 3 for if the Z axis rotation had been first and the X axis rotation last the final orientation would have the Y axis pointing up in the final orientation.

Each degree of freedom was a system variable. The system variables for the maxilla are measured relative to the global coordinates of the capture volume. The system variables for the mandible are measured relative to the maxilla. Measuring the motion of the mandible relative to the maxilla allowed the motion of the mandible to be directly recorded with motion of the head within the capture volume removed from the mandible data.

System variables were each given a number within the problem definition. The variables for the maxilla were numbered one through six. The maxilla translations along the global X, Y, and Z axes were variables one, two, and three. The maxilla rotations about X, Y, and Z maxilla body axes were variables four, five, and six. The mandible translations along the maxilla X, Y, and Z axes were variables seven, eight, and nine. The mandible rotations about the X, Y, and Z mandible body axes were variables ten, eleven, and twelve. The values of the system variables were listed first then the identifying number in the data file (App. A).

The order in which each system variable was changed to fit the orientation of the bodies to the recorded marker positions was defined in the mapping file. The order was chosen so the variables with the largest expected changes in value were used first in the computations. The order of axis rotations of the maxilla in the position computations were Y, X, and then Z. The Y, X, Z rotation order made motions of the model maxilla match the relative magnitudes of the head motions of rotation, nodding, and tilting. The order of axis rotations of the mandible in the position computations were X, Y, and then Z. The X, Y, Z rotation order made motions of the model mandible match the relative magnitudes of the mandible motions of lowering and raising the chin, rotating the chin left and right, and twisting about the chin.

The scaling definition set the allowed adjustments of the marker positions relative to the body to fit the general model to actual bodies. Fixed landmarks on a study body were added to the problem definition as temporary markers. The body position within the capture volume to be used for model scaling was also set in the scaling definition. Temporary markers were placed on the body during scaling in addition to the permanent markers used during motion capture. The general model was scaled by matching the location of the scaling markers in the model to the temporary markers on body landmarks. Scaling also recorded the position of permanent markers on the body. Permanent marker positions were measured in the local coordinate system of the body. The scaling temporary markers were placed on the rearmost existent molars and the canines of each mandible and maxilla casting. The Universal Tooth Numbering System was used to note the location of the scaling markers since the rearmost existent molars varied between subjects. Canine teeth used for placement of the temporary markers were teeth numbered 6 and 11 on the maxilla and teeth numbered 22 and 27 on the mandible.

Video Images to Captured Three-dimensional Motion

All preparations for motion capture were complete once the model had been scaled to the body under study. Motion capture began with initiating recording of video camera image data. The image recording rate of the cameras for this study was 60 frames per second. The first frame of video was recorded as a complete grayscale image. The complete grayscale image allowed assignment of proper identification numbers to the retroreflective markers visible in each camera image. All subsequent frames recorded only pixels that showed the retroreflective markers. The system screened out pixels that did not reach a preset image brightness threshold. Ignoring non-marker pixels reduced the amount of data that had to be processed and stored. After video-recording was initiated the motion to be captured commenced. Recording was stopped once the motion was complete.

The recorded original data was composed of the initial full images from each camera and the marker pixel positions from the rest of the recorded motion. The author manually identified each marker with its assigned number for the model in the initial image from each camera. The motion creation processes started with identification of the retroreflective markers in a video frame using the identified markers in the initial frame. Marker identification was done automatically by a tracking algorithm that takes into account the allowed motions in the model. The accuracy of marker identification of the tracking algorithm was dependent on the distance moved by the markers in the camera views between frames of recorded video. The smaller the distance moved between frames the greater the identification accuracy. Marker misidentifications were corrected by the author.

The second part of the motion creation process fitted the permanent markers in the model to the recorded marker spatial locations. The motion creation process adjusted the orientation of the bodies in the model until the recorded marker positions and the defined model marker positions converged. Marker convergence was defined to occur when the total error between the recorded marker positions and the model marker positions was minimized. The system variables were adjusted until the position error between the model markers and the recorded markers had been minimized over all the markers. The position of the model body would then match that of the recorded body. Multiple markers on a body increased the accuracy of motion capture. The error being minimized over all the markers reduced the effect of changes in the location of any single marker on the body or relative motion between the markers. Random motion due to marker vibration was removed from body position by minimizing the error over all the markers.

Motion was recorded as a frame-by-frame set of system variable values. Variable values were linear displacements and angular orientations for each body. Linear displacements were of the origins of the body coordinate systems recorded relative to the defined reference for each of the bodies. The rotational orientation of the body was recorded using Euler angles about the local body axes. The non-uniqueness of Euler angle positions was accounted for in the next processing step.

The captured motion was formed at this point from the position and orientation of the body determined for each frame of recorded video in isolation from the other frames. Captured motion requires further processing to remove noise in the motion and mathematically allowed but physically impossible body orientations. Motion noise appears as high frequency vibration or twitching in the motion due to sudden position and orientation changes between frames. Motion noise was removed in a step termed motion refining which had three components. First, the paths of the markers in space were smoothed removing motion noise from individual marker motion. The local coordinates of the markers were optimized removing noise due to relative motion between markers on the same body. Finally, changes in body position and rotational orientation were smoothed eliminating mathematically optimized but physically impossible body orientation changes between frames.

Camera Placement and Capture Volume Properties

The motion capture system configuration used for recording human chewing utilized four cameras. Four cameras were used to ensure that all retroreflective markers would be recorded by at least three of the cameras at all times. Cameras were placed in a 90° arc centered on the medial or middle vertical plane of the head. Cameras were placed so they did not all lie in the same horizontal plane. Two of the four cameras were positioned so the lenses were approximately level with the nose of the subject. One of the other two cameras was placed at approximately 15 cm above the first two cameras while the last camera was placed 20 cm above the first two cameras. The motion capture system camera arrangement is presented in Fig. 4 with the reference position of the mandible and maxilla castings in calibration positions. The camera arrangement allowed for simultaneous recording of most of the retroreflective markers by all of the cameras during chewing. The staggered vertical arrangement of the cameras produced a line-of-sight for each camera that was spatially separate from the others which improved the accuracy of the calculated locations of the retroreflective markers.

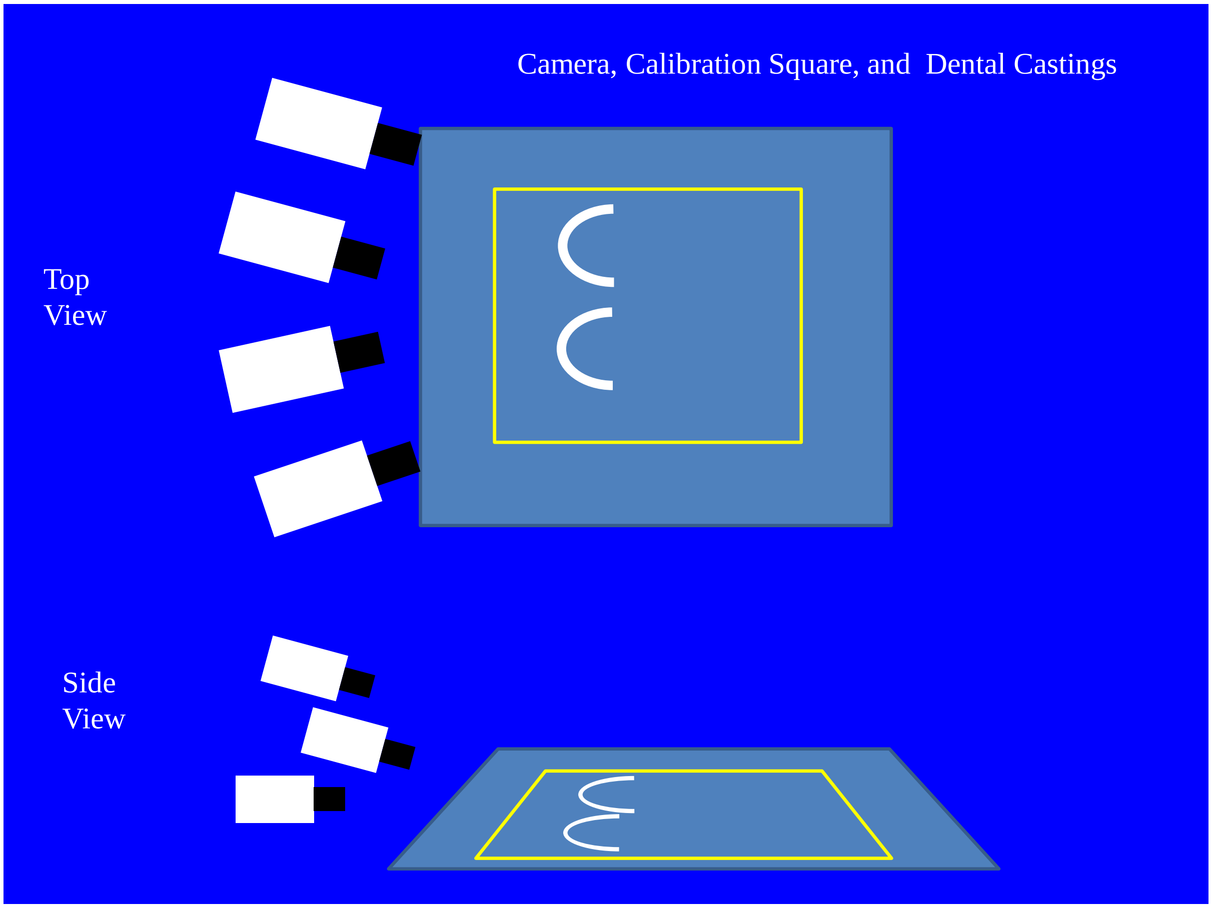


Figure 4. Chewing motion capture camera arrangement and outlines marking calibration boundary of capture volume. U-shapes are scaling positions for dental castings.

The cameras were positioned as close as practical to the subject's head, usually about 45 cm. The close positioning of the cameras produced a small focused capture volume. A small capture volume makes small motions of the markers result in large pixel position changes in the camera recordings. Motion capture system resolution was increased when the capture system was focused on a small volume. The recorded video images were 640 x 480 pixels. The width of an image was about 60 cm with the cameras placed approximately 45 cm from the head. The spatial resolution of the system was approximately 0.09 mm per pixel for the human chewing setup. The system detected the position of the center of the markers to $1/10^{th}$ of a pixel. The high spatial resolution of the small capture volume combined with the system sensitivity allowed for precise measurement of position changes in the markers to 0.1 mm. Typical calibration errors were 0.05 mm or less for the capture volume as a whole. The error value was smaller than the spatial resolution of the system.

The capture volume calibration equipment consisted of a platform mounted on a tripod and a retroreflective marker bead attached to a rod mounted on a square base so the center of the bead was 15.24 cm (6 in) above the platform (Fig. 5). The platform was marked so the marker bead could be consistently placed at the corners and center of the 15.24 cm (6 in) cube which defined the positions of the known calibration points. The platform was moved out of the capture volume when chewing captures were made. Markings were placed on the laboratory floor to insure that the calibration platform was consistently placed before the cameras.

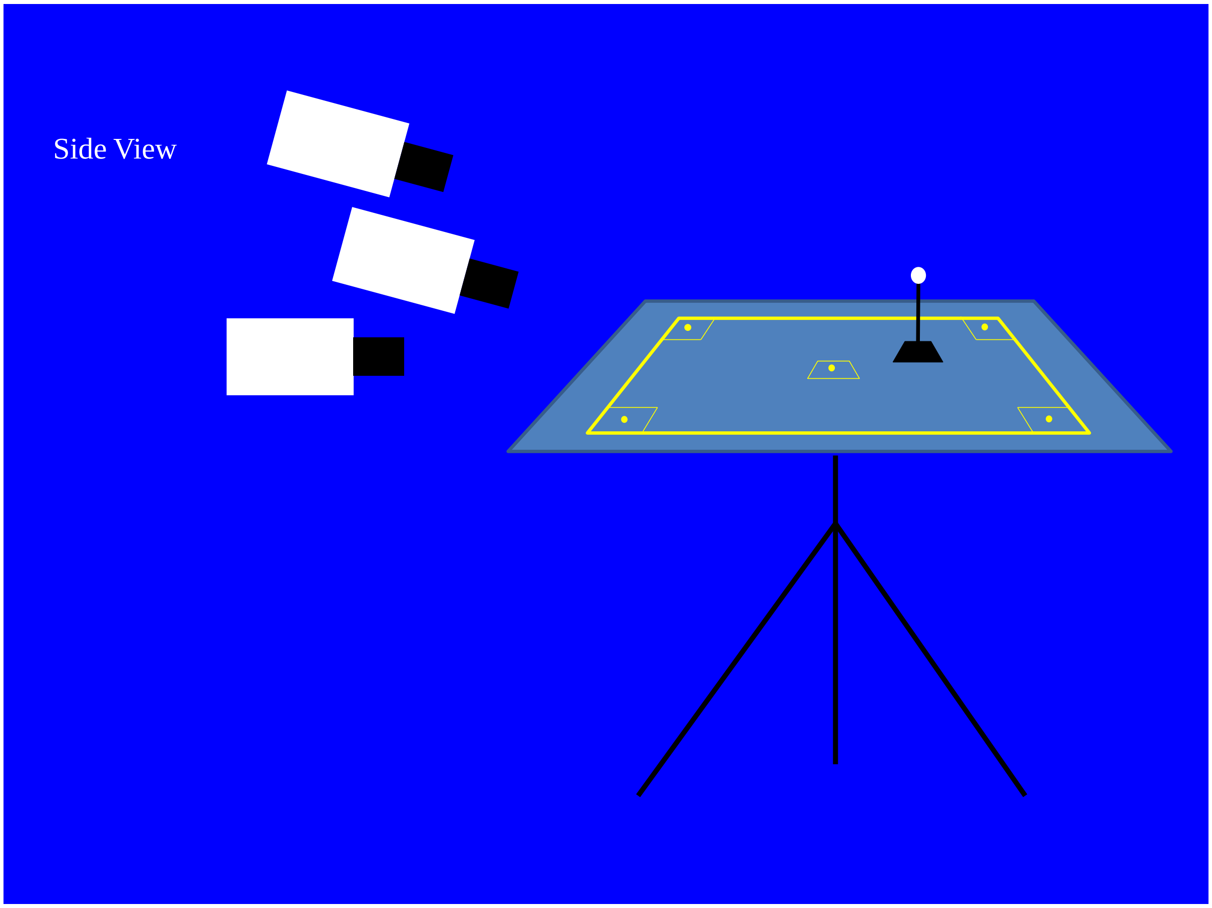


Figure 5. Chewing motion capture camera calibration apparatus for capture volume (not to scale).

Mandible Marking Apparatus

A motion capture recording of the full three-dimensional orientation and motion of an object required the object to have at least three non-collinear markers. The non-collinearity was required for rotation of an object to be detected. A motion capture system cannot detect rotation of individual markers because rotations about the center of a marker produce no pixel position changes in video images. The more markers on an object the more accurately the model of the object can be fitted to the actual object position.

The markers for the mandible and maxilla were mounted on modified Hawley orthodontic appliances designed by the author (Fig. 6). Hawley orthodontic appliances were chosen because of the properties of positive locking to the teeth and not interfering with the teeth contacting during chewing. The markers were connected to the rigid structures of the maxilla and mandible which greatly reduced motion measurement errors. Measurement errors were introduced into the studies discussed in the Literature Review section by placing markers on soft tissues. Hawley orthodontic appliances are commonly referred to as retainers. The modified retainers were easily and precisely fitted by subjects which consistently positioned the retroreflective markers relative to the teeth.

The modifications made to the Hawley orthodontic appliances for the study were the addition of five wires welded perpendicular to the metal bows of each retainer which rested against the outside of the upper and lower incisors, Universal Numbering System tooth numbers 7-10 and 23-26. Placing motion capture markers on ends of the wire extensions allowed the markers to be rigidly attached to the mandible and maxilla while residing outside the lips. Motion capture markers consisted of a wooden bead covered in retroreflective tape placed on the end of each wire. Markers mounted on wires away from the teeth magnified the motion of the mandible and maxilla by simple leverage. Small rotations of the maxilla and mandible produced easily detected displacements of the markers on the ends of the wires. Resting the lips on the wires damped wire vibration during mandible motion.

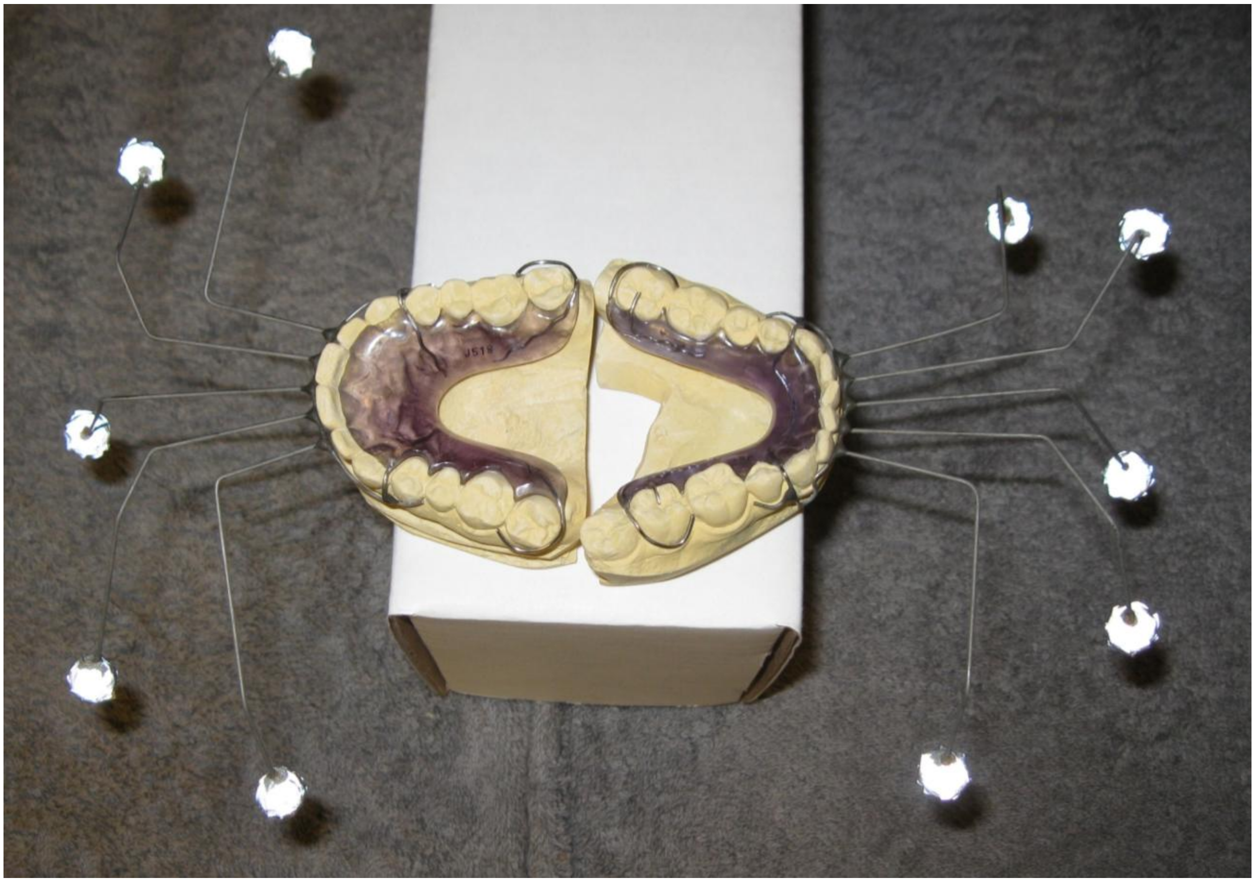


Figure 6. Modified Hawley orthodontic appliances mounted on dental castings.

Five markers were attached to each of the retainers to optimize accuracy of model fit, detectability of all rotations, full marker visibility in all cameras, and complexity of marker identification. More markers increase fit accuracy but also reduce the visibility of the markers in the camera recording fields with some markers eclipsing others. Eclipsing of markers, *i.e.* markers being hidden by other markers, can result in marker misidentification during the motion capture process. Marker attachment wires were bent so retroreflective marker beads would be separated in three-dimensional space (Fig. 7). Markers being separated in three-dimensional space improved the visibility of each marker and reduced possible eclipsing of the markers. Three-dimensional marker separation also enhanced the sensitivity of the motion capture system to detection of rotations of the mandible. Configuration of the retroreflective markers varied slightly between subjects.

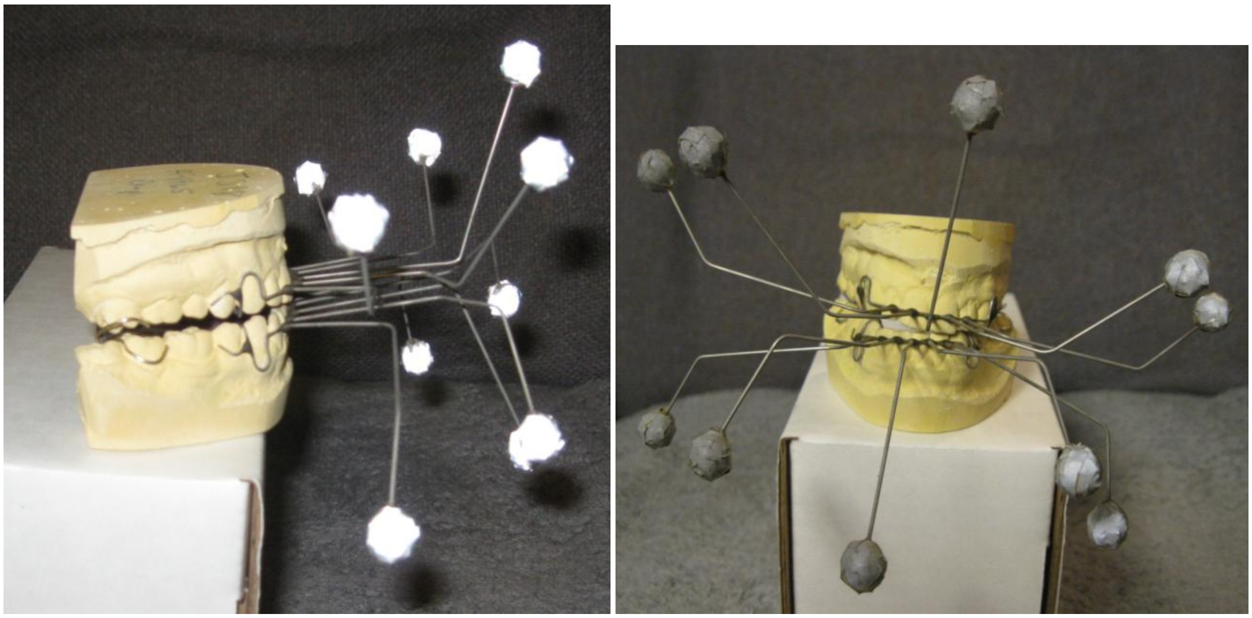


Figure 7. Modified Hawley orthodontic appliances mounted on dental castings in natural chewing orientation showing marker spacing.

