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Roadmap for In-Vitro Investigation of Interaction Between Food and Teeth

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***Abstract*—Investigating the interaction of teeth and food materials is beneficial for both oral health and the food industry. This paper presents the concept of in-vitro study of the interaction between the teeth and the food bolus through simulation of chewing process by means of a four-degree-of-freedom redundantly actuated parallel robot (RAPR). The required steps to address this research aim are presented, the constraints and technical challenges for each step are discussed, and preferred approaches to follow these steps are introduced. Finally, applications of this concept are presented and the necessity of this study for texture analysis of food materials for the food industry is highlighted.**

Keywords—Parallel robots; actuation redundancy; chewing robots; dynamics; kinematics

I. INTRODUCTION

The human digestive process can be divided into voluntary and automatic phases. Mastication at the beginning of the voluntary phase is the process of exerting forces on food materials by the teeth to apply plastic deformation and/or fracture of the food materials. Mastication increases the surface to volume ratio of the food materials, which allows for more effective action of enzymes on the food. The relationship between our diet and chewing performance requires close investigation to facilitate informed recommendation in oral hygiene. Investigating chewing performance requires studying the interaction of the food items with the teeth, and its effects on chewing related diseases such as pain in the temporomandibular joint (TMJ), pain in chewing muscles, and toothache. Moreover, investigating the interaction between the food items and the teeth benefits the food industry by analyzing the texture of the food materials. This investigation can be carried through a robotic chewing simulator, which is capable of bio-mimicking simulation of the mastication to recreate the complex cycle-to-cycle varying chewing process.

Many researchers have studied the human mastication system over last three decades. Xu et al. reviewed the human chewing mechanism and chewing robots in 2008 [1]. Both parallel [2], [3] and serial [4], [5] robots have been used to simulate mandibular movements. However, most of these robots have a parallel architecture because of the intrinsic advantages of such structures compared to the conventional serial architecture. Teeth, lips, cheeks, tongue, palate, salivary glands, TMJs, mandible, maxilla, and the muscles that articulate the mandible are body organs involved in mastication system. However, in robotic simulation of the mastication process, some of the softer tissues such as the lips, cheeks, and tongue are neglected depending on the purpose of the robotic device. Knowing the lines of action of masticatory muscles is a fundamental requirement for designing masticatory robots. In this regard, the direction of action of human masticatory muscles was studied through magnetic resonance imaging in [6].

Researchers have proposed different mechanisms for modeling and measuring the mandibular movements. Takanobu et al. [7] have developed WJ dental training robots as early as 1986. The prototype was the mouth opening WJ-1 training robot with one degree of freedom (DOF). Moreover, 3-DOF WJ-series robots were developed and studied in [8]–[12]. However, a robotic mandible requires more than three DOFs relative to the maxilla to reproduce natural mandibular movements. Therefore, aforementioned 1-DOF or 3-DOF robotic simulators cannot mimic the movements of the mandible. To tackle this problem, researchers proposed 6-DOF masticatory robots. WY-5 and WY-6 with six DOFs could be the first generation of such robots, which are studied in [13]–[15]. Moreover, a 6-DOF masticatory robotic device with six linear actuators was proposed and studied in [16]–[18]. Another 6-DOF chewing robot with 6SPS structure (S and P stand for a spherical joint and an active prismatic joint,

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respectively), in which linear actuations realized by combination of rotary motors and ball screws, was presented in [19]. A 6RSS (S and R stand for a spherical joint and an active revolute joint, respectively) chewing robot with six DOFs was introduced and studied in [2], [3].