Chaos Analysis Software

The Contemporary Signal Processing for Windows version 1.2 (cspW) chaos analysis software package made by Applied Nonlinear Sciences, LLC/Randle Inc. was used for the dynamic analysis of captured motion in this study. The cspW chaos analysis software package algorithms and their use are explained by Abarbanel [22]. Chaos analysis with cspW software produced the Lyapunov exponents and associated chaos analysis parameters for captured human chewing motion. Captured three-dimensional motion data was converted with an author-written C++ program (App. B) to meet the requirements of the cspW software.

The author written data conversion program extracted one-dimensional motion data of a point on the mandible where the top edges of the middle incisors, teeth numbers 24 and 25, met.

The position and Euler angles of the mandible were converted to maxilla Y-axis positions of the incisor-edge-meet point using rotation matrix calculations for each frame of video. The Y-axis positions values were then divided by the length of the mandible measured from a line connecting the back edges of the rearmost molars to the top edge of the middle incisors. The maxilla Y-axis position divided by the mandible length nondimensionalized the data allowing direct comparisons between subjects with different sized mandibles. The final operation performed by the data extraction program was the expansion of the number of data points by linear interpolation to 10,000. The expansion of the number of data points was required to use the cspW algorithms.

Food for Recorded Chews

The foods used during the capture of human chewing motion were ripe bananas, shortbread cookies, and sirloin steaks. The foods were chosen as representatives of the three major mechanical property food groups, soft, crunchy and chewy. Bananas are easily mashed and offer little resistance during chewing. The mechanical property of bananas is described as soft. Shortbread cookies are brittle and crumble offering only momentary resistance during chewing. A food with such mechanical properties is commonly referred to as crunchy. The sirloin steak cooked to beef-well-done temperature is springy and offers considerable resistance to being broken down during chewing. Steak requires many chewing cycles to be rendered to a swallowable state. The mechanical properties of steak are commonly described as chewy.

The foods were all cut into cubes and used while at food-safe cold temperature. The banana cubes ranged in weight from 3 g to 8.1 g. Size variation in the banana cubes allowed for the comparison of study results with results reported by other researchers. Shortbread cookie cubes ranged in weight from 2.8 g to 5.1 g. Cube mass variation was due to the crumbly mechanical nature of shortbread cookies. The steak cubes ranged in weight from 2 g to 4.8 g. The range in steak cube size allowed for comparison of the current study results to results reported by other researchers.

Human Research Participant Recruitment

The investigation of the motion of the mandible in natural chewing required the observation of human subjects in the act of chewing. The participation of human subjects in this research was approved and overseen by the Auburn University Human Research Protection Program, Auburn University, Auburn, Alabama, USA. The research protocol was submitted to the Institutional Review Board for the Protection of Human Subjects in Research at Auburn University for approval before participation of human subjects in the research (App. C). The Board approved the submitted protocol for 15 human subjects. Fifteen subjects, 8 male and 7 female were recruited between the ages of 18 and 35.

All subjects signed an informed consent letter approved by the institutional review board. The informed consent letter explained the experimental protocol and listed possible consequences. Under Alabama law two consent letters were created; one for adults and one for participants below the age of 19. Subjects under 19 years of age required the permission of a parent or guardian in addition to their agreement. Subjects were to be volunteers solicited from the student body of the university.

Each volunteer was examined by a licensed dentist contracted to aid in the research project. To participate in the study, each subject was required to have full and normal dentition. Subjects were informed of any results of the dental exam that, in the opinion of the dentist, would require dental treatment. Dental castings of the upper and lower teeth of selected subjects were made by the dentist. The dental castings were sent to a dental laboratory so modified Hawley orthodontic appliances could be made for each subject.

Each subject was given a unique alphanumeric identifier which was used for record keeping and to identify any personalized experimental apparatus. Subject identifiers were simplified for clarity in reporting study results. The subjects were divided by sex and then numbered sequentially. The eight male subjects were referred to as male subject 1, male subject 2, male subject 3, and so forth to male subject 8. The seven female subjects were referred to as female subject 1, female subject 2, female subject 3, and so forth to female subject 7.

Motion Capture Procedure for Recording Chewing

The human chewing motion capture procedure began by focusing the cameras on the capture volume and adjusting the lights to provide optimum illumination of the retroreflective markers in the recording fields of all cameras. The motion capture system was then calibrated by capturing the known and unknown calibration points. Calibration points were then used to generate coefficients of the pixel-position-to-spatial-coordinate transform equation.

The modified Hawley orthodontic appliances of a subject were placed on the dental casting of the subject. The dental castings of the mandible and maxilla with teeth pointing up were placed side by side on the calibration platform in the capture volume (Fig. 4). Temporary scaling markers were placed on the canine teeth and rearmost molars of the mandible and maxilla. The motion capture system scaling routine was activated recording the location of the temporary markers on the mandible and maxilla and the permanent markers attached to the orthodontic appliances. Markers were manually identified in the recorded images and a unique computer model scaled to fit the jaws of the subject was prepared. Local coordinates of the permanent markers relative to the maxilla and mandible were then available for motion generation from captured video images.

The above procedures were used to prepare for motion capture of the chewing of all 15 subjects. Subjects were seated in a chair so the markers of the maxilla and mandible were centered in the capture volume. The subject was given the orthodontic appliances and told to place them on their teeth. The subject was instructed to move their mandible to acclimate to having the appliance in their mouth and the marker support wires touching their lips. While the subject was acclimating to the appliances, the foods were cut into cubes and the weight of each cube was recorded. The banana and steak cubes were skewered on toothpicks to facilitate handling. Chewing and motion capture procedures were explained to the subject.

Once the subject indicated they were ready to begin a motion capture session, they were given a cube of food. They placed the food into their mouth and paused until the motion capture system began recording. The subject chewed the food cube until it was broken down to the point they swallowed it. After swallowing, the subject indicated to the researcher that the food had been swallowed and the motion capture recording was stopped. The subject was asked if they would like to rinse their mouth and were given a short rest period (about 2 minutes) before chewing the next food cube.

Subjects were recorded chewing at least five cubes of each food type. The order foods were presented in was banana, cookie, and finally steak. Food order was intended to help acclimate the subject to wearing the orthodontic appliances while chewing. Food order meant the easiest to chew food was first and the food requiring the most chewing was last. It was assumed by the author that the more practiced the subject was with the appliances the more natural the chewing motion. After the last food cube had been swallowed, the subject removed the appliances and the investigator cleaned, dried, and stored them with the subject's dental castings.

After the chewing motion data had been recorded for all subjects, the motion capture system motion creation procedures were performed. The markers were manually assigned their identification numbers in the first recorded frame of video. The motion creation program using automatic marker tracking was then run to create the original motion of the mandible and maxilla. The automatically produced motion was then viewed by the investigator to check for marker misidentification. After the original motion was manually checked, the motion refinement program was run to remove noise from the motion. The frame-by-frame motion data was then rendered to its final form (App. A) and could be displayed as an animation.

An animation was produced by placing a simple graphical representation of the teeth onto the models of the mandible and maxilla. The maxilla was set as fixed in the animation so only the relative motion of the mandible was displayed. A visual tracking point was set along the edge of the teeth at the point the middle incisors meet on the mandible. The trajectory of the tracking point as it moves in three-dimensions was displayed along with the graphic of the teeth. The trajectory of the tracking point formed a three-dimensional Posselt diagram of human chewing (Fig. 8). Any point on the mandible could be used as a tracking point. The meeting point of the middle incisors, teeth numbers 25 and 24, was chosen to permit comparison of study trajectories to Posselt's original diagrams.

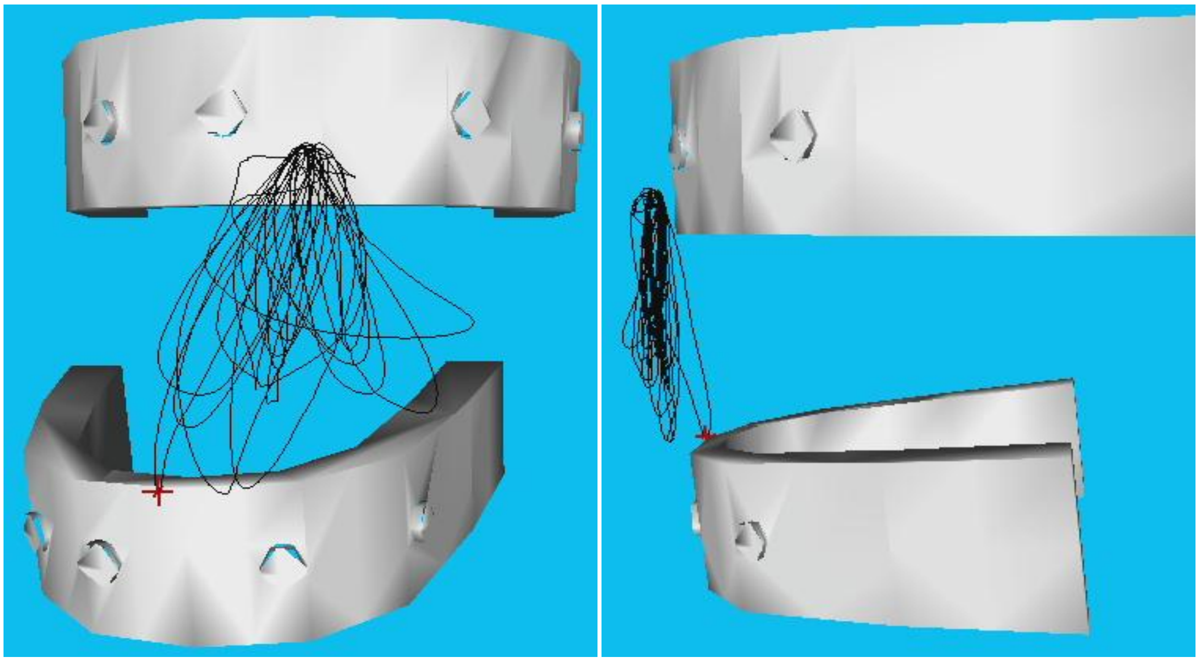


Figure 8. Three-dimensional Posselt diagram formed by trajectory tracing of meeting point of the middle incisors.

The mandible motion at this point completed the motion capture process. All further processing and analysis was done outside of the motion capture system. The movement of the meeting point of the middle incisors was computed from the full three-dimensional motion data of the mandible. Each degree of freedom of chewing motion had to be investigated individually to use the cspW chaos analysis software. The investigator made the assumption that the degree of freedom with the largest changes in value over the course of a chew would be the most likely to show chaotic behavior. A chew for this study was the recorded motion from the time when mandible motion began until the broken down food morsel was swallowed. The Y-axis displacement of the mandible was observed to have the greatest change during the course of a chew. The Y-axis displacement of the meeting point of the middle incisors relative to the maxilla thus became the focus for the analysis of the dynamic character of chewing motion.

Processing Chewing Motion Data for Chaos Analysis

Before the cspW software could be used, displacement data had to be extracted from the captured three-dimensional human chewing motion of the mandible. Extraction of the displacement data was accomplished using an author-written C++ program (App. B). The data processing program extracted the Y-axis displacement relative to the maxilla at the point on the top edge of the teeth where the middle incisors meet on the mandible. The Y-axis data extraction calculations started with the linear displacement of the mandible as a whole. The extraction program then used transformation matrices to transform the Euler angles recorded by the motion capture system into displacements along the maxilla Y-axis. The linear and Euler angle displacements were then added together.

A 10,000 data point sample was required by the cspW software. Each food chew varied in duration between subjects and food types so data sets varied in the number of recorded points. The number of data points for an extracted Y-axis chewing displacement was increased to 10,000 by linear interpolation between recorded data points. Linear interpolation was chosen as the expansion method to minimize data distortion. The time interval between recorded data points was $1/60^{th}$ of a second because the cameras used had a frame rate of 60 Hz. The recorded mandible motion did not have a high velocity so the Y-axis displacements between recorded data points were small. The assumption of linear motion on the Y-axis between the recorded data points was thus considered reasonable due to the small distance between data points.

The expanded data set was nondimensionalized by dividing all Y-axis displacement values by the length of the mandible when measured from the front of the middle incisors to the back of the rearmost molars. Nondimensionalized Y-axis displacement values allowed for comparisons to be made between the subjects. The nondimensionalized Y-axis displacement data set was then written to a file that began with identifying information on the subject, food, and chew number.

Chaos Analysis of Chewing Motion Data

Expanded and nondimensionalized Y-axis displacement data sets were analyzed by the cspW chaos analysis software. The cspW software generated the Lyapunov exponents that described the chaotic character of the chewing motion. The cspW software uses four steps to generate Lyapunov exponents. The data is first entered into the cspW program from the expanded data file. The number of global dimensions in state space required to analyze the data are computed from the data set (App. D). State space is a mathematical space containing the variables defining the dynamic state of the system. The number of dimensions was extracted from the data set by the changes in value with time of the data points. The local state space dimensions for the data were then computed using the global dimensions and data set (App. D). The number of global and local dimensions set the parameters of the Lyapunov exponent algorithm. Finally, the Lyapunov exponent algorithm was used to compute the Lyapunov exponents for the Y-axis chewing data (App. D). Computation of Lyapunov exponents marked the end of data processing. Each captured chewing motion was processed in turn which produced 231 Lyapunov exponents in all. Each of the 15 subjects had their chewing motion captured for multiple morsels for each of the three food types.

Graphs of the phase space trajectory of the Y-axis chewing data were prepared by plotting the Y-axis displacement vs. the Y-axis velocity. The Y-axis velocity was calculated numerically using a central difference scheme. The phase trajectories were smoothed for display by using a spline plotting to remove artifacts in the velocity derived by the finite difference approximation of the time derivative.

Chapter 3: Results and Discussion

Captured Motion of the Mandible in Chewing

The position and orientation of the mandible during chewing was recorded in three-dimensions from initial food cube position to swallowing. During the recorded chewing, the subjects brought their lips into contact with the projecting wires of the marker apparatus. Active closing of the lips onto the wires minimized the effect of the presence of the wires on the chewing to no more than impolite chewing with slightly parted lips for the largest observed mouth opening. Liquids were not part of any of the food morsels so the slight parting of the lips did not cause the subjects to deviate from natural chewing of the morsels. Contact between the apparatus wires and the lips helped to damp out vibrations of the wires that would have appeared as noise in the captured motion.

The greatest observed mandible motion was the vertical displacement of the chin. The second greatest motion in magnitude was side-to-side displacement of the chin perpendicular to the medial plane. Traces of the motion of the point where the top edges of the middle incisors meet produced Posselt diagrams in three-dimensions for chewing from initial position of the food cube to swallowing of the bolus. Examples of the relative magnitudes of mandible motions in Posselt diagrams during chewing are presented in Figure 9.

The number of chewing cycles increased with increased resistance of the food cubes to being broken down to a swallowable state. Banana food cubes required the fewest chewing cycles, the cookie cubes were next, and the steak cube required the most cycles. The actual number of chewing cycles depended on the subject and the initial size of the food cube. Each subject had their own unique set of conditions for when a food cube had been chewed enough to swallow. The number of chewing cycles varied by subject even with food cubes of the same size and type. Larger food cubes were chewed for more cycles before being swallowed.

Three-dimensional Posselt diagrams show a variety of shapes and displacement magnitudes between subjects, food types, and food cubes of the same type. Figure 9 presents examples of Posselt diagrams for three chews representative of the general patterns seen in the recorded chews. Male subject 4 cookie chew 1, female subject 2 steak chew 2, and female subject 3 cookie chew 5 were chosen for the clarity with which their Posselt diagrams illustrated the general patterns. Some subjects kept the chewing movement symmetric and near the medial plane (Fig. 9a). Other subjects horizontally displaced their mandible across the width of the mandible during chewing (Fig. 9b). In a third group the mandible trajectories resided entirely on one side of the mandible (Fig. 9c). Some subjects repeated the same trajectory pattern throughout chewing while others showed great variation in chewing path from cycle to cycle.

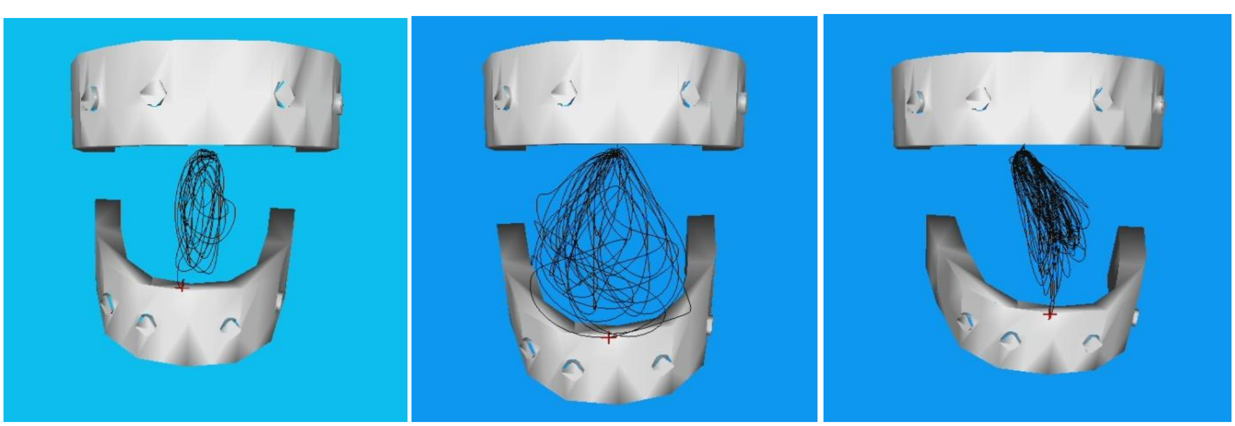


Figure 9. Front views of 3-dimensional Posselt diagrams (left-to-right) for (a.)male subject 4 cookie chew 1, (b.)female subject 2 steak chew 2, and (c.)female subject 3 cookie chew 5.

The variability seen in the Posselt diagrams does not limit direct comparison between chews to gross displacements and qualitative measures. The extraction and nondimensionalization of the Y-axis displacements relative to the maxilla of the point on the top edge of the teeth where the middle incisors meet on the mandible for each chew allows for a quantitative analysis of the character of the motion. Each captured chew can be characterized by analyzing the extracted Y-axis displacements. Figures 10a, 10b, and 10c show the Y-axis displacement plotted with time for the male subject 4 cookie chew 1, female subject 2 steak chew 2, and female subject 3 cookie chew 5 from Posselt diagrams (Fig. 9a, 9b, 9c). A comparison of the cookie and steak chew plots in Fig. 10 reveals that at the study capture rate of 60 frames per second the brittle fracture behavior of the cookie is not resolved. If resolved, the brittle fracture would appear as a pause in the motion as the force produced by the muscles of mastication on the cookie increased to the point it fractures then there would be a sudden jump in position of the mandible. Pause-jumps do not appear in the cookie plots (Fig. 10a and 10c) and look similar to the steak plot (Fig. 10b). Faster frame capture rates should allow for the rapid high acceleration mandible motion of brittle fracture of crunchy foods to be investigated. At the frame capture rate used in the current study, the very short motions caused by brittle fracture would be most likely be indistinguishable from noise in the recordings. The indistinguishability of brittle fracture accelerations from noise would not have an effect on data analysis for dynamic character of chewing motion.

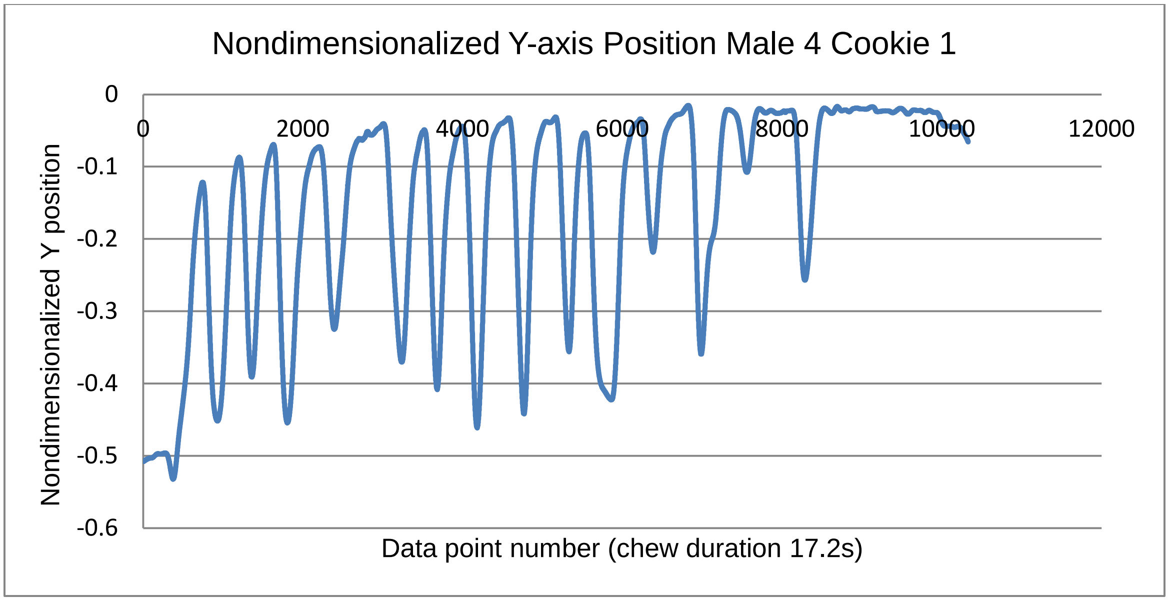


Figure 10a. Nondimensionalized Y-axis position data of male subject 4 cookie chew 1 ready for chaos analysis. Y-axis position plotted versus data point number.

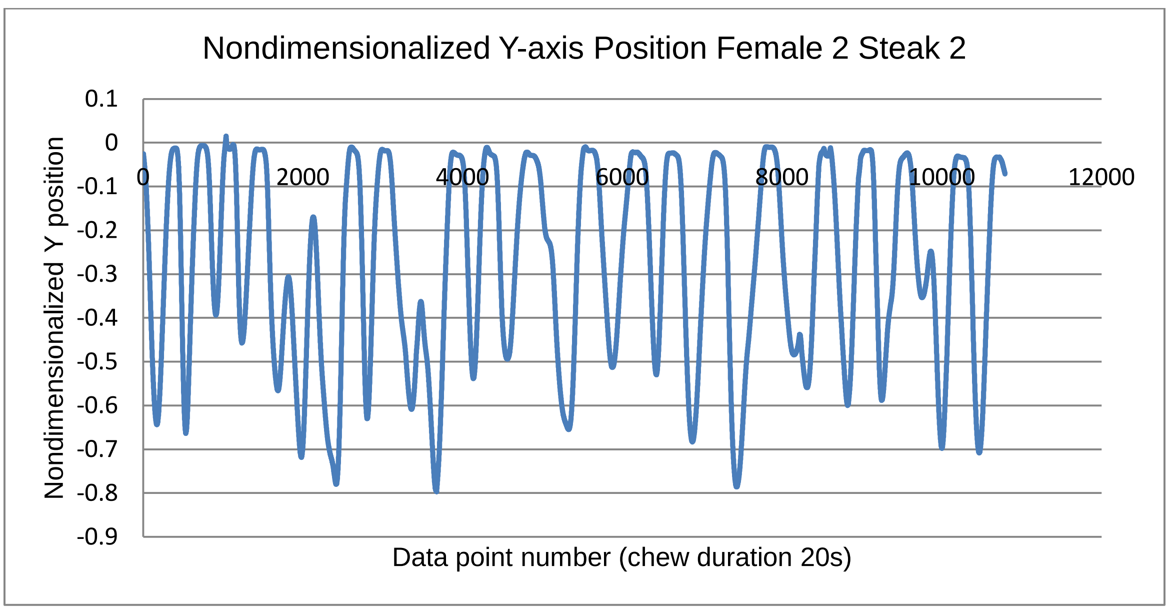


Figure 10b. Nondimensionalized Y-axis position data of female subject 2 steak chew 2 ready for chaos analysis. Y-axis position plotted versus data point number.

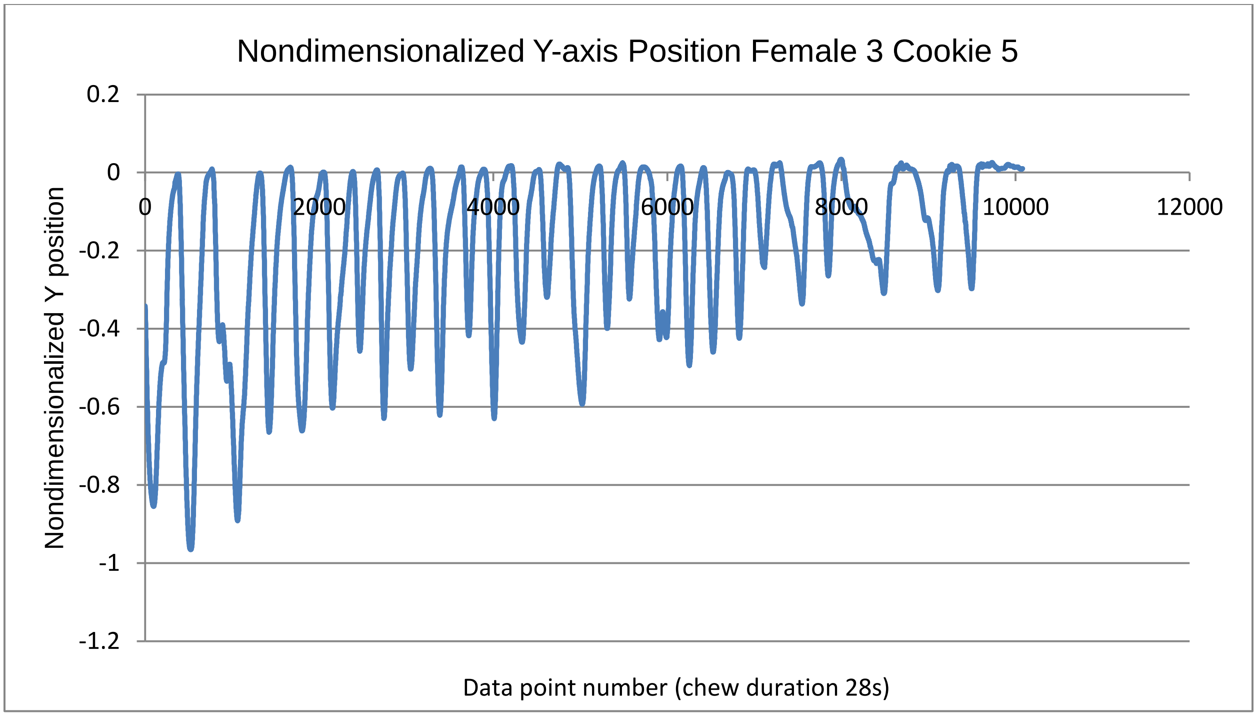


Figure 10c. Nondimensionalized Y-axis position data of female subject 3 cookie chew 5 ready for chaos analysis. Y-axis position plotted versus data point number.

Chaos Analysis of Mandible Chewing Motion

Phase Space Diagrams

Chaos analysis of the chewing data began by plotting Y-axis displacement versus Y-axis velocity to create phase-space diagrams. Phase-space is a mathematical space with the axes being the motion variables. Phase-space diagrams were created by plotting points using the displacement and velocity measured at the same moment in time as the coordinate values for the data points. Phase-space trajectories for the motions were formed when the phase-space points were connected with a smooth curve in the diagrams.

The phase-space trajectories for the Y-axis motion depicted in Fig. 9 of the chews for male subject 4 cookie chew 1, female subject 2 steak chew 2, and female subject 3 cookie chew

5 are presented in Fig. 11. The chew phase-space trajectories show chaos attractor behavior in that they stay within an enclosing shape but do not follow a single repeating path. Comparing the enclosing shapes and closeness of the trajectories in the phase-space diagrams produces a qualitative measure of the dynamics of the chewing motion. The phase-space diagrams show that the chewing motion dynamics are compact in phase-space indicating that the dynamics can have chaotic character. If the dynamics of the motion had periodic character the phase-space diagrams would be closed curved figures. Phase-space trajectories of simple periodic motion form simple closed figures as a circle or ellipse. Periodic motion trajectories retrace exactly the same path as time progresses. Aperiodic motion produces a phase-space diagram without any repeating patterns or enclosing shape. Aperiodic motion trajectories form open curves.

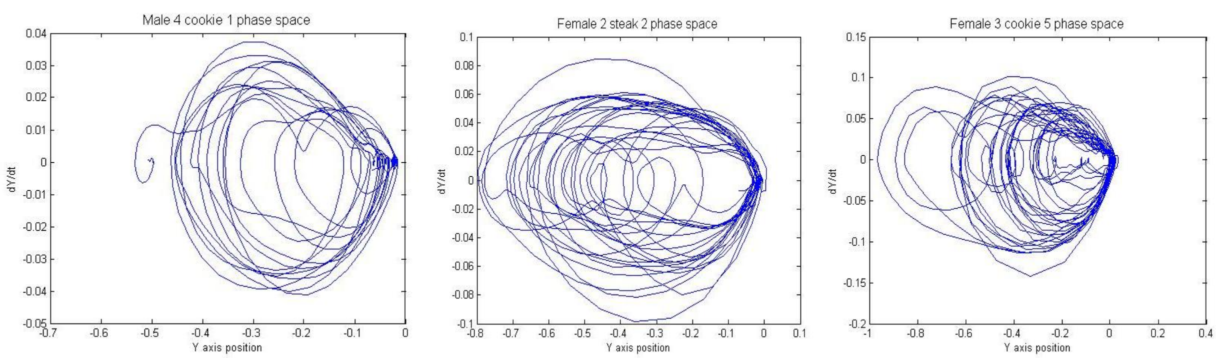


Figure 11. Phase-space trajectories of Y-axis motion for (left-to-right) (a.)male subject 4 cookie chew 1, (b.)female subject 2 steak chew 2, and (c.)female subject 3 cookie chew 5.

Quantitative Chaos Analysis by Lyapunov Exponents

The quantitative analysis of motion dynamics of the Y-axis displacement was done using the cspW chaos analysis program. The cspW program produced a set of Lyapunov exponents for the extracted Y-axis displacements for each captured chew. The value of the greatest positive Lyapunov exponent produced from the Y-axis displacement data of each chew indicated the dynamic character of the chewing motion so the greatest positive exponent was the only exponent considered in the following analysis of Lyapunov exponents. The value of the greatest positive Lyapunov exponent is referred to as the maximum Lyapunov exponent in scientific literature dealing with chaos phenomena [22]. A value of greater than zero for the greatest positive Lyapunov exponent indicated the dynamics of chewing motion had chaotic character. The greater the positive value of the greatest positive Lyapunov exponent the more chaotic the character of the motion dynamics. The greatest positive Lyapunov exponents for captured chews ranged from 0 indicating the chew was periodic in character to 5.3 indicating the chew was chaotic in character. The greatest positive Lyapunov exponent produced for all the recorded chews had a value of 11.64 and was for banana chew 2 by male subject 4. The value of 11.64 was twice that of any other recorded chew and was more than three times the next greatest value for male subject 4 banana chews so it was considered an outlier. The 11.64 value was not used in the computations of the average greatest positive Lyapunov exponents or ranges of the greatest positive Lyapunov exponent values. The averaged values of the greatest positive Lyapunov exponents for each of the subjects are plotted in Fig. 12. The variability in the greatest positive Lyapunov exponents of chews is readily apparent. The variation exists across all subjects and within and between the male and female groups. The greatest positive Lyapunov exponents were used in all of the following analyses. The Lyapunov exponents referred to henceforth will be the greatest positive exponent for each chew determined using the cspW program.

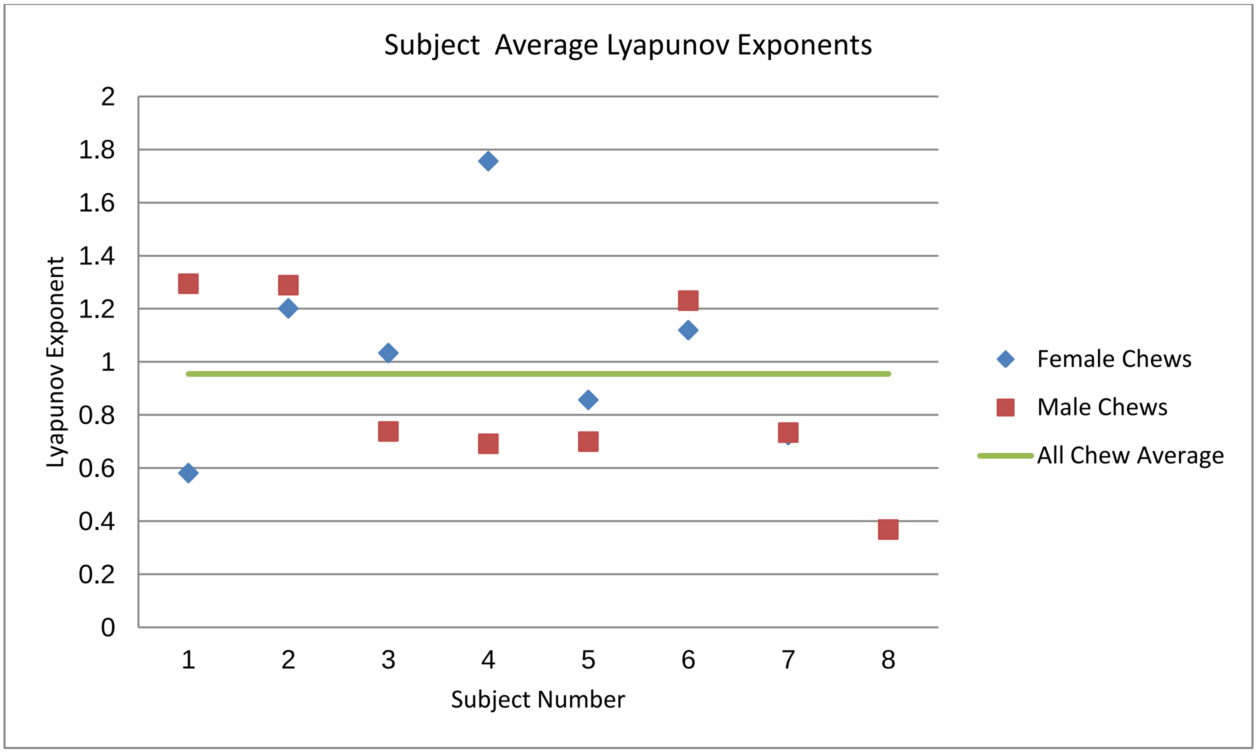


Figure 12. Average of greatest positive Lyapunov exponents of each subject and an all chew average computed using all recorded chews for the subjects.

The average Lyapunov exponents for the male subjects by food type are plotted in Fig. 13. The values of the average Lyapunov exponents for the different food types did not follow any consistent pattern for the male subjects. The greatest average Lyapunov exponents for male subjects 1, 2, 3, 7, and 8 were for cookie chews while the greatest for male subjects 4 and 6 were for banana chews. The greatest average Lyapunov exponent values for male subject 5 were recorded for both steak and cookie chews. The average Lyapunov exponents were compared across the food types for the male subjects showed that male subject 8 had the least chaotic chewing motion. The average Lyapunov exponents across food types were the greatest for male subjects 1 and 2 which indicated that they had the most chaotic chewing motion. The values of the Lyapunov exponent averages for food types compared to the overall average changed with each male subject.

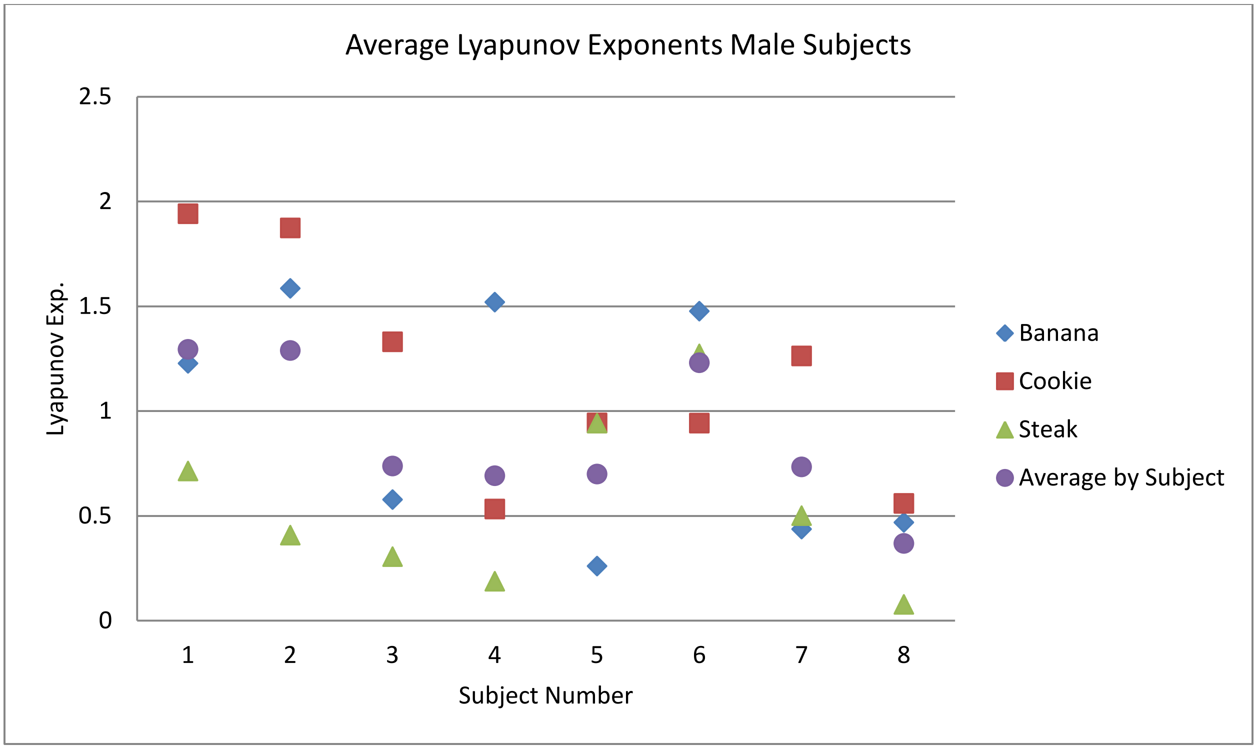


Figure 13. Average male subject Lyapunov exponents for each food type by subject and overall average by subject.

The average Lyapunov exponents for the chews of the female subjects revealed no pattern as with the male subjects (Fig. 14). The greatest average Lyapunov exponents for female subjects 1, 3, 5, and 6 were for the cookie chews. The greatest average value for female subject 2 was for banana, and for female subjects 4 and 7 was for steak. The average Lyapunov exponent across all food types for female subjects was the least for female subject 1 and the greatest for female subject 4. Female subject 1 had the least chaotic chewing motion and female subject 4 the most chaotic chewing. Similar to male subjects, female subjects overall Lyapunov exponent averages varied as did food type averages.

Significant variations were seen in the values of the average Lyapunov exponents across subjects chewing the same type of food in both the male and female groups. Values of the average Lyapunov exponents by food types compared to overall averages were also seen to vary significantly within and between the male and female groups. The presence of significant variation was consistent with the dynamics of chewing motion being chaotic in character. Dynamic systems with chaotic character show sensitivity to small changes in initial conditions. Each subject had their own set of initial conditions for each chew.

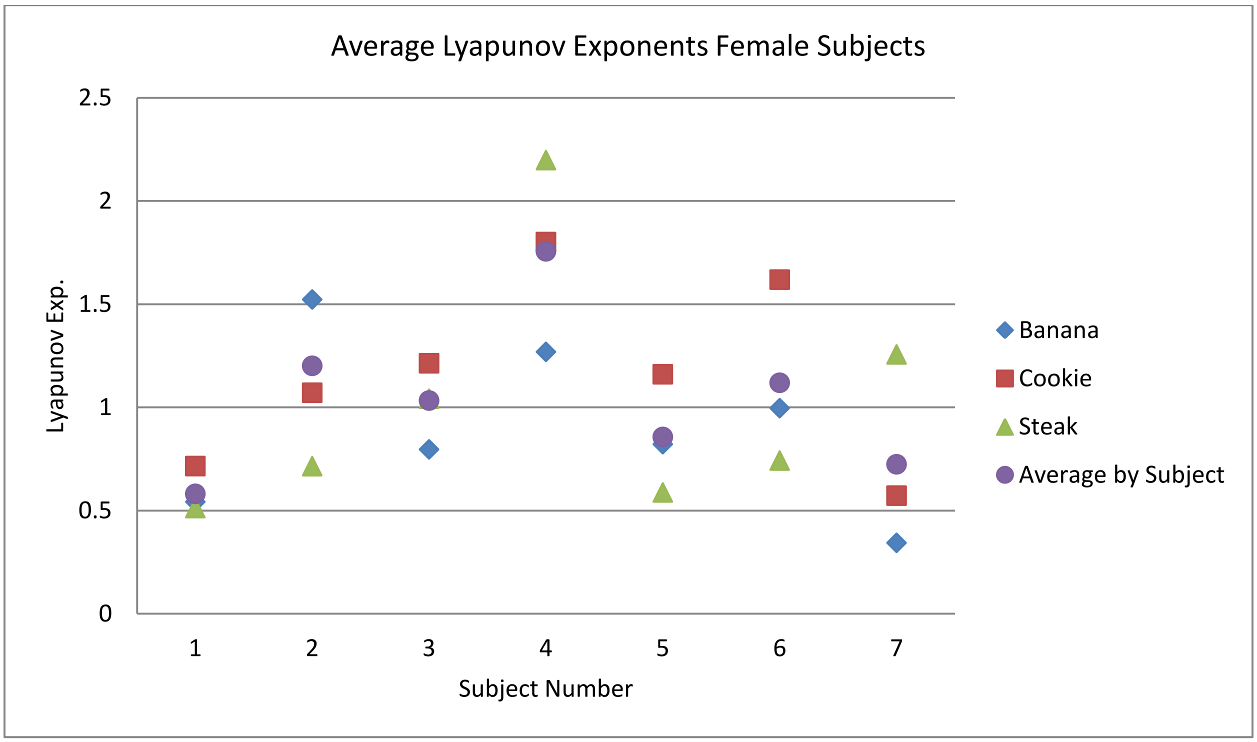


Figure 14. Average female subject Lyapunov exponents for each food type by subject and overall average by subject.

Variation between subjects in average Lyapunov exponents occurred for all food types. The food type with the least variation between subjects was a soft food represented by banana. Figure 15 shows that the average Lyapunov exponents ranged in value for banana chews from 0.26 to 1.58. Average banana chews range in dynamic character from almost periodic to chaotic. The variation in average Lyapunov exponents between male and female groups was negligible for banana chews. A male and a female subject both had an average Lyapunov exponent just greater than 1.5 (male 2 and female 2) for the most chaotic banana chews. Likewise, a male (male 5) and a female (female 7) had the least chaotic banana chews with average Lyapunov exponents near 0.25. The banana chew Lyapunov exponent value for female 7 was 0.1 greater than male 5. The average Lyapunov exponent for all the subject banana chews was 0.92.