Redundantly actuated parallel robots (RAPRs) employ more actuators than the overall DOFs of the mechanism. The biological masticatory system is a redundantly actuated mechanism due to being actuated by more muscles than the degrees of freedom of the mandible. Thus, a RAPR structure is more biologically congruent with the masticatory system than nonredundant parallel robots. Therefore, using RAPR structures in design of chewing robots enhances reproducing mandibular movements. Moreover, a critical issue in design of chewing robots is mechanical design of the TMJs. TMJs are sliding hinges where the mandible joints into the maxilla. TMJs are arguably the most complicated joints in the human body that provide the mandible with compound rotational and translational degrees of freedom. Thus, the bio-inspired 4-DOF 6PUS [20] and 4-DOF 6RSS [21] redundantly actuated chewing robots, which recreate these compound DOFs of TMJ, are the most advanced chewing simulators. These RAPRs were designed to bridge the gap between biological human chewing system and its robotic simulators. Although a number of research has been conducted regarding the chewing robots, further research is required to investigate the redundantly actuated parallel chewing robots and the interaction of a chewing robot with foods.

II. The 6RSS RAPR Structure

This paper discusses the investigation of teeth interaction with foods through a chewing robot depicted in Fig. 1. The robot has six actuators and four DOFs including two translational and two rotational DOFs. Therefore, this chewing robot is a RAPR with two degrees of redundancy (DOR). In this RAPR, two point contact higher kinematic pairs function as TMJs. The TMJs are implemented using point contacts between a curved slot and a ball. Fig. 2 shows the mechanical design of the robot's left TMJ. In this design, the curved slot fixed to the skull (base platform) represents the mandibular fossa, while the ball fixed to the mandible (moving platform) models the condyle. Six links, each of which comprised of a crank and a coupler, joint the base platform of the RAPR to its moving platform. Cranks are attached to the shafts of the actuators to realize the active revolute joints in the RAPR's structure. Each coupler is connected to both a crank and the mandible by spherical joints. Therefore, the RAPR is a 2-DOR 4-DOF 6RSS robot.

Three main steps, inverse kinematics, inverse dynamics, and model-based control of the 6RSS RAPR must be studied sequentially to investigate the interaction of the foods and the RAPR's teeth. These steps along with the application of the 6RSS robot will be presented in the following sections. Fig. 3 shows that the output of each step is an input for the next step and highlights the necessity of each step in realization of the other steps. In other words, each of these steps is a foundation for its following ones.

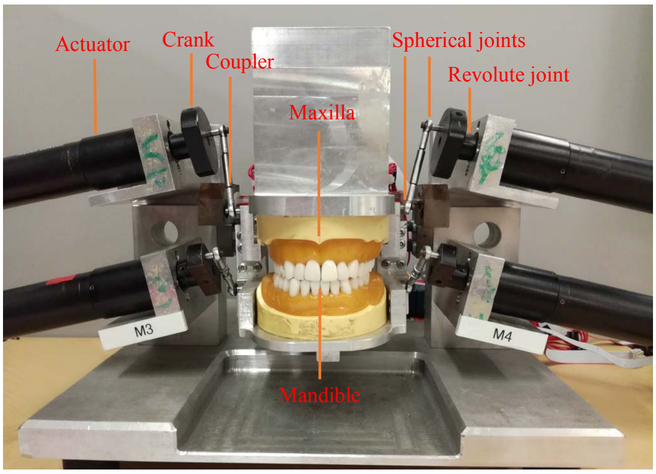

Fig. 1. Prototype of 6RSS RAPR.

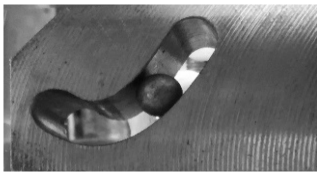

Fig. 2. Left TMJ model in 6RSS RAPR.

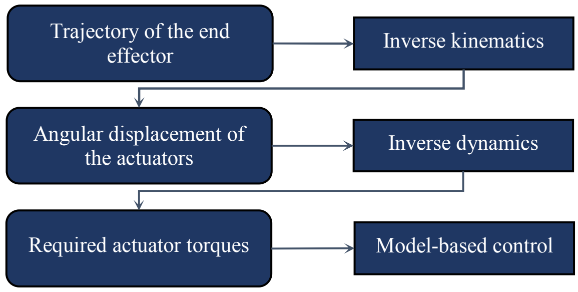

Fig. 3. Sequence of the steps for addressing the RAPR-food interaction.