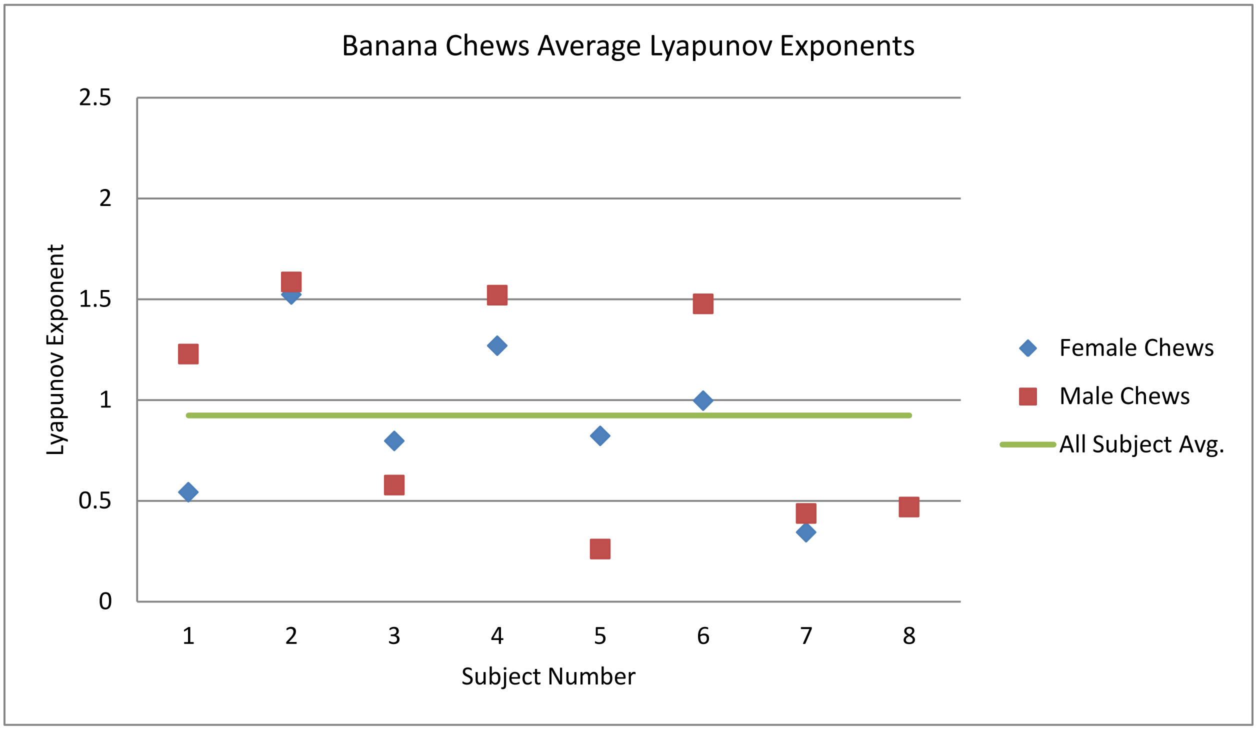


Figure 15. Banana chews average Lyapunov exponents by subject and all subject average.

The values of the average Lyapunov exponents for cookie chews fell between those for banana and steak (Fig. 16). The average Lyapunov exponents for the cookie chews ranged from 0.53 to 1.94. The average Lyapunov exponent for all the cookie chews was 1.17. The cookie chews all had Lyapunov exponent values indicative of motion dynamics with chaotic character. The male chews for cookies showed slightly greater range in Lyapunov exponent values than did female chews for cookies. The variation in Lyapunov exponent values for cookie chews within the male and female subjects groups was approximately the same. Neither males nor females overall had cookie chew dynamics more chaotic in character than the other. Variation in average Lyapunov exponents between subjects for cookie chews indicated that the chewing motion dynamics was chaotic in character.

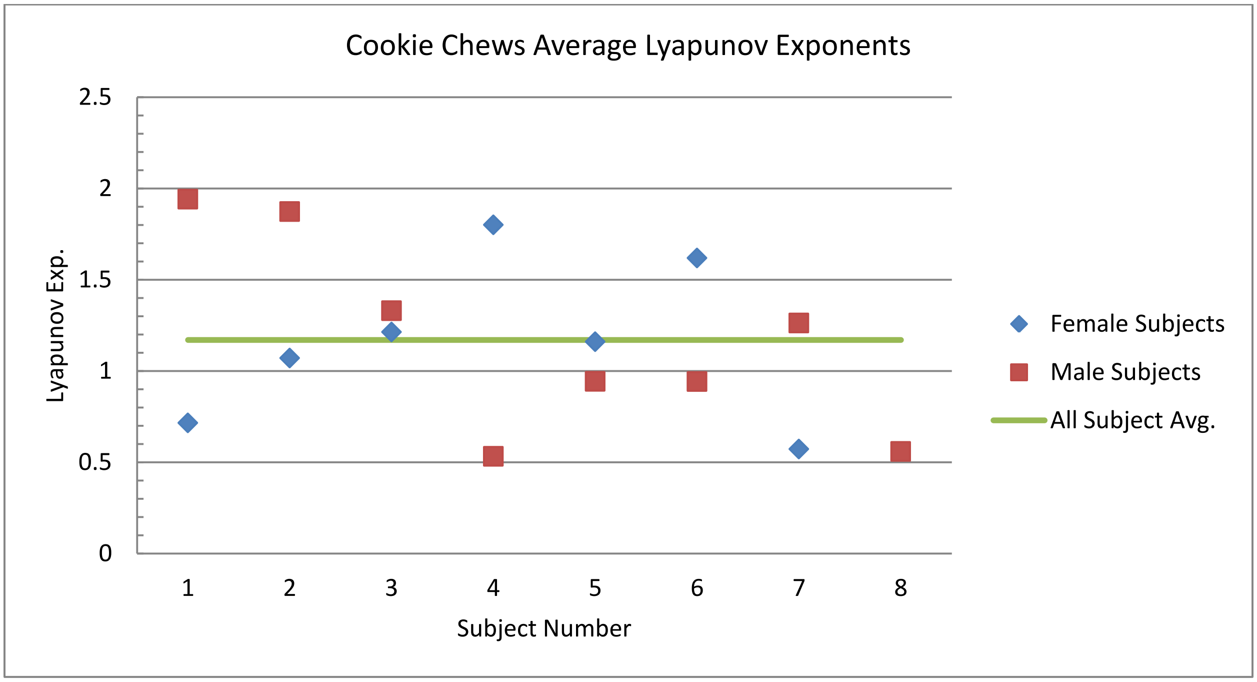


Figure 16. Cookie chews average Lyapunov exponents by subject and all subject average.

The greatest variation in average Lyapunov exponents occurred for the chewy food type represented by the sirloin steak. The average Lyapunov exponents for the steak chews ranged from 0.08 to 2.2 (Fig. 17). The motion dynamic character of the steak chews range from almost periodic to the most chaotic of all recorded chews. The greatest value for average Lyapunov exponents for steak chews was 2.2 by female subject 4. The least value of average Lyapunov exponents for steak was 0.08 by male subject 8. When female subject 4 was excluded, the variation in value of the average Lyapunov exponents for all subjects was similar to that for banana and cookie chews. The variation in Lyapunov exponent values for steak chews indicated the chaotic character of the chewing motion. The average Lyapunov exponent for steak chews for all subjects was 0.76.

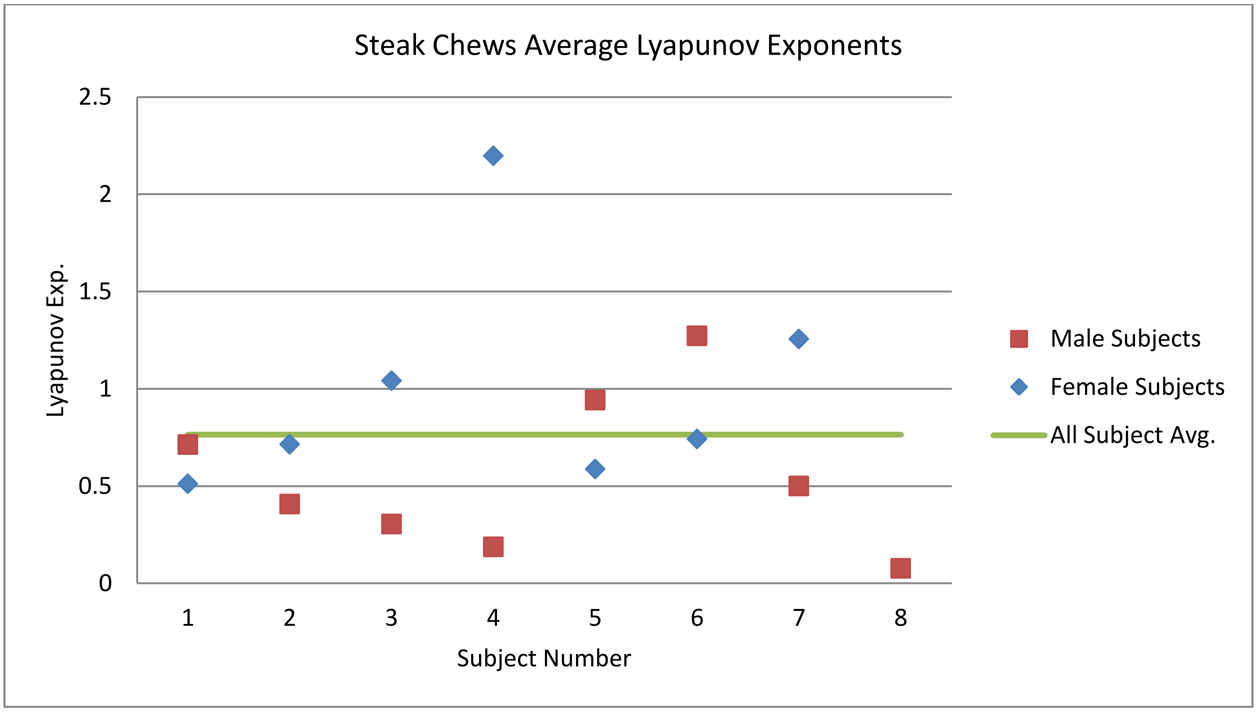


Figure 17. Steak chews average Lyapunov exponents by subject and all subject average.

The all-subject-average Lyapunov exponents provide a measure of the magnitude of chaotic character of the chewing motion for different food types. The food type with the most chaotic chewing dynamic character was the crunchy represented by a shortbread cookie with an all-chews-average Lyapunov exponent value of 1.17. The second most chaotic character chewing motion was measured for the soft food type represented by banana with an all-chews-average Lyapunov exponent value of 0.92. The motion with the least chaotic character occurred with the chewy food type represented by steak with an all-chews-average Lyapunov exponent value of 0.76. The number of chews necessary to reduce a food to a swallowable bolus did not correlate with magnitude of the chaotic character of the chews. A correlation occurred between measured chaotic character and the mechanical properties of a food type. Cookies would undergo the greatest change in mechanical properties during chewing from its initial state of brittle solid to swallowable bolus.

Lyapunov Exponent Ranges by Food Type and Subject

Variability in Lyapunov exponent values occurred for chews of the same food type by the same subject. The magnitude of variation in the value of the Lyapunov exponents changed with subject. The range in value of the Lyapunov exponents for the banana chews of the male subjects is shown in Fig. 18. The greatest recorded Lyapunov exponent value for male subject banana chews was 3.5 by male subject 4. Male subject 4 also exhibited the greatest range of exponent values for banana chews of approximately 3. Male subject 1 had the least range of Lyapunov exponent values for banana chews at approximately 0.8.

Male subjects 3, 5, 7, and 8 all had banana chews with Lyapunov exponents of zero (Fig. 18). A zero value indicated a periodic dynamic character for the chewing motion. The finding of periodic dynamic character in some chews does not contradict that the mandible motion had chaotic dynamic character. Chews showing periodic character demonstrated that initial conditions existed that minimized chaotic character of mandible motion. Changes in dynamic character from periodic to chaotic occur in simple mechanical systems such as a forced pendulum and electronic circuits [25] [26] (App. E) The range of Lyapunov exponents for male subjects 3, 5, 7, and 8 also included chews with Lyapunov exponent values greater than zero indicating banana chews with motion dynamics of a chaotic character. The range of Lyapunov exponents for male subjects 1, 2, 4, and 6 had lower limits of approximately 0.5 or greater indicating all their banana chews had motion dynamics of a chaotic character. Small changes in food cube size and conditions at the beginning of each banana chew resulted in measureable and for some subjects large changes in the Lyapunov exponents produced. Sensitivity to initial conditions is a hallmark of systems with motion dynamics of chaotic character. The variation observed in the range of Lyapunov exponents for male subject banana chews also supports that motion dynamics of chewing is chaotic in character. Variation in performance is expected between subjects in human biomechanics research. Subjects with similar performance levels should have similar results but the large variations seen within and between subjects for banana chews was further indication that chewing motion dynamics is chaotic in character.

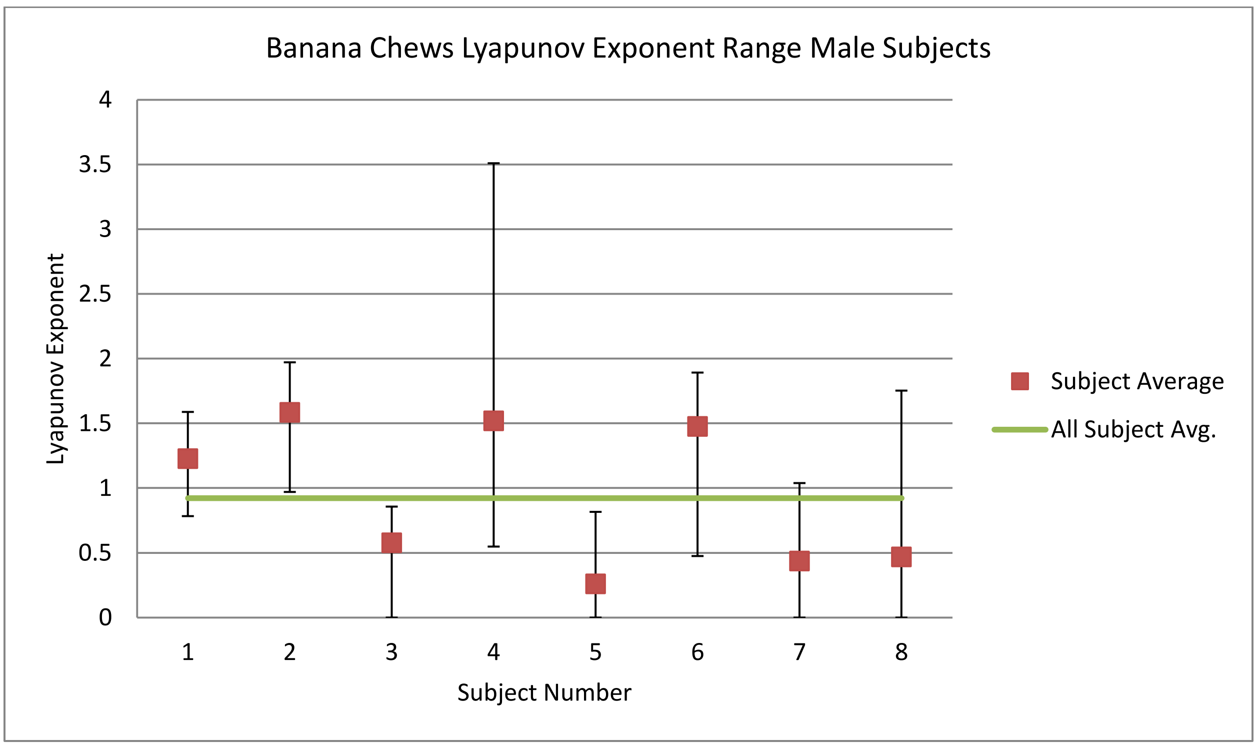


Figure 18. Male subjects banana chews Lyapunov exponent value ranges by subject and all subject averages.

The banana chews of the female subjects had slightly greater variation in Lyapunov exponents than the male subjects. The greatest range in Lyapunov exponents for female banana chews was 0 to 3.2 observed for female subject 2 (Fig. 19). Female subjects 1, 2, 4, and 7 each had one banana chew that produced Lyapunov exponents of zero indicating dynamics of a periodic character, but female subjects 1, 2, and 4 also had banana chews that produced Lyapunov exponents of approximately one and greater indicating dynamics of a chaotic character. Female subject 7 had the least range of Lyapunov exponents 0 to 0.51 of all subjects for banana chews. Female subjects 3, 5, and 6 had Lyapunov exponents with value range minimums of approximately 1 or a little less for banana chews. Subjects 3, 5, and 6 had all banana chews indicative of dynamics of a chaotic character.

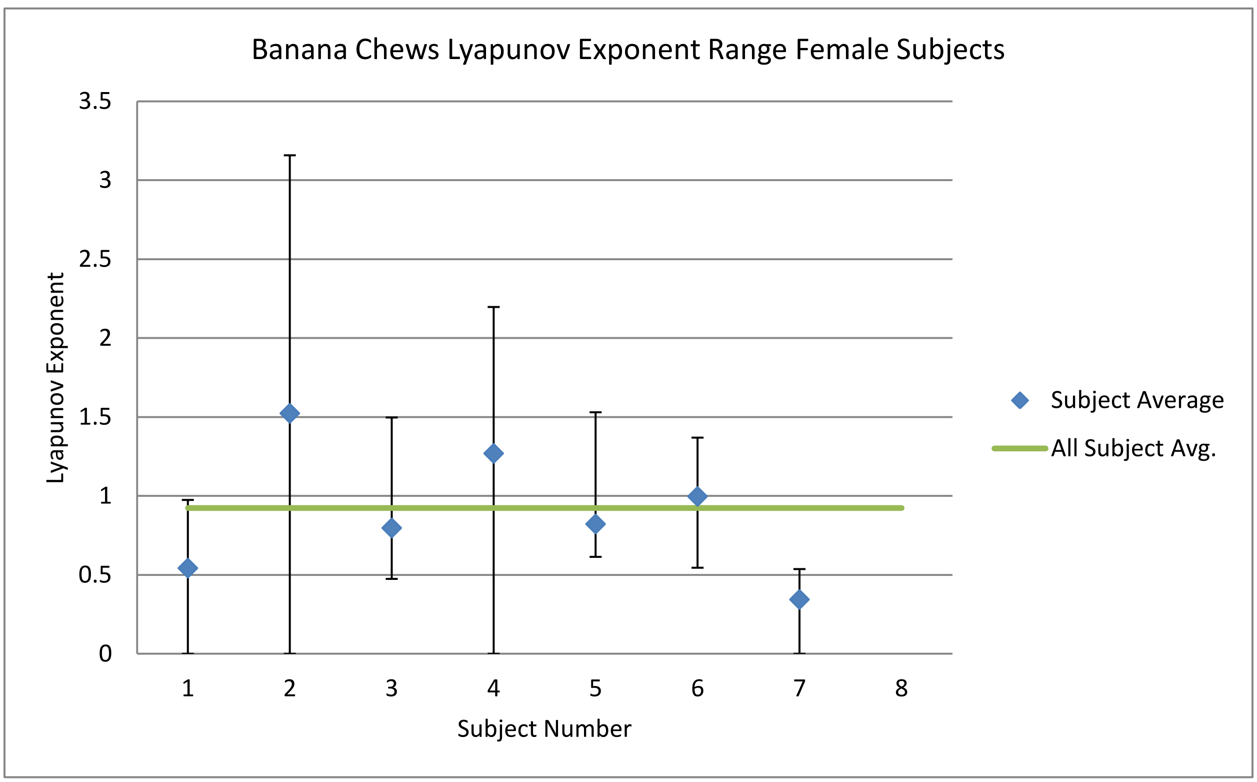


Figure 19. Banana chews Lyapunov exponent value ranges by female subjects and all subject average.

The range of Lyapunov exponent values was greatest for cookie chews by male subjects. Male subject 1 had cookie chews with a Lyapunov exponent range of 0.95 to 5.3 (Fig. 20). Male subjects 1, 2, and 3 cookie chews all had minimum Lyapunov exponents greater than 0.5. Male subjects 4 through 8 cookie chews had Lyapunov exponent minimums of zero. Male subject 7 cookie chews had a range of Lyapunov exponents as great as that for all other male subject banana chews. Male subjects 4 through 8 had cookie chews with dynamics ranging in character from periodic to chaotic. Male subjects 1, 2, and 3 cookie chews all had Lyapunov exponents greater than 0.5 indicating dynamics of chaotic character. The variation in Lyapunov exponent values between the male subjects for cookie chews supports the chaotic character of the dynamics of the chewing motions.

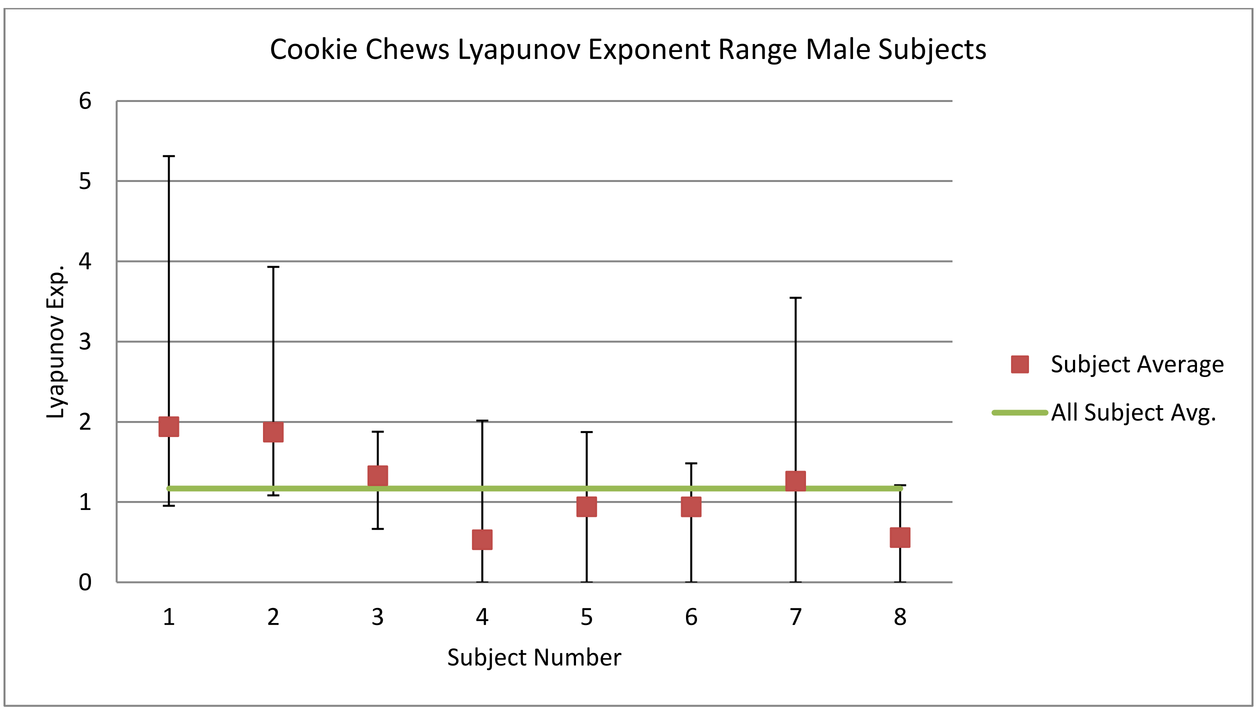


Figure 20. Cookie chews Lyapunov exponent value ranges by male subjects and all subject average.

The female subject cookie chews ranged from 0 to 3.9 in Lyapunov exponents which exceeded that for the banana chews of all the other subjects (Fig. 20). Female subjects 1, 2, 5, 6, and 7 had minimum Lyapunov exponents of zero indicating cookie chews with dynamics of a periodic character but they also had cookie chews with Lyapunov exponents of 1 or greater indicating chewing dynamics of a chaotic character. Female subjects 3 and 4 had all cookie chews with Lyapunov exponents greater than 0.5 indicating that all their chews had dynamics with chaotic character. The variation in Lyapunov exponent ranges supports the dynamics of the cookie chews being of a chaotic character.

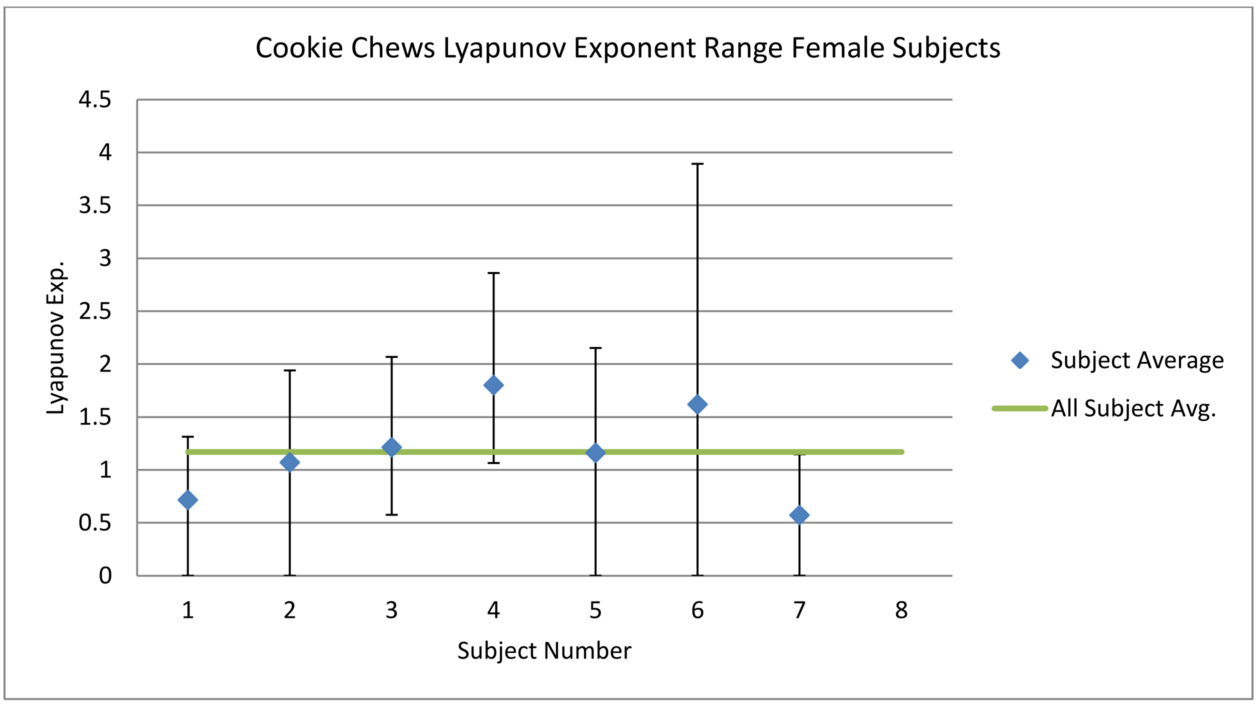


Figure 21. Cookie chews Lyapunov exponent value ranges by female subjects and all subject average.

The male subject steak chews had the smallest range of Lyapunov exponents of all the chew sets. Male subject 5 had steak chews with the largest range in Lyapunov exponent values, 0 to 1.5, for male steak chews (Fig.22). Male subject 8 had the smallest range 0.45 in Lyapunov exponents of the male steak chews. The steak chews of male subject 8 had the smallest range in Lyapunov exponents of all recorded chews, 0.39. All male subjects except male subject 6 had steak chews with zero as a minimum Lyapunov exponent. Steak chews had the most periodic character dynamics of all male subject chews. The range variation of Lyapunov exponents for steak chews between male subjects was the smallest for all male subject chews. Even with the small variation in Lyapunov exponents for the male subject steak chews, all male subjects had chews with Lyapunov exponents greater than zero indicating chewing dynamics of chaotic character. The chewy nature of the steak is the likely source of the high incidence of periodic character dynamics and small range in Lyapunov exponents. The mechanical properties of the steak undergo small changes for each cycle of the chewing motion. Many chewing cycles are required to breakdown the steak, thus initial conditions for sequential chewing cycles are similar.

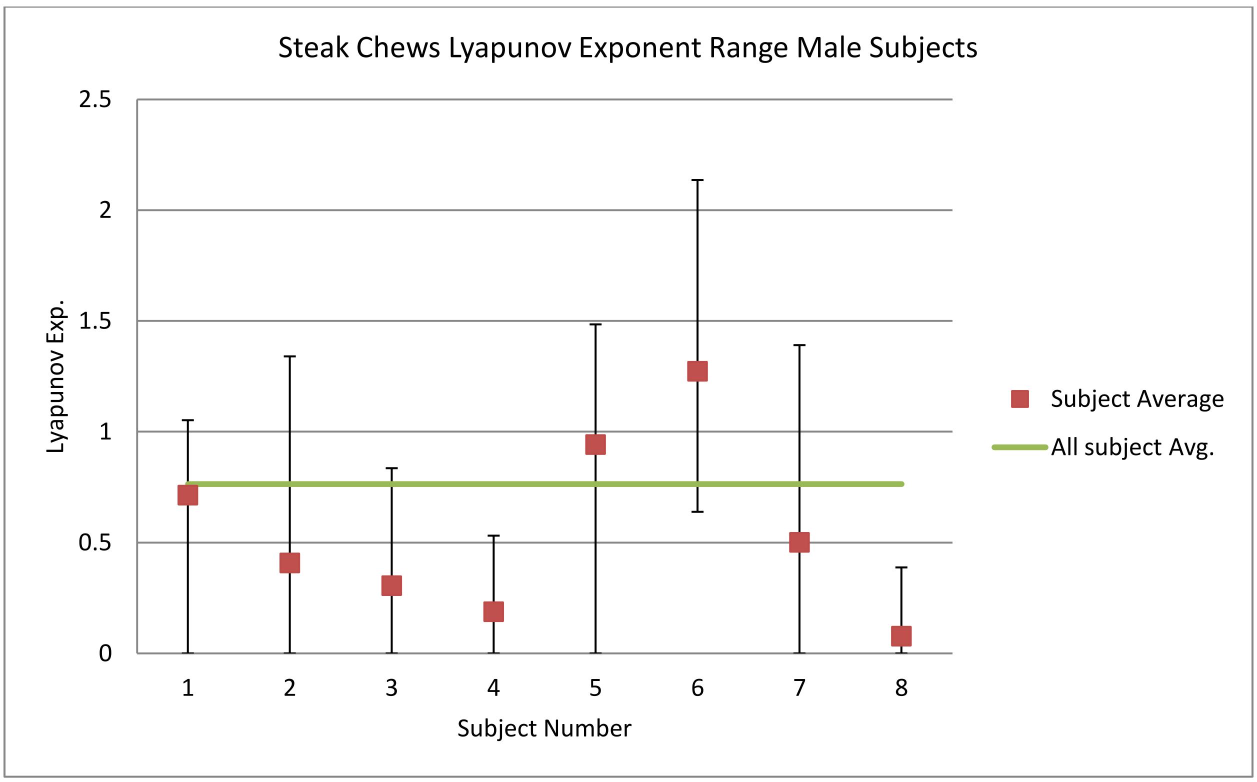


Figure 22. Steak chews Lyapunov exponent value ranges by male subjects and all subject average.

Steak chews of female subject 4 had the largest range in Lyapunov exponents for a given subject of all the recorded food chews (Fig. 23). Female subject 4 had a Lyapunov exponent range of 0 to 4.95 for steak chews. The smallest range in Lyapunov exponents 0 to 0.95 for female steak chews was for female subject 1. All female subjects except subject 3 had steak chews with a minimum Lyapunov exponent value of zero. Female subject steak chews had the most periodic character dynamics for all female subject chews. All female subjects had Lyapunov exponents of 1 or greater which was consistent with the dynamics of chewing being chaotic in character. Steak food cube size varied only a small amount between subjects, but the Lyapunov-exponent-range variation was large indicating noticeable sensitivity to small changes in initial conditions.

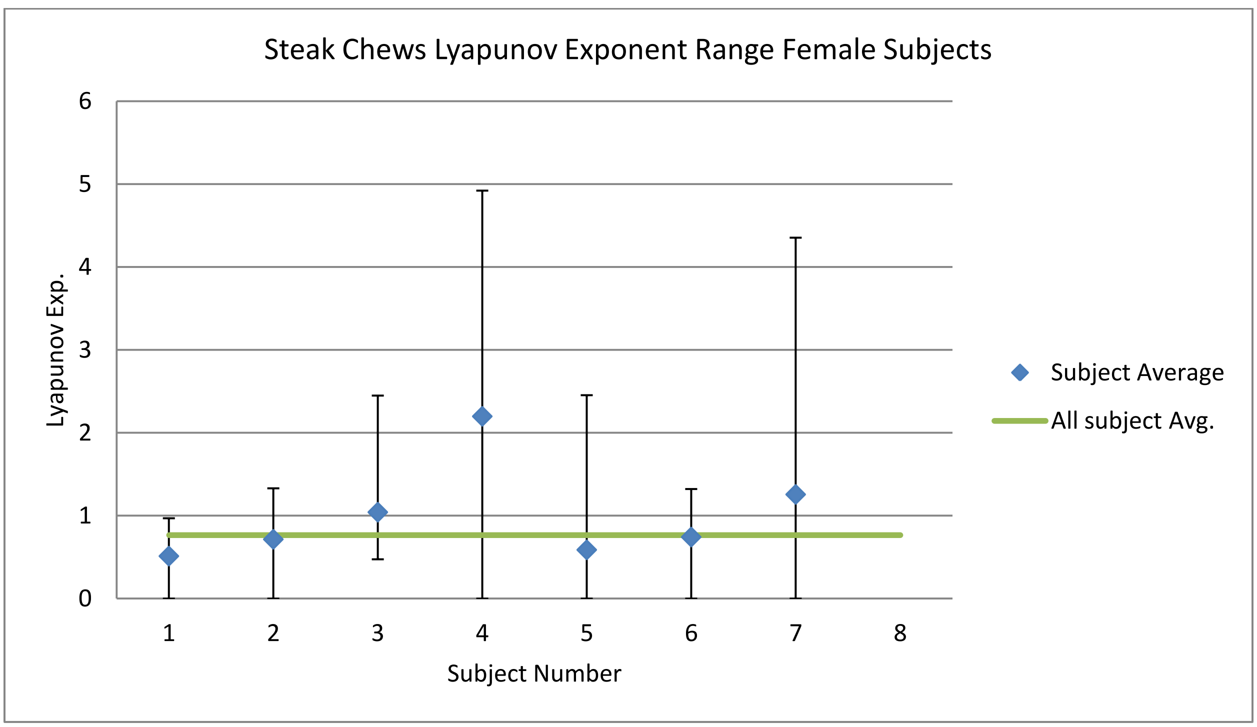


Figure 23. Steak chews Lyapunov exponent value ranges by female subjects and all subject average.

Chapter 4: Study Conclusions

The four camera Motion Reality Inc. motion capture system was capable of making the high resolution motion recordings necessary to study the dynamic character of mandible motion. Retroreflective markers placed on wire extensions added to Hawley orthodontic appliances moved the motion of the mandible outside the mouth which made it detectable by the cameras. The low mass of the retroreflective markers and lack of dental occlusion interference by the modified Hawley orthodontic appliances minimized chewing motion distortion. High resolution of the motion capture system combined with minimized distortion from the test apparatus made possible precise three dimensional recording of mandible motion during natural human chewing.

Recorded natural chewing motions permitted the creation of three-dimensional Posselt diagrams of human chewing from initiation of mandible motion to swallowing of food bolus. Three-dimensional diagrams extended the maximum envelopes of mandible motion previously available making it possible to study natural human chewing motion. Characteristics of original Posselt diagrams reproduced by study motion capture methods confirmed that natural human chewing motion was precisely recorded.

Analysis of natural human chewing motion indicated that the dynamic character of human chewing was chaotic. Chewing dynamics of a chaotic character were determined for all three of the mechanical food types, soft, crunchy and chewy. Some chews were determined to be periodic but this finding did not contradict the finding of chewing dynamics with chaotic character because finding chaotic and periodic results for chewing the same food by the same subject supports the overall chaotic character of the chewing dynamics. The transition of the chewing dynamics from periodic to chaotic because of variation in initial conditions is fully consistent with a chaotic dynamic system. The chaotic and variable dynamic character of chewing is plausible for a biomechanical system with six degrees of freedom driven by eight primary muscles and many more secondary ones. The greater the freedom of motion and complexity of a mechanical system the more probable is it to have dynamics with chaotic character.

The chaotic dynamic character of human mandible motion must be taken into account to fully understand the human mandible as a biomechanical mechanism. Mechanical systems with chaotic dynamic character are very sensitive to changes in initial conditions. Minor changes in initial conditions of experimental treatments in mandible motion can result in significant differences in treatment outcomes. Human mandible motion analysis methods must take into account the chaotic character of the motion dynamics to correctly evaluate experimental results.

Medical and Dental Applications

The novel measurement method developed in this study will better prepare medical and dental practitioners to determine the actual effects of diseases and treatments on mandible motion. The ability to observe the actual three-dimensional motion of the mandible will improve the effectiveness of patient treatment. The chaotic dynamic character findings of this study reveal that medical and dental practitioners need to consider chaotic motion of the mandible as indicative of a healthy state in diagnostic and treatment procedures. Medical and dental practitioners need to take into account that varied and variable motions of the mandible are a natural occurrence for a biomechanical system with chaotic dynamic character.

Future Research

The effectiveness of the new motion capture method for recording natural mandible motion combined with analysis of motion for its dynamic character increases research possibilities. A study of a larger number of subjects to investigate the biomechanics of natural human chewing would provide a baseline of natural chewing that could be compared to specific cases of chewing particular foods or changes in biomechanics caused by disease or injury. Results from a baseline study of biomechanics of natural human chewing could be used to develop algorithms to study the effects of changing variables on mandible motion or to predict mandible motion for a given set of conditions.

Once a fuller understanding of the dynamic character of healthy mandible motion is achieved investigation into the biomechanics of pathologic mandibles could be undertaken. The pathologies of the temporomandibular joint are of great interest to the dental community. The actual mandible motion and dynamics of those suffering from pain and dysfunction of the temporomandibular joint could be studied without interference from the measurement method. The improved study methods could increase understanding of the causes and effects of temporomandibular joint problems.

The methods used in the current study can be applied to investigate the effects of any disease, injury, dysfunction, or surgery on mandible motion dynamics. Beyond medical, dental, and biomechanics studies the mechanical properties of foods could be quantified to evaluate food products. The findings and new techniques of the current study increase our understanding and ability to investigate the dynamic character of human mandible motion.

References

[1] Alomar X, Medrano J, Cabratosa J, Clavero JA, Lorente M, Serra I, Monill JM, Salvador A, (2007) Anatomy of the Temporomandibular Joint. Seminars in Ultrasound, CT, and MRI 28(3):170-183

[2] Koolstra JH (2002) Dynamics of the Human Masticatory System. Critical Reviews in Oral Biology & Medicine 13(4):366-376

[3] Yamada N (1995) Chaotic swaying of the upright posture. Human Movement Science 14: 711-726

[4] Kurz MJ, Stergiou N, Heidel J, Foster ET (2005) A template for the exploration of chaotic locomotive patterns. Chaos, Solitons, and Fractals 23:485–493

[5] Stergiou N, Decker LM (2011) Human movement variability, nonlinear dynamics, and pathology: Is there a connection? Human Movement Science 30:869–888

[6] Rashidi S, Fallah A, Towhidkhah F (2013) Nonlinear analysis of dynamic signature. Indian Journal of Physics 87(12):1251–1261

[7] Walker WE (1896) Movements of the mandibular condyles and dental articulation. Dental Cosmos 38: 573-83.

[8] Posselt U (1952) Studies in the Mobility of the Human Mandible. Acta Odontologica Scandinavica vol. 10, supp. 10.

[9] Soboļeva U, Lauriņa L, Slaidiņa A (2005) Jaw tracking devices - historical review of methods development. Part I. Stomatologija, Baltic Dental and Maxillofacial Journal, 7:67-71.

[10] Koak JY, Kim KN, Heo SJ (2000) A study on the mandibular movement of anterior openbite patients. Journal of Oral Rehabilitation 27:817–822.

[11] Jankelson B (1980) Measurement accuracy of the mandibular kinesiograph – A computerized study. J Prosthetic Dent vol. 44, iss. 6:656-66.

[12] Pinheiro AP, Pereira AA, Andrade AO, Bellomo D (2011) Measurement of jaw motion: the proposal of a simple and accurate method. Journal of Medical Engineering & Technology; 35(3-4): 125-133.

[13] Röhrle O, Anderson IA, Pullan AJ (2005) From Jaw Tracking Towards Dynamic Computer Models of Human Mastication. IFBME Proceedings of 12th International Conference on Biomedical Engineering, Singapore, 7–10.

[14] Furtado DA, Pereira AA, Andrade AO, Bellomo DP, da Silva MR (2013) A specialized motion capture system for real-time analysis of mandibular movements using infrared cameras. BioMedical Engineering OnLine 12:17. Available: http://www.biomedical-engineering-online.com/content/12/1/17 Accessed 16 October 2013

[15] Anderson K, Throckmorton GS, Buschang PH, Hayasaki H (2002) The effects of bolus hardness on masticatory kinematics. Journal of Oral Rehabilitation 29:689-696

[16] Bhatka R , Throckmorton GS, Wintergerst AM, Hutchins B, Buschang PH (2004) Bolus size and unilateral chewing cycle kinematics. Archives of Oral Biology 49:559-566

[17] Wintergerst A, Throckmorton GS, Buschang PH (2008) Effects of bolus size and hardness on within-subject variability of chewing cycle kinematics. Archives of Oral Biology 53:369-375

[18] Crane EA, Rothman ED, Childers D, Gerstner GE (2013) Analysis of temporal variation in human masticatory cycles during gum chewing. Archives of Oral Biology 58:1464-1474

[19] Peck CC, Hannam AG (2007) Human jaw and muscle modeling. Archives of Oral Biology 52:300-304

[20] Szymanski DJ, McIntyre JS, Szymanski JM, Molloy JM, Madsen NH, Pascoe DD (2006) Effect of wrist and forearm training on linear bat-end, center of percussion, and hand velocities and on time to ball contact of high school baseball players. Journal of Strength and Conditioning Research 20(1):231–240

[21] Szymanski DJ, Szymanski JM, Schade RL, Bradford TJ, McIntyre JS, DeRenne C, Madsen NH (2010) The relation between anthropometric and physiological variables and bat velocity of high-school baseball players before and after 12 weeks of training. Journal of Strength and Conditioning Research 24(11):2933-2943

[22] Abarbanel HDI (1995) *Analysis of Observed Chaotic Data*, Springer-Verlag, New York, NY.

[23] Allard P, Blanchi J, Aïssaoui R (1995) Bases of Three-Dimensional Reconstruction in Allard P, Stokes IAF, Blanchi J (Eds.) *Three-Dimensional Analysis of Human Movement.* (19-40) Champaign, IL: Human Kinetics

[24] Glodstein H (1980) *Classical Mechanics,* pp. 143-148 Addison-Wesley, Reading, MA.