III. Kinematics of 6RSS RAPR

Inverse kinematics of the 6RSS RAPR is the problem of finding the angular displacement of the actuators, i.e. θ_i, i=1,2,3,…,6, for a given trajectory, $\mathbf{q} = [X, Y, \beta, \gamma]^T$, where the variables X, Y, β, and γ are the four independent DOFs of the RAPR's mandible relative to its skull. The X and Y denote two independent translational DOFs of the mandible in a plane and β and γ are two independent rotational DOFs of the mandible around the Y-axis of the plane and the axis normal to the plane (Z-axis), respectively. Using the analytic method to solve the inverse kinematics problem of the RAPR results in closed form expressions for θ_i. However, the chewing trajectory is required as the input data for the inverse kinematics problem. Value of the variables X, Y, β, and γ can be acquired by capturing the mandibular movements of a human subject while he/she is chewing some food materials.

A custom-made brace (see Fig. 4) and an optical motion capture system, e.g. Vicon, can be used for capturing the subject's mandibular motion.

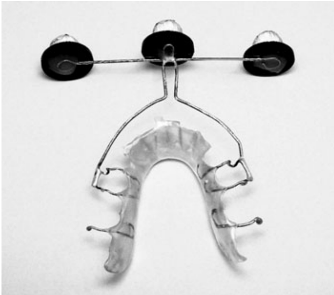

Fig. 4. Custom-made brace with three reflective markers [22].

Three reflective markers are required to be fixed to the subject's lower jaw in a nonlinear manner. Capturing the motion of three markers allows for capturing the rigid body motion of the mandible. The rigid body motion is required for acquiring both rotational (β and γ) and translational (X and Y) mandibular movements. These three markers can be fixed to the custom-made brace (see Fig. 4). A motion capture system can be employed to track these markers, while the human subject is wearing the brace and chewing food items. However, using the brace for capturing the motion of the mandible needs some considerations in terms of cancellation of inevitable motion of the subject's head during mastication. The motion of the head can be cancelled by placing other three reference markers on the subject's forehead. These markers record the motion of the head, afterwards, this motion will be excluded from the recorded motion of the mandible. Using an elastic headband is suggested for putting the forehead markers over it, which results in cancelling the relative motion of the soft tissue of the forehead with respect to the skull [23].

It is worth mentioning that bonding three markers directly on the subject's lower teeth to capture the motion of the mandible is not practical due to the limited visible area of the teeth during mastication. Experiments with a motion capture system have demonstrated that these cameras cannot distinguish the motion of individual small markers with a diameter of 3mm, when the inter-marker distances are less than two centimeters. Moreover, the markers cannot be bonded directly over the skin of the subject's mandible to capture the mandibular motion because of the relative motion of the soft tissue (muscles and skin) with respect to the jawbone. This relative motion affects the accuracy of the captured mandibular motion dramatically.

The Jacobian matrix can relate the velocities in the Cartesian space into the actuator velocities in the joint space. The Jacobian matrix of a RAPR is not a square matrix since the number of actuators is more than the robot's overall DOFs. In the case of 6RSS RAPR, the Jacobian matrix, $\boldsymbol{J}$, is a 6×4 matrix that relates the 4×1 vector of velocity of the mandible, $\dot{\mathbf{X}}$, to the 6×1 vector of velocity of the actuators, $\dot{\boldsymbol{\theta}}$.

$$\dot{\boldsymbol{\theta}} = \boldsymbol{J}\dot{\mathbf{X}} \ . \qquad (1)$$

IV. Dynamics of 6RSS RAPR

There are two main problems regarding the dynamics of the robots, including