[25] D'Humieres D, Beasley MR, Huberman BA, Libchaber A (1982) Chaotic States and Routes to Chaos in the Forced Pendulum. Physical Review A 26(6):3484-3496

[26] Peters RD (2005) Spice Modeling of the Vilnius Chaotic Oscillator. *arXiv:physics/0503049v1 [physics.ed-ph]*

Appendices

Appendix A

Motion Capture Data File Example

```
Bio System Variable File
v1.00
580
12
 Results for frame 1
    Value      #   Description
      -0.2146   1
       2.0849   2
     -14.6552   3
      -6.2877   4
       0.1947   5
      -0.0116   6
       0.1137   7
      -0.3953   8
      -0.0355   9
       0.2618  10
      -0.0152  11
       0.0576  12
 Results for frame 2
    Value      #   Description
     -0.20686   1
      2.09852   2
     -14.6821   3
     -6.28125   4
     0.195542   5
   -0.0138225   6
     0.111536   7
    -0.374532   8
   -0.0444768   9
     0.224302  10
   -0.0181096  11
    0.0631814  12
 Results for frame 3
    Value      #   Description
    -0.201403   1
      2.09974   2
     -14.6862   3
     -6.28106   4
     0.199284   5
   -0.0130932   6
     0.110451   7
    -0.361706   8
   -0.0416515   9
     0.181705  10
   -0.0214053  11
    0.0638878  12
```

Appendix B

Y-axis Displacement Data Extraction C++ Program

```
#include <stdio.h>
#include <iostream.h>
#include <assert.h>
#include <string.h>
#include <math.h>

void discardline(FILE* fp)
{
   char c;
   c='s';
   while (c!='\n')
   {
      fscanf(fp,"%c",&c);
   }
}

struct Matrix
{
   double row0[3];
   double row1[3];
   double row2[3];
   Matrix();
   void setToY(double theta);
   void setToX(double theta);
   void setToZ(double theta);
   void YrotTofixed(double theta);
   void XrotTofixed(double theta);
   void ZrotTofixed(double theta);
   Matrix operator=(const Matrix& m);
   Matrix operator*=(const Matrix& m);
};

Matrix::Matrix()
{
   row0[0]=1;
   row0[1]=0;
   row0[2]=0;
   row1[0]=0;
   row1[1]=1;
   row1[2]=0;
   row2[0]=0;
   row2[1]=0;
   row2[2]=1;
}

void Matrix::setToY(double theta)
{
   double c=cos(theta);
   double s=sin(theta);
```

```
   row0[0]=c;
   row0[1]=0;
   row0[2]=-s;
   row1[0]=0;
   row1[1]=1;
   row1[2]=0;
   row2[0]=s;
   row2[1]=0;
   row2[2]=c;
}

void Matrix::setToX(double theta)
{
   double c=cos(theta);
   double s=sin(theta);
   row0[0]=1;
   row0[1]=0;
   row0[2]=0;
   row1[0]=0;
   row1[1]=c;
   row1[2]=s;
   row2[0]=0;
   row2[1]=-s;
   row2[2]=c;
}

void Matrix::setToZ(double theta)
{
   double c=cos(theta);
   double s=sin(theta);
   row0[0]=c;
   row0[1]=s;
   row0[2]=0;
   row1[0]=-s;
   row1[1]=c;
   row1[2]=0;
   row2[0]=0;
   row2[1]=0;
   row2[2]=1;
}

void Matrix::YrotTofixed(double theta)
{
   double c=cos(theta);
   double s=sin(theta);
   row0[0]=c;
   row0[1]=0;
   row0[2]=s;
   row1[0]=0;
   row1[1]=1;
   row1[2]=0;
   row2[0]=-s;
   row2[1]=0;
   row2[2]=c;
```

```
}

void Matrix::XrotTofixed(double theta)
{
   double c=cos(theta);
   double s=sin(theta);
   row0[0]=1;
   row0[1]=0;
   row0[2]=0;
   row1[0]=0;
   row1[1]=c;
   row1[2]=-s;
   row2[0]=0;
   row2[1]=s;
   row2[2]=c;
}


void Matrix::ZrotTofixed(double theta)
{
   double c=cos(theta);
   double s=sin(theta);
   row0[0]=c;
   row0[1]=-s;
   row0[2]=0;
   row1[0]=s;
   row1[1]=c;
   row1[2]=0;
   row2[0]=0;
   row2[1]=0;
   row2[2]=1;
}


Matrix Matrix::operator=(const Matrix& m)
{
   row0[0]=m.row0[0];
   row0[1]=m.row0[1];
   row0[2]=m.row0[2];
   row1[0]=m.row1[0];
   row1[1]=m.row1[1];
   row1[2]=m.row1[2];
   row2[0]=m.row2[0];
   row2[1]=m.row2[1];
   row2[2]=m.row2[2];
   return *this;
}

Matrix Matrix::operator*=(const Matrix& m)
{
   double t0=row0[0]*m.row0[0]+row0[1]*m.row1[0]+row0[2]*m.row2[0];
   double t1=row0[0]*m.row0[1]+row0[1]*m.row1[1]+row0[2]*m.row2[1];
   double t2=row0[0]*m.row0[2]+row0[1]*m.row1[2]+row0[2]*m.row2[2];
   row0[0]=t0;
```

```
   row0[1]=t1;
   row0[2]=t2;
   t0=row1[0]*m.row0[0]+row1[1]*m.row1[0]+row1[2]*m.row2[0];
   t1=row1[0]*m.row0[1]+row1[1]*m.row1[1]+row1[2]*m.row2[1];
   t2=row1[0]*m.row0[2]+row1[1]*m.row1[2]+row1[2]*m.row2[2];
   row1[0]=t0;
   row1[1]=t1;
   row1[2]=t2;
   t0=row2[0]*m.row0[0]+row2[1]*m.row1[0]+row2[2]*m.row2[0];
   t1=row2[0]*m.row0[1]+row2[1]*m.row1[1]+row2[2]*m.row2[1];
   t2=row2[0]*m.row0[2]+row2[1]*m.row1[2]+row2[2]*m.row2[2];
   row2[0]=t0;
   row2[1]=t1;
   row2[2]=t2;
   return *this;
}

void buildBodyGlobalMatrix(Matrix& m,double X,double Y,double Z)
{
   Matrix xm,zm;
   m.setToY(Y);
   xm.setToX(X);
   zm.setToZ(Z);
   m*=xm;
   m*=zm;
}

int main()
{
   // Point of interest local coordinates
   double Point1Lcoord[3];
   double Point2Lcoord[3];
   double Point3Lcoord[3];

  // Data input routine
 cout << "Jaw position data conversion program" << endl;
 cout << "Enter number of data files to process : ";
   int nf;
   cin >> nf;
   cout << endl;
   cout << "Number of files to process = " << nf << endl;
   {
      int filen=0;
      for (;filen<nf;filen++)
      {
        char filename[200];
        char output[200];
//        char atext[200];

        cout << "For data file #" << filen << ", enter name." << endl;

        cin >> filename;

        cout << "Processing file " << filename << endl;
```

```
        cout << "Enter Point 1 mandible local X:" << endl;

        cin >> Point1Lcoord[0];

        cout << "Enter Point 1 mandible local Y:" << endl;

        cin >> Point1Lcoord[1];

        cout << "Enter Point 1 mandible local Z:" << endl;

        cin >> Point1Lcoord[2];

        cout << "Enter Point 2 mandible local X:" << endl;

        cin >> Point2Lcoord[0];

        cout << "Enter Point 2 mandible local Y:" << endl;

        cin >> Point2Lcoord[1];

        cout << "Enter Point 2 mandible local Z:" << endl;

        cin >> Point2Lcoord[2];


        cout << "Enter Point 3 mandible local X:" << endl;

        cin >> Point3Lcoord[0];

        cout << "Enter Point 3 mandible local Y:" << endl;

        cin >> Point3Lcoord[1];

        cout << "Enter Point 3 mandible local Z:" << endl;

        cin >> Point3Lcoord[2];

        FILE* fp=fopen(filename,"r");

//        float af=(float)accuracy;
        strcpy(output,filename);
        strcat(output,".chin10k");
        cout << "Output file name = " << output << endl;
        discardline(fp);
        discardline(fp);

        int numFrames;
        fscanf(fp,"%d",&numFrames);
        discardline(fp);
        // assert(numFrames==NUMFRAME);
        int numVar;
        fscanf(fp,"%d",&numVar);
        discardline(fp);
```

```
int frameNum=0;

const int NUMFRAMES=10500;

// Motion file data arrays
double xtrans[NUMFRAMES];
double ytrans[NUMFRAMES];
double ztrans[NUMFRAMES];
double xrot[NUMFRAMES];
double yrot[NUMFRAMES];
double zrot[NUMFRAMES];


// Data input rotine
for (;frameNum<numFrames;frameNum++)
  {
    discardline(fp);
    discardline(fp);
    int vn=0;

    for (;vn<numVar;vn++)
      {
        double v;
        int n;
        fscanf(fp,"%lf %d",&v,&n);
        discardline(fp);
        switch (n)
         {
          case 7:
         {
            xtrans[frameNum]=v;
           }
          break;
          case 8:
         {
            ytrans[frameNum]=v;
           }
          break;
          case 9:
         {
            ztrans[frameNum]=v;
           }
          break;
          case 10:
         {
            xrot[frameNum]=v;
           }
          break;
          case 11:
         {
            yrot[frameNum]=v;
           }
          break;
          case 12:
```

```
                {
                   zrot[frameNum]=v;
                  }
                 break;
                 default:
                  {
                  }
                 break;
                }
              }
           }
         fclose(fp);

         // Point position computation

        double point1xupjaw[NUMFRAMES], point1yupjaw[NUMFRAMES],
point1zupjaw[NUMFRAMES];
        double point2xupjaw[NUMFRAMES], point2yupjaw[NUMFRAMES],
point2zupjaw[NUMFRAMES];
        double point3xupjaw[NUMFRAMES], point3yupjaw[NUMFRAMES],
point3zupjaw[NUMFRAMES];

        Matrix xr, yr, zr, point1L, point2L, point3L;
        Matrix point1upjaw, point2upjaw, point3upjaw;

        // Point local coord matrices
        point1L.row0[0]=Point1Lcoord[0];
        point1L.row1[0]=Point1Lcoord[1];
        point1L.row2[0]=Point1Lcoord[2];

        point2L.row0[0]=Point2Lcoord[0];
        point2L.row1[0]=Point2Lcoord[1];
        point2L.row2[0]=Point2Lcoord[2];

        point3L.row0[0]=Point3Lcoord[0];
        point3L.row1[0]=Point3Lcoord[1];
        point3L.row2[0]=Point3Lcoord[2];

        // Transformation of coords
        int fnc=0;

        for(;fnc<numFrames;fnc++)
          {
            xr.XrotTofixed(xrot[fnc]);
            yr.YrotTofixed(yrot[fnc]);
            zr.ZrotTofixed(zrot[fnc]);

            point1upjaw=xr;
            point1upjaw*=yr;
            point1upjaw*=zr;
            point1upjaw*=point1L;

            point2upjaw=xr;
            point2upjaw*=yr;
```

```
            point2upjaw*=zr;
            point2upjaw*=point2L;

            point3upjaw=xr;
            point3upjaw*=yr;
            point3upjaw*=zr;
            point3upjaw*=point3L;

            point1xupjaw[fnc]=point1upjaw.row0[0]+xtrans[fnc];
            point1yupjaw[fnc]=point1upjaw.row1[0]+ytrans[fnc];
            point1zupjaw[fnc]=point1upjaw.row2[0]+ztrans[fnc];

            point2xupjaw[fnc]=point2upjaw.row0[0]+xtrans[fnc];
            point2yupjaw[fnc]=point2upjaw.row1[0]+ytrans[fnc];
            point2zupjaw[fnc]=point2upjaw.row2[0]+ztrans[fnc];

            point3xupjaw[fnc]=point3upjaw.row0[0]+xtrans[fnc];
            point3yupjaw[fnc]=point3upjaw.row1[0]+ytrans[fnc];
            point3zupjaw[fnc]=point3upjaw.row2[0]+ztrans[fnc];
          }

        //Data expander routine
        double Addpoints;
      //double testaddp;
        double Wantnum=1e4;
        int Totalpoints;
        int Taddpc;
        int addpc;

        Addpoints=ceil((Wantnum-numFrames)/(numFrames-1));
      //testaddp=(Wantnum-numFrames)/(numFrames-1);

      //cout <<"Wantnum "<< Wantnum << " Addpoints " << Addpoints <<"
testaddp "<<testaddp << endl;


        Totalpoints=numFrames+Addpoints*(numFrames-1);
      //cout << "Totalpoints "<< Totalpoints <<" numFrames "<< numFrames
<< endl;

      const int Workspace=25e4;


        double expandset[Workspace];

        fnc=0;
        Taddpc=0;

        for(;fnc<(numFrames-1);fnc++)
          {

                expandset[Taddpc]=point2yupjaw[fnc];
                addpc=1;
```

```
                for(;addpc<=Addpoints;addpc++)
                  {
                        Taddpc+=1;


expandset[Taddpc]=point2yupjaw[fnc]+((point2yupjaw[fnc+1]
                                -point2yupjaw[fnc])/(Addpoints+1))*addpc;

                  //cout<<"Taddpc "<< Taddpc<<" fnc "<<fnc<< endl;
                }
            Taddpc+=1;
          }

       expandset[Taddpc]=point2yupjaw[numFrames-1];

      //cout<<"Taddpc "<< Taddpc<<" Totalpoints "<<Totalpoints <<"
expandlast "<< expandset[Taddpc] << endl;

        //Nondimensionallizer
        int pn=0;

        for(;pn<Totalpoints;pn++)
          {
                expandset[pn]/=Point2Lcoord[2];
          }

        // Data output routine
        FILE* fpo=fopen(output,"w");

        fprintf(fpo,"Filename: %50s \n",output);
        fprintf(fpo,"Nodimensionalized chin y position data expanded to
10k data points. \n");
        //fprintf(fpo,"Coordinates are in inches measured from the Upper
Jaw. \n");
        //fprintf(fpo,"Upper Jaw axes origin is between the rear molars
with the X axis pointing to the left, /n");
        //fprintf(fpo,"Y axis points up, and the Z axis points out the
front teeth. /n");^M
        //fprintf(fpo,"/n /n");
        //fprintf(fpo,"Frame# Point1X Point1Y Point1Z Point2X Point2Y
Point2Z Point3X Point3Y Point3Z /n");

        fprintf(fpo,"Total data points in file=%1i \n", Totalpoints);
        fprintf(fpo,"\n \n");

        pn=0;

        for(;pn<Totalpoints;pn++)
          {
                fprintf(fpo,"%1f \n", expandset[pn]);
          }

        //int fn=0;^M
        //for(;fn<numFrames;fn++)
```

```
        //  {^M
        //     fprintf(fpo,"%1f ",fn+1);
        //     fprintf(fpo,"%1f %1f %1f
",point1xupjaw[fn],point1yupjaw[fn],point1zupjaw[fn]);
        //     fprintf(fpo,"%1f %1f %1f
",point2xupjaw[fn],point2yupjaw[fn],point2zupjaw[fn]);
        //     fprintf(fpo,"%1f %1f %1f
/n",point3xupjaw[fn],point3yupjaw[fn],point3zupjaw[fn]);
        //  }

        fclose(fpo);
       }
    }
 }
```

Appendix C

AUBURN UNIVERSITY
INSTITUTIONAL REVIEW BOARD
PROTOCOL FOR RESEARCH INVOLVING HUMAN SUBJECTS

ALL RESEARCH INVOLVING HUMAN SUBJECTS WHETHER CONDUCTED BY FACULTY, STAFF, OR STUDENTS MUST BE REVIEWED AND APPROVED UNDER AUIRB PROCEDURES BEFORE HUMAN SUBJECTS MAY BE INVOLVED. NEITHER THE SOURCE OF FUNDS NOR LACK OF FUNDING FOR SUCH RESEARCH HAS ANY BEARING ON THIS REQUIREMENT.

A COMPLETE SET OF ALL PROTOCOL INFORMATION MUST BE SUBMITTED TO THE OFFICE OF HUMAN SUBJECTS
FOR BOARD REVIEW - ORIGINAL AND 11 COPIES
EXEMPT REVIEW - ORIGINAL

********ONLY TYPEWRITTEN PROTOCOLS WILL BE ACCEPTED********

Joseph McIntyre ______ Ph.D. Student ___ Mech. Engr. 887-3374
NAME OF PRINCIPAL INVESTIGATOR TITLE DEPT PHONE

PROJECT TITLE: Quantitative Three-Dimensional Measurement of Human-Jaw Motion
____

PROPOSED DATES OF STUDY: MARCH 1, 2001 ________ THROUGH JUNE 30, 2001
SOURCE OF FUNDING: DR. JEFFERY WATSON, DDS ________________

____
NAME OF CO- INVESTIGATOR TITLE DEPT PHONE

Dr. Nels Madsen ________ Associate Prof. ________ Mech. Engr. 4-4820
NAME OF FACULTY ADVISOR TITLE DEPT PHONE
IF A FACULTY ADVISOR IS REQUIRED, WILL THE RESULTS OF THIS PROJECT BE USED FOR A STUDENT'S
THESIS? ________ DISSERTATION? ________ OTHER? RESEARCH PAPER ____
(EXPLAIN)

SIGNATURES:

______________ ____
CO-INVESTIGATOR DATE PRINCIPAL INVESTIGATOR DATE

______________ __________
FACULTY ADVISOR DATE DEPARTMENT HEAD DATE

==

FOR AUIRB USE ONLY **AUTHORIZATION # ________________**

____

DESIGNATION: AT RISK ______________________ DATE APPROVED______________

MINIMUM RISK _________________ EXPIRATION OF APPROVAL

APPROVED: ____

AUIRB ADMINISTRATOR DATE

1. **PURPOSE OF STUDY.** Please provide a complete statement of objectives for conducting this research project (What do you hope to learn?).

The motion of the human jaw during chewing is complex and is difficult to measure using standard biomechanical measurement techniques. The jaw moves in three dimensions simultaneously as the lower teeth are brought to meet the upper teeth in chewing. The jaw joint is not a hinge rigidly connected to the skull so the pivot point moves during chewing. The jaw motion is hidden behind the highly flexible lips and cheeks.

The purpose of this study is to quantitatively measure the three-dimensional motion of the human jaw of physiologically normal adults during chewing.

2. **SUBJECT POPULATION.** (Describe the criteria have you established for subject selection).

Ten people with normal jaw joints and dentition. The subject population will be recruited from the students of Auburn University. The subjects must have "normal-healthy" dentition, jaws, facial muscles, and facial muscle control. Subjects will be excluded if they have a history of facial or cranial surgery beyond the extraction of wisdom teeth, or disease or malformation of the gums, teeth, jaw, or jaw joint.

Can these subjects be described as a vulnerable population?______Yes___X________No

(If YES, provide additional, acceptable justification for use of these subjects.)

What is the

Minimum number of subjects you need to validate the study? 10____

Maximum number of potential subjects you plan to recruit? 10____

Maximum number you will include in the study? 10____

How will you recruit subjects? (If you are advertising or using flyers, please attach a copy.)

Mr. McIntyre will directly ask possible subjects both personally and by addressing classes in the Mechanical Engineering and Health and Human Performance departments with the permission of the instructors. Mr. McIntyre will not recruit in the classes were he is a teaching assistant. The script for subject recruitment is the following.

Hello, my name is Joseph McIntyre and I am a Ph.D. student in Mechanical Engineering. I am preparing to do a study of the three-dimensional movement of the jaw during chewing. This is the first study, and is intended to produce baseline data of "normal healthy" chewing patterns. The way the chewing is going to be recorded is using a Biomechanics Inc. motion capture system to create computer animations that move exactly like the persons under study.

The motion capture system works by using four video cameras to record the position of reflective markers placed on the subject. (Show marker to audience.) The location of the marker up-and-down and left-and-right in each camera's view is combined with calibration information to produce the location of the marker in space. The distance from the origin point and the height off the floor. A computer model of the anatomy under study is created with markers located in the same position as on the subject. It takes a minimum of three markers to orient a modeled body in space. The computer fits the model to the subjects markers. The process of fitting creates a model that reproduces the subjects motion.

The markers for the chewing study will be mounted on a retainer.(Show marker appliance to audience.) The markers are mounted on extension wires so they will pass through your lips and out of the mouth. While wearing a marker appliance you will be asked to chew ten pieces of banana(show banana cube), ten pieces of shortbread cookie(show cookie cube), and ten pieces of steak(show steak cube). You will chew each piece separately as you are recorded by the motion capture system. You will be sitting in a chair while chewing and given a break if you need it between chews.

As this is a study of "normal healthy" chewing each subject is going to be examined by a dentist to see if your teeth and bite are in the normal range. You will also be asked questions to see if you have or have had any chewing problems or past medical problems or surgeries that would alter your chewing pattern. If your teeth and chewing are "normal and healthy" then a casting of your teeth will be made by the dentist to use as a model for the marker appliance. The exam and casting will take about an hour.

Your reward for participating in the study is a dental hygiene kit. You work with a dentist you get free toothbrushes, toothpaste, etc. And of much more interest to a student a free lunch at a restaurant.

Describe how you will determine group assignments (random vs criteria) and number of subjects to be assigned to each group, the number of groups needed, provisions for controls, or any other clarifying information regarding subject population you feel is appropriate.

As the purpose of this study is to measure jaw motion and see the normal range of that motion all subjects will be in one group.

3. **EXPERIMENTAL METHODS AND STUDY DESIGN.**
(Please provide a description of all procedures you plan to use during the course of this research, in lay language. Without a complete description of all procedures the AUIRB will not be able to review the protocol).

The motion of the subject's jaw will be recorded using a Biomechanics Inc. motion capture system. The system consists of four cameras each with its own cool flourescent light and two computers. The computers digitize and record the images sent from the cameras. The system automatically tracks reflective markers placed on the subject. The system computes the three-dimensional coordinates of the markers in space and uses those coordinates to position a computer model of the anatomy under study to the position of the subject's anatomy for each frame of digitized video. An animation of the subject is produced when the frames are displayed in sequence. The subject will wear a dental appliance based on the standard orthodontic retainer as a mounting platform for the reflective markers. The reflective markers will be placed on wires that project out through the subjects mouth, thus only FDA approved dental materials will be used inside a subject's mouth.

1. Subject Screening.
The subjects shall fill out the consent form and then the screening form. Those subjects that pass the screening questions will have their teeth examined by a licensed dentist and a standard dental chart of their teeth will be recorded. The examining dentist will be Dr. James L. Carroll, DDS licenced in Alabama. The exams and dental castings will be made at Dr. Carroll's office located at 337 A East Magnolia in Auburn. The details of the exam are listed in the attached letter from Dr. Carroll. If Dr. Carroll finds any disease or abnormality during the exam the subject will be notified and advised as to the course of action that should be taken. Subjects that have a disease or abnormality discovered in the exam will be dropped from the study.

2. Dental casting of subjects teeth.
A cast of the subject's teeth will then be made by one of the dental hygienists in Dr. Carroll's employ. The casting will be used to construct the dental marker appliance for use with the Motion Capture System. The marker appliance is a modified Hawley orthodontic appliance, commonly known as a retainer.

3. Food preparation.
All food will be prepared in the kitchen of Mr. McIntyre's residence. All persons handling the food items will wear gloves or use tongs in handling the food items. Food items will be weighed on a digital balance. The platform of the digital balance will be covered with wax paper. The wax paper will be changed between food types and after any pauses in the preparation process. The banana rectangles will be cut to a mass of 8 grams and then placed into plastic container with an air tight lid. The cookie cubes will

be cut to 8 grams and placed in an air tight plastic container. The steak will be roasted in an oven to the “beef well ” range on a meat thermometer. The cooked steak will then be cut into 6 gram cubes. The steak cubes will be placed in an air tight plastic container. The banana and steak will be prepared the day before the experiment and refrigerated until just before use. The banana and steak will be transported in ice chests and kept on ice until used.

3. Data Collection.
The subject will have several photographs of the head taken to allow the measurement of the dimensions of the head and jaw.

The subject will sit in a chair facing the four cameras of the system. The subject will be given sunglasses to ensure the lights are not too bright for comfort. The experiment will proceed as follows:

1. Warm up. Subject will place marker appliance in mouth and chew one stick of non-stick chewing gum until they acclimatize to the presence of the appliance. If the subject reports that the marker appliance is slipping during chewing Fixodent or an equivalent denture adhesive will be applied to the appliance. Subject will be given glass of water to rinse mouth if needed.

2. Gum Chewing. Subject will chew a stick of non-stick chewing gum while the Motion Capture System records 10 chews on the right side and 10 chews on the left side of the mouth. Subject will then spit out the gum. Subject will rest 30 seconds before starting on the next food type.

3. Banana Chewing. Subject will be given an 8 gram fresh banana rectangle on a toothpick. Subject will be told to chew up and swallow the banana at their own pace. The eating of the banana rectangle will be recorded with the Motion Capture System. Subject will be given a glass of water to rinse their mouth. Subject will rest 30 seconds before repeating or starting on the next food type. Each subject will repeat the banana chewing 10 times. The subject will eat ten banana rectangles.

4. Cookie Chewing. Subject will be given an 8 gram shortbread cookie cube. Subject will be told to chew up and swallow the cookie cube at their own pace. The eating of the cookie cube will be recorded with the Motion Capture System. Subject will be given a glass of water to rinse their mouth. Subject will rest 30 seconds before repeating or starting on the next food type. Each subject will repeat the cookie chewing 10 times. The subject will eat ten cookie cubes.

5. Steak Chewing. Subject will be given a 6 gram steak cube. Subject will be told to

chew up and swallow the steak cube at their own pace. The eating of the steak cube will be recorded with the Motion Capture System. Subject will be given a glass of water to rinse their mouth. Subject will rest 30 seconds before repeating or starting on the next food type. Each subject will repeat steak chewing 10 times. The subject will eat ten steak cubes.

4. **BENEFITS.** (Describe realistic benefits to subjects and general population).

Each subject shall receive a free dental exam. At the completion of the data collection each subject will receive a dental hygiene kit(toothbrush, dental floss, etc.) and a dinner at a restaurant.

This study will provide one of the first three-dimensional recordings of human chewing. The data will form a baseline of a normal chewing motions to be used for comparison. This baseline motion set can be used in diagnosis and treatment of jaw-joint and chewing disorders.

5. **RISKS.** (Identify which of the following risks subjects might encounter if they decide to participate in this research? (Place a check mark beside all that apply.)

Physical	X	Social	______
Psychological	______	Other	______
Deception	______	None	______

Describe the reasonable risks that are associated with this protocol.

There is always a slight risk of choking during eating. There is also a possibility of undiagnosed food allergies in the subjects. Subjects may also suffer dental injury while chewing.

6. **PRECAUTIONS.** (Describe all precautions you have taken to eliminate or reduce reasonable risks. If you are using deception in this study, please justify why and be sure to attach a copy of your debriefing form.)

Subjects will be screened for dental and chewing pathologies by form and a licensed dentist. Subjects will be asked if they are allergic to the foods used in the study. Subjects will acclimatize to the marker appliance by chewing gum before attempting to eat with the appliance in their mouth. The procedures of the study will not increase the risk of dental injury above that normally experienced during chewing. Personnel trained in the Heimlich Maneuver will be present. Subjects will be provided with sunglasses for use with the lights of the Motion Capture System. A telephone will be located in the Motion Capture Lab so that if a medical emergency arises paramedics will be called to the scene.

7. **LOCATION** of experiments. (Please be as specific as possible.)

Shop Building Three in the Motion Capture Lab.

8. **PROTECTION OF DATA**.

Will data be confidential? _X____Yes ______No Anonymous? Yes __ No _X
Will data be coded in any way? ______Yes _X____No
If YES, explain reason (e.g., ensure confidentiality of sensitive information, to follow-up initial contacts, collate data, etc.) and describe the method you will use for coding data.

Will you be videotaping subjects? _X____yes ______no
audio-taping? ______yes ______no

Where will identifiable information (e.g., coded data, pictures, tapes, etc.) be stored? (If not applicable, please indicate n/a.)

Digital pictures will be stored under password protection on the IRIS computer in the Motion Capture Lab. Video cassettes, information forms and photographs will be stored in Dr. Madsen's Office in Ross Hall.

Who will have access to identifiable information? (If not applicable, please indicate n/a.)
Joseph McIntyre, Dr. Nels Madsen, Dr. Jeffery Watson. Dr. Watson is the dental technical expert for the project. He will be asked questions about the subjects teeth and provide technical assistance during the data collection. As a persons teeth and dental information can be used to establish that persons identity Dr. Watson will have access to identifiable information. He will not have access to subjects names or contact information.

Where will code lists be stored? (If not applicable, please indicate n/a.)

N/A

How is the location(s) secured during your absence? (If not applicable, please indicate n/a.)

The door to the Motion Capture Lab is locked. The IRIS machine is password protected. Materials to be worn or consumed by subjects will be stored off campus at Joseph McIntyre's private residence 2059 S. Evergreen Dr. Auburn AL, 36830. Mr. McIntyre does not have any non-family members as house mates.

How will identifying information (e.g., code lists, pictures, tapes, etc.) be destroyed? (If not applicable, please indicate n/a.)

Video tapes will be degaussed. Forms and photographs carrying identifying subject information will be shredded. Files containing digitized images of subjects will be erased and made unrecoverable.

What is the latest date on which identifiable data (e.g., code lists, pictures, tapes, etc.) will be destroyed? (If not applicable, please indicate n/a.)

March 31, 2002.

NOTE: Research data which cannot be linked in any way to an individual participant of the project may be retained indefinitely.

9. **ATTACH A SAMPLE OF ALL INSTRUMENTS, SURVEYS, DRAWINGS, ETC.** you will use in this study. if you are (or will be) developing the questionnaire, etc., please provide a general description of the instrument. if you are using interview procedures, please include a general script of interview.

10. **ATTACH A COPY OF ALL INFORMED CONSENTS AND/OR INFORMATION DOCUMENTS** you have developed for use in this study. be sure each form is applicable to the proposed procedures and that the form contains all of the requirements for compliance with the regulations regarding informed consent.

The subjects shall be asked to provide following contact information to allow them to be informed of the schedule of the experimental data collection. The contact information will be the subject's phone number, mailing address, and E-mail address. It is the experience of the investigator that E-mail is the most effective way to stay in contact with a group of students.

The subjects will be asked their age as this has a direct impact on the teeth present in the jaw. The subjects shall be asked their sex as the sex of the subject effects the size and shape of the jaw. The subjects shall be asked about their current and past dental health and surgeries or therapies that have been performed to the head and neck. Some surgeries and therapies alter the chewing pattern. As the purpose of the study is to collect data on "normal healthy" chewing and altered pattern is reason to exclude a subject from the study.

The subjects will be asked about any food allergies they have to the ingredients of the foods used in the study. While peanuts are not going to be used as a food in the study, peanuts and peanut products are used in the food preparation area used for the study.

Subject Contact Information
for
Quantitative Three-Dimensional Measurement of Human-Jaw Motion During Chewing

Subject number for experimental data and information bookkeeping. __________________

Name____ Phone #

Address

E-mail

Subject Information Sheet

Subject Number **_______________**

Gender **M** **F** Age

Questions

1. Have you ever had surgery or radiation therapy involving your face, head, or neck? Please specify.

2. Do you currently have or have any history of any of the following: difficulty swallowing, orofacial diseases such as the following: herpes(cold sores), monoliasis; salivary disorders such as ptyalism, sialorrhea, xerostomia; necrotizing ulcerative gingivitis(trench mouth); facial nerve disorders such as Bell's Palsy, tic deloreaux; disorders of the jaw joint(tempomandibular joint) know as TMJ syndrome? Please specify.

3. Do you wear dentures or other dental appliances to replace missing teeth?

4. Are you allergic to beef, bananas, wheat, butter, or peanut products? Please specify which foods and the severity of your reaction.

Informed Consent
for
Quantitative Three-Dimensional Measurement of Human-Jaw Motion During Chewing

You are invited to participate in a study of human jaw motion during chewing. We are working to produce a detailed information on the three-dimensional motion of the human jaw during chewing. The data collection method is new, so data we will be collecting will be some of the first of its kind . The data could be used as a base line measure of normal human chewing patterns in the diagnosis and treatment of chewing and jaw disorders.

Your participation will consist of two parts, preparation for the experiment and then the actual data collection during the experiment.

Preparation

You will have your teeth examined by Dr. James L. Carroll, DDS and a dental chart of your teeth will be made. You will be asked questions about your medical and dental history during the exam. As the study is intended to measure normal human chewing you might be excluded from the study if have had a history of dental, chewing, or swallowing problems. You could also be excluded if the dentist finds any abnormalities or diseases during the exam. You will be informed of any findings of dental abnormalities or disease and advised on what course of action should be taken. A dental casting of your teeth will then be made by a dental hygienist. All dental personnel will be licensed practicing professionals. The exam and casting will take about an hour and be done in Dr. Carroll's office located at 337 A East Magnolia in Auburn. The preparation activities will be done several weeks in advance of the data collection.

Experimental Data Collection

You will wear a modified retainer (Hawley orthodontic appliance) made from your dental castings on both your upper and lower teeth during the experiment. The retainers are made of plastic molded to your teeth, gums, and palate. Three wires are mounted in the plastic two passing between molars on each side of your mouth, the third wire forms a bow across your front teeth. The bow wire passes through your teeth at the eye teeth. The retainers have extension wires placed on them that will pass between the lips and out of the mouth. Mounted on the end of each wire is a reflective marker used to track the position of the jaws.
You will be asked the chew/eat the following food items:

1. Chewing gum.
2. Banana.
3. Short bread cookie.
4. Beef steak.

All food items will be cut into small bite sized pieces. The chewing motion will be recorded by four digital video cameras that will measure the position of the jaws. Then you will also be recorded using still photographs and video recordings to document the procedure.

Participant's Initials

Informed Consent
for
Quantitative Three-Dimensional Measurement of Human-Jaw Motion During Chewing

You will be asked to chew/eat 10 small pieces of each food item with a rest period between each recorded chew. The reason that ten recordings are made is to insure the accuracy of the study by showing that the recorded event is not a one-time-only event . The total amount of food you will consume is approximately equivalent to a standard sandwich.

Disclaimer

In chewing and swallowing one could conceivably choke or suffer a dental injury. However, a warm-up period will be provided for you to become comfortable with the retainers and thus minimize the likelihood of injury. In the unlikely event of injury resulting from participation in this study you will be required to assume the responsibility for your own medical or dental care. There is also a small chance that you could be allergic to the foods used in the study. Personnel trained in the Heimlich Maneuver will be on hand in case of a choking incident.

Any information obtained in connection with this study that can be identified with you will remain confidential.

Your decision whether or not to participate will not jeopardize your future relations with Auburn University, the Department of Health and Human performance, and the Mechanical Engineering Department. Further, you may discontinue participation at any time without penalty. If you decide later to withdraw from the study, you may also withdraw any identifiable information which has been collected about you.

If you have any questions now or later, please feel free to contact Joseph McIntyre at (334)887-3374, E-mail at mcintjs@eng.auburn.edu , Or Dr. Nels Madsen at (334)844-4820, E-mail at nmadsen@eng.auburn.edu . You will be given a copy of this form to keep.

For more information regarding your rights as a participant you may contact the Offices of Research Programs, Ms. Jeanna Sasser at (334)844-5966, E-mail sassejb@auburn.edu or Dr. Steven Shapiro at (334)844-6499, E-mail shapisk@auburn.edu .

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

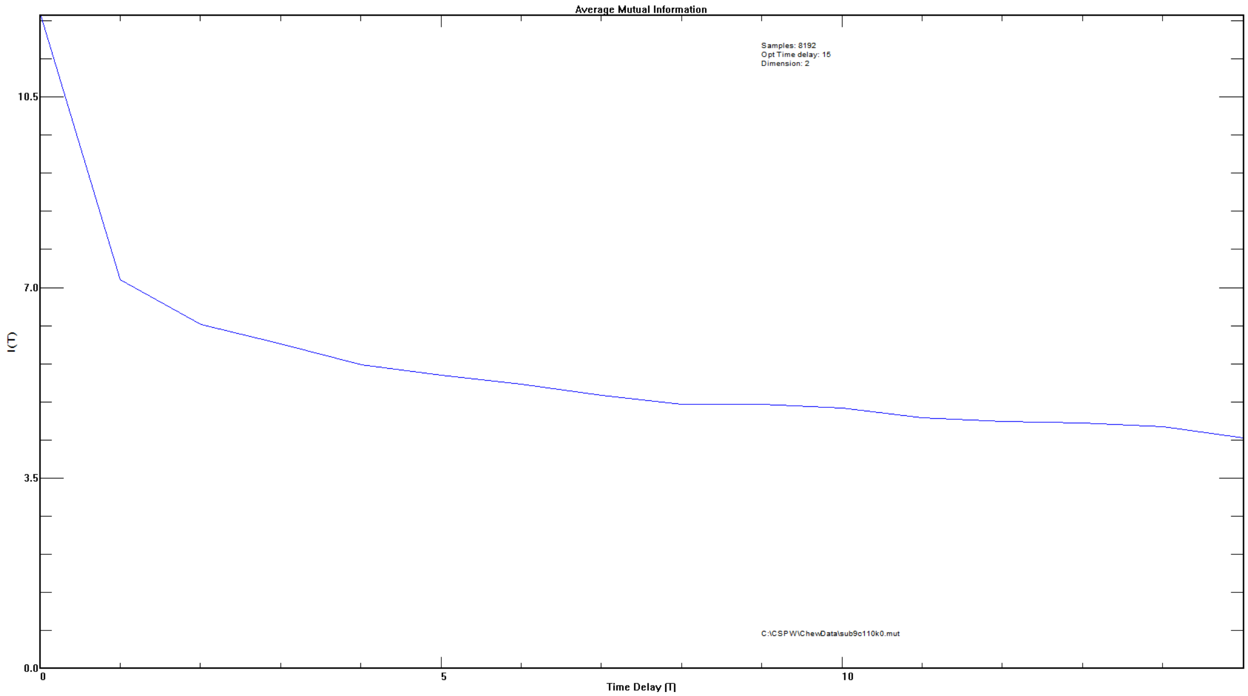
____
Participant’s signature Date Time

____
Investigator’s signature Witness

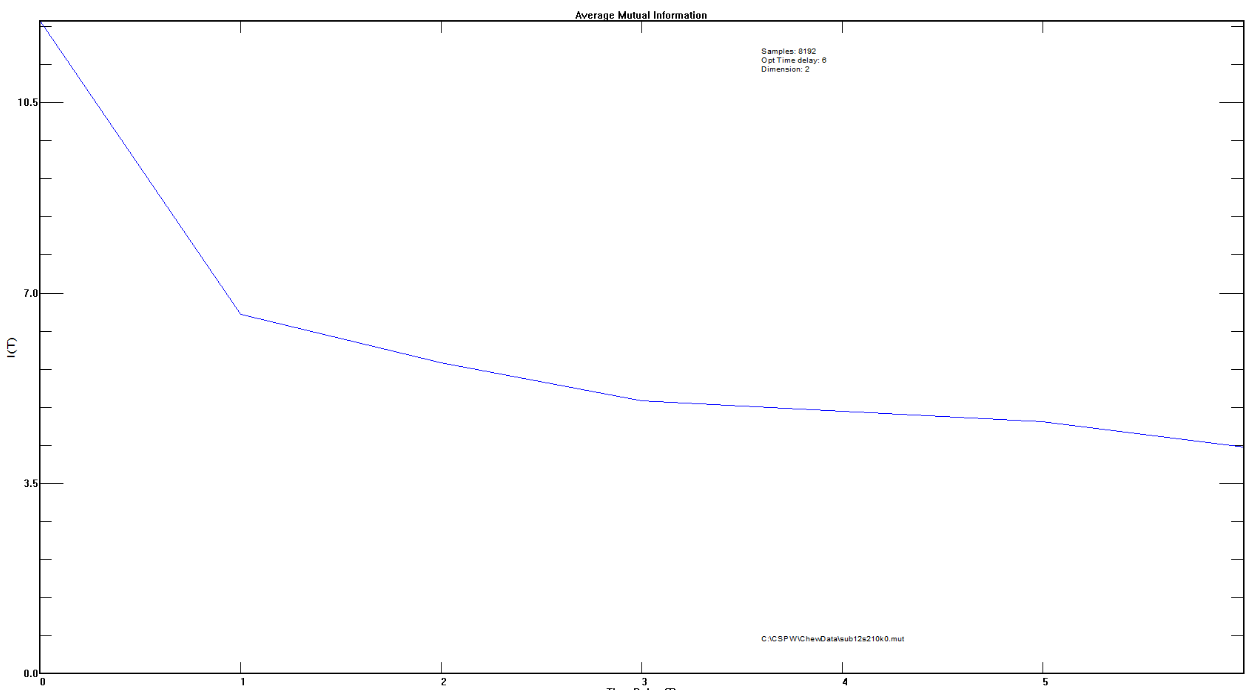
Page 2 of 2.

Appendix D

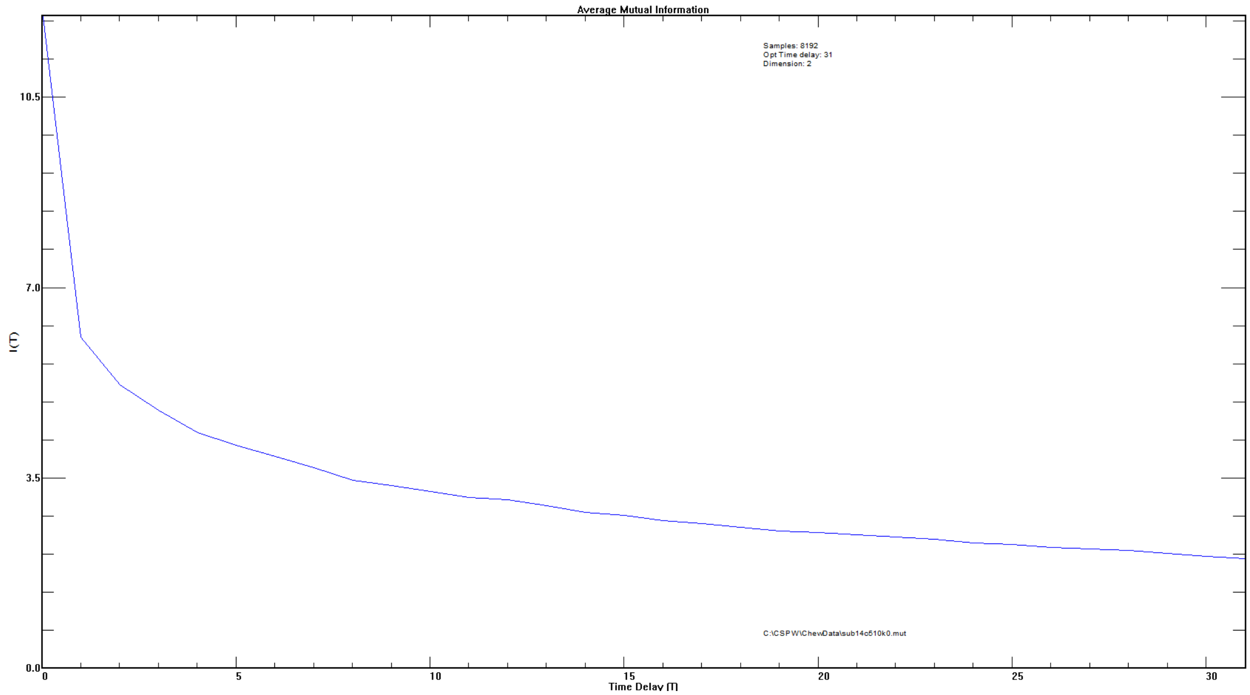
Graphs generated by the Contemporary Signal Processing for Windows version 1.2 for Male subject 4 cookie chew 1, Female subject 2 steak chew 2, and Female subject 3 cookie chew 5. Graphs given in order generated during analysis.



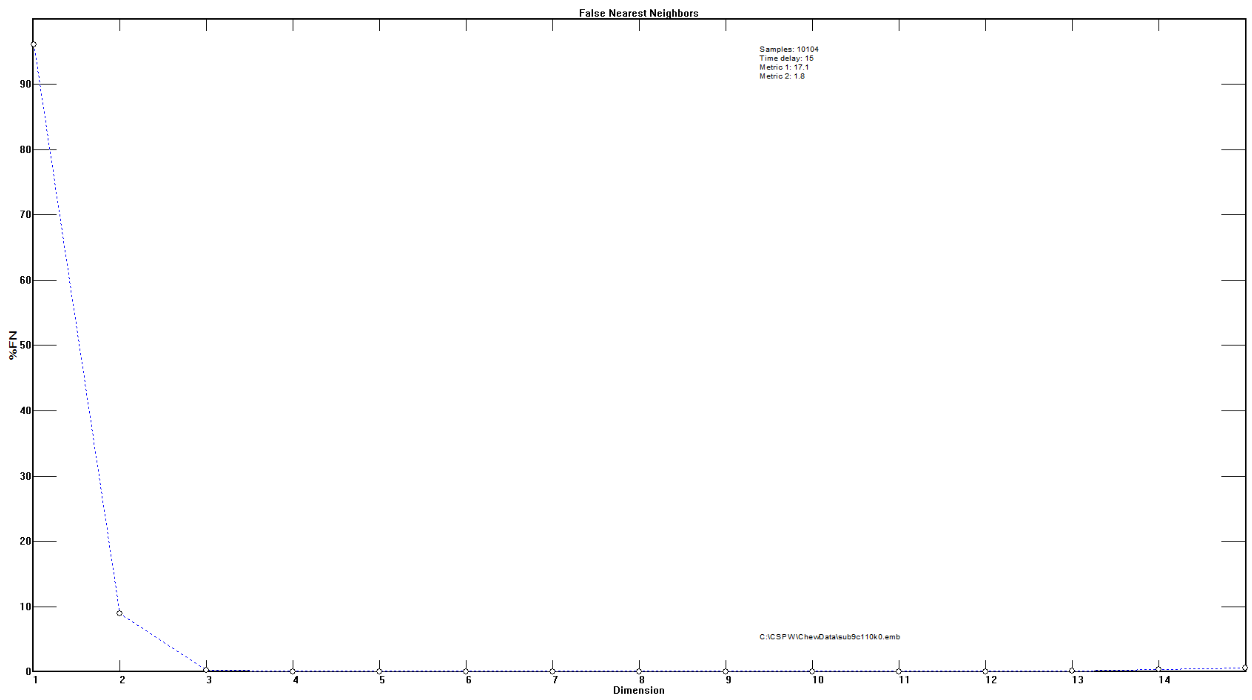
D 1. Male subject 4 cookie chew 1 AMI



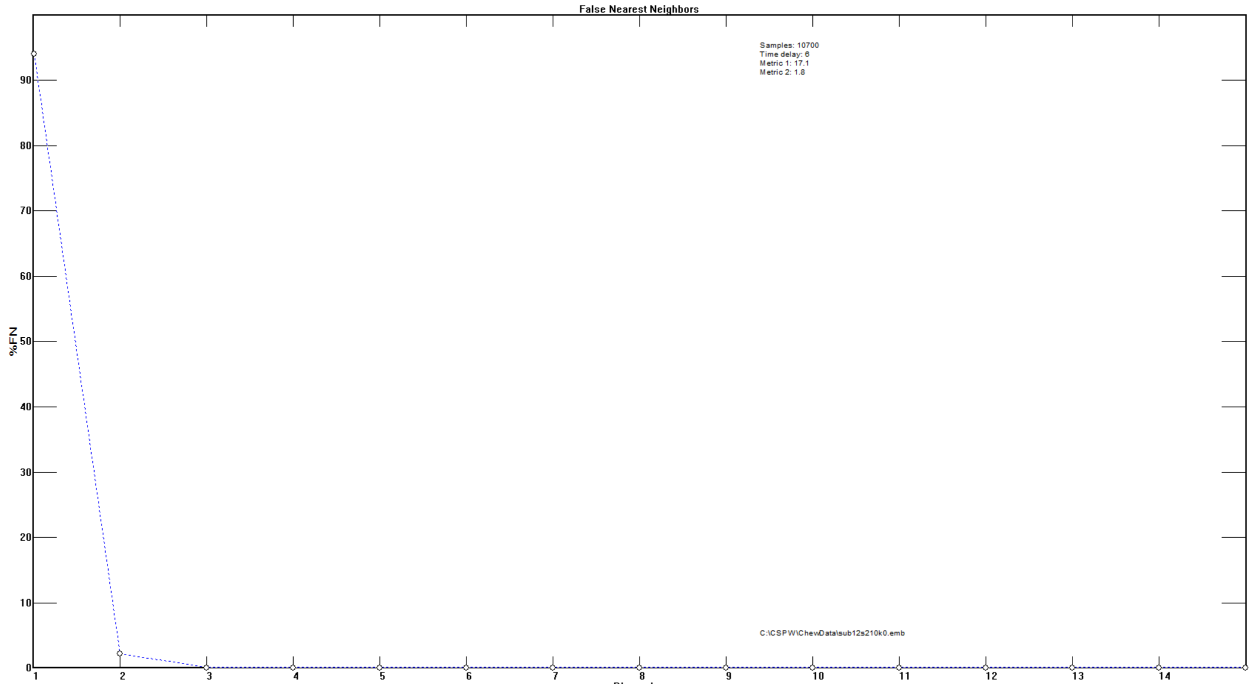
D 2. Female subject 2 steak chew 2 AMI



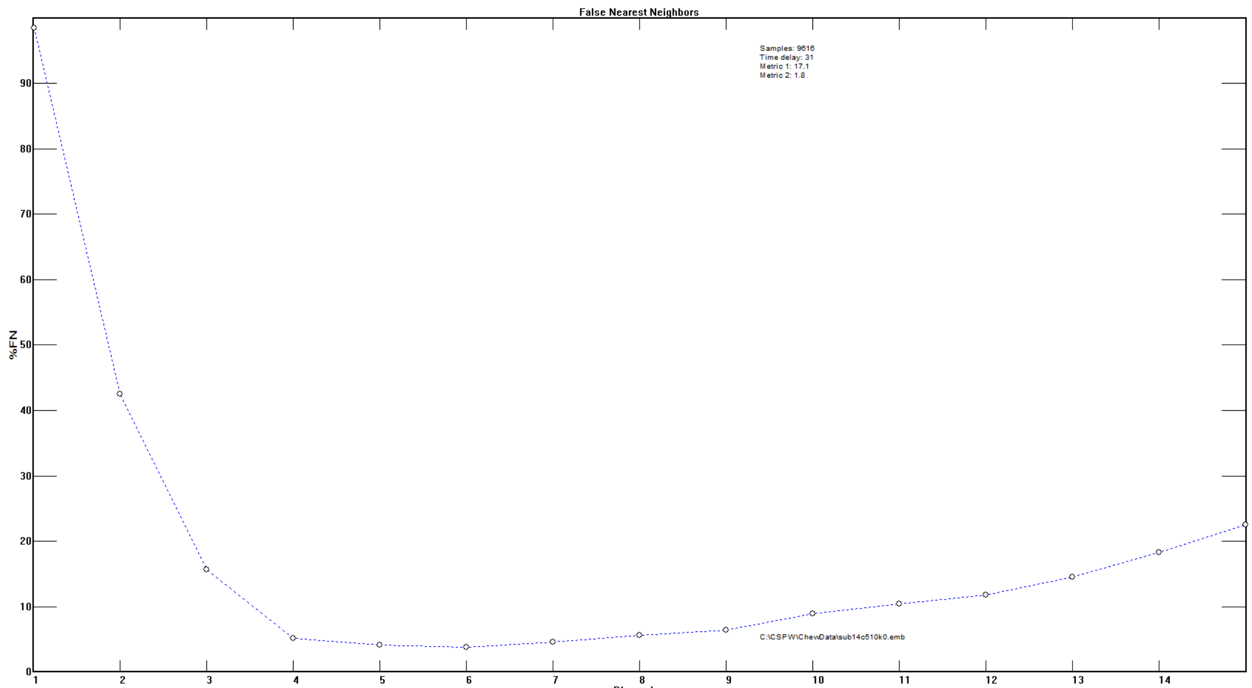
D 3. Female subject 3 cookie chew 5 AMI



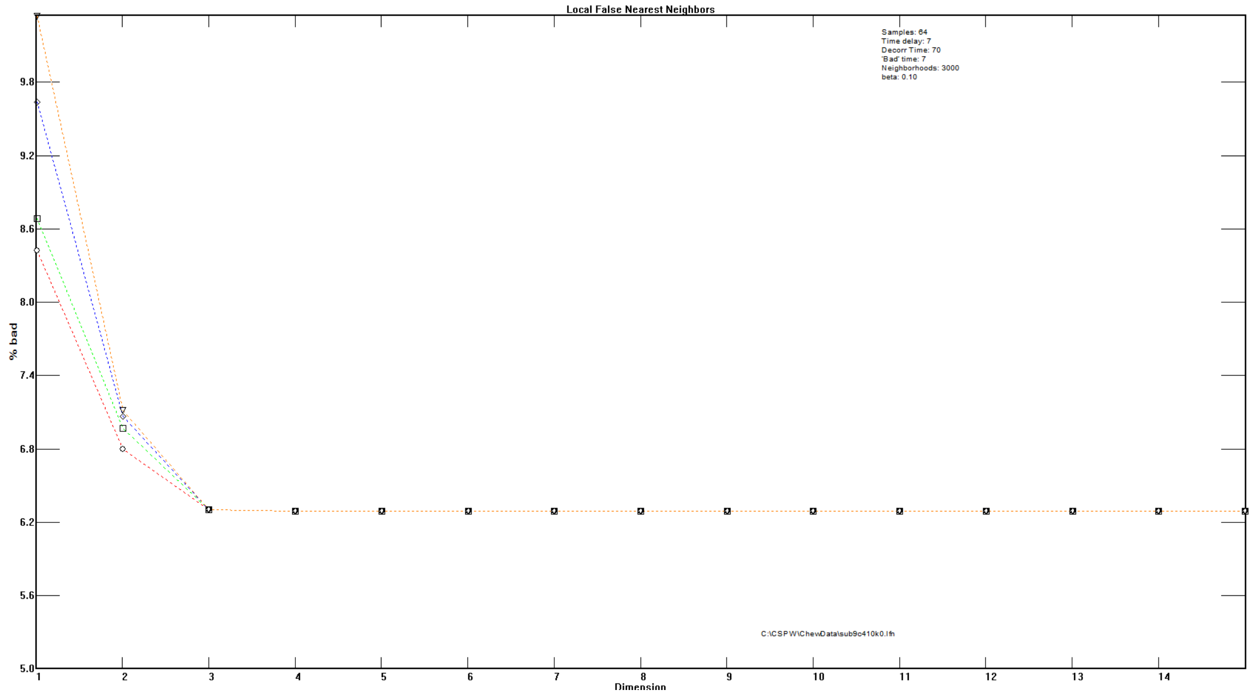
D 4. Male subject 4 cookie chew 1 Global dimension



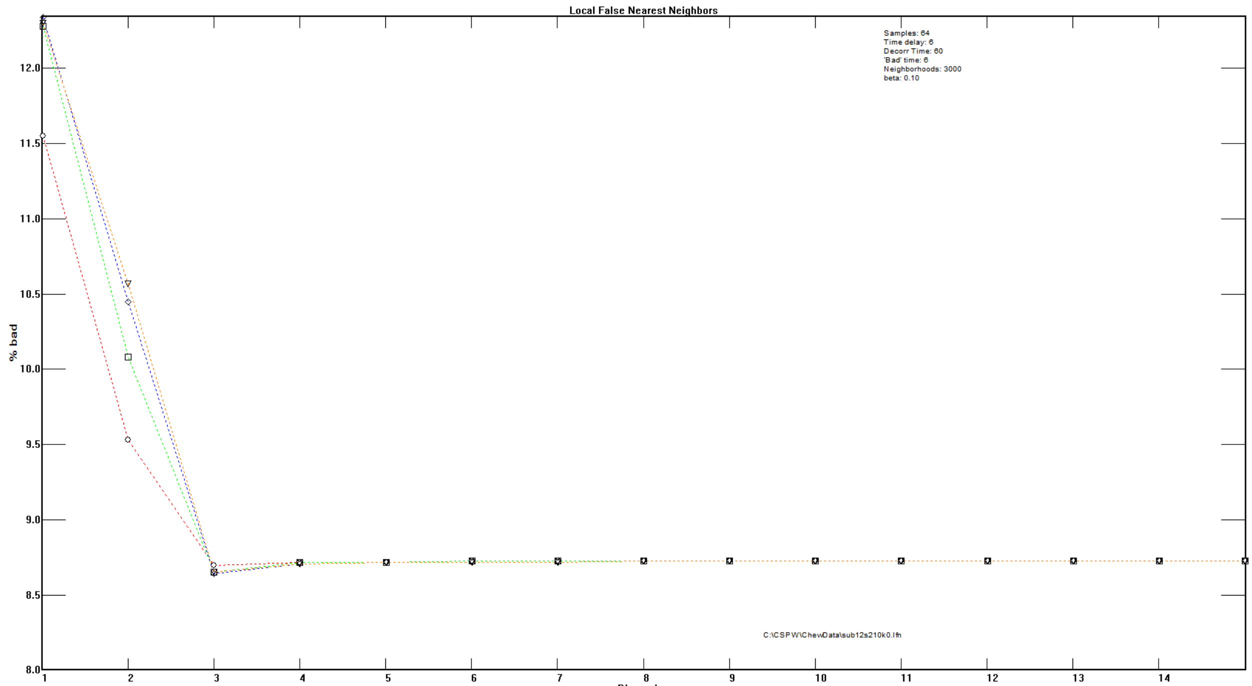
D 5. Female subject 2 steak chew 2 Global dimension



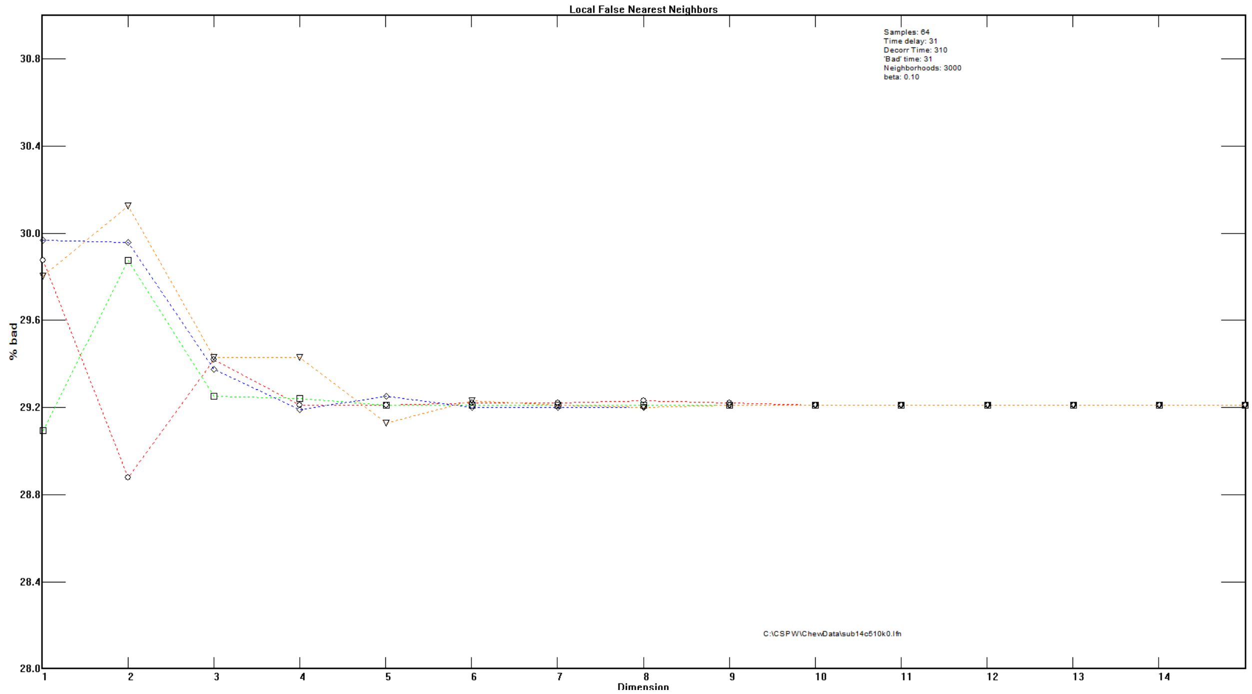
D 6. Female subject 3 cookie chew 5 Global dimension



D 7. Male subject 4 cookie chew 1 Local dimension



D 8. Female subject 2 steak chew 2 Local dimension



D 9. Female subject 3 cookie chew 5 Local dimension

Appendix E

Phase diagrams of physical systems that exhibit transition from periodic to chaotic dynamic character.

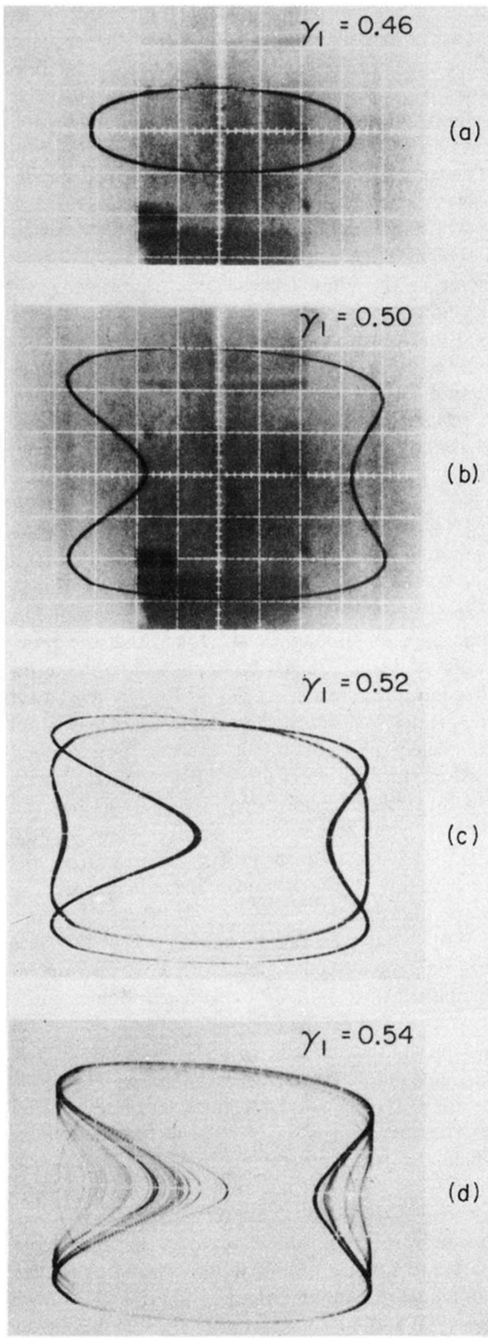
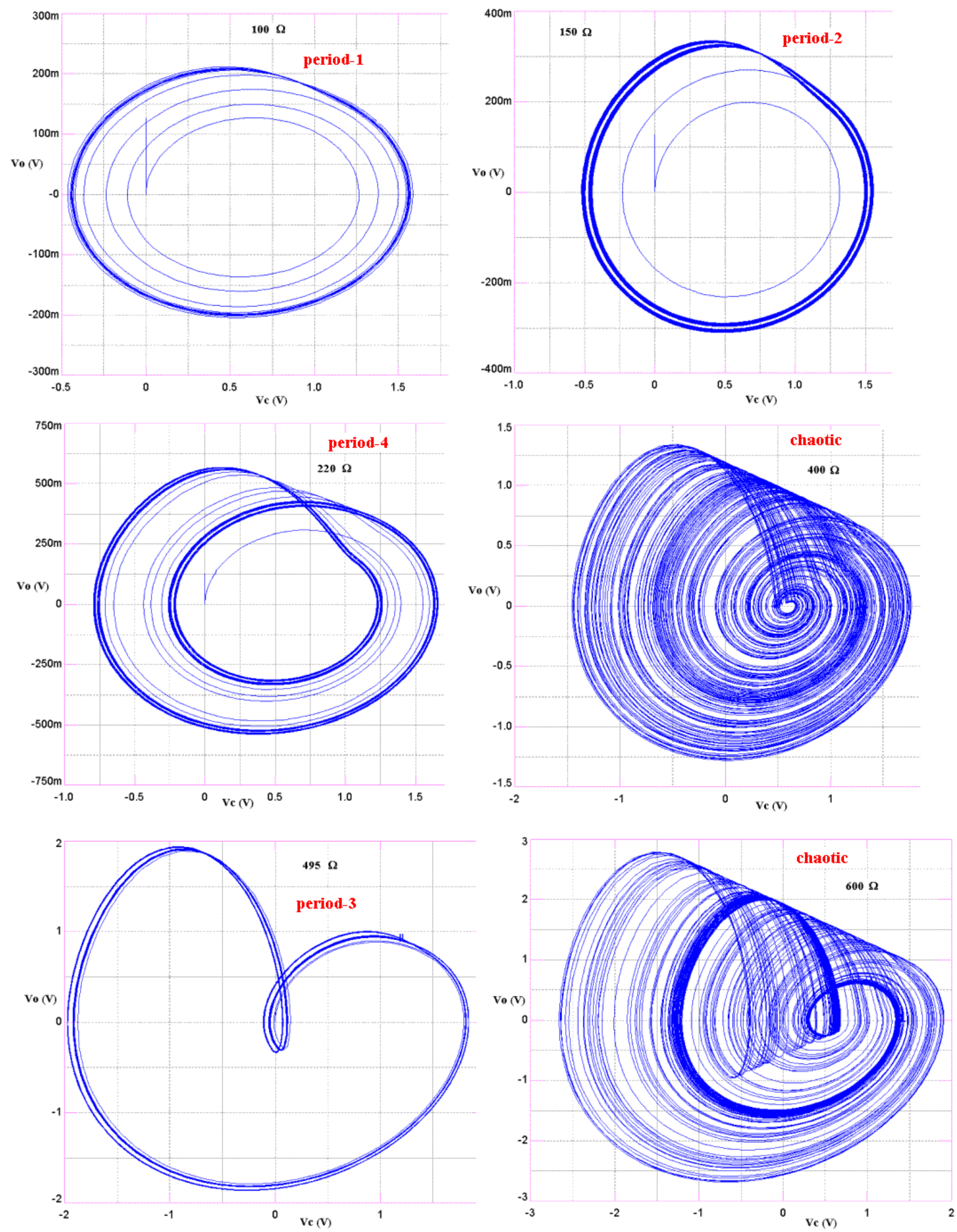


FIG. 5. (a) Evolution of the phase-space portraits ($\dot{\theta}$ vs $\sin\theta$) for increasing driving amplitude γ_1 at fixed frequency $\omega=0.67$. (b) Note the symmetry breaking, (c) followed by period doubling, (d) followed by chaos.

E 1. Forced Pendulum phase diagrams periodic to chaotic transition [25].



E 2. Phase diagrams for the Vilnius Chaotic Oscillator [26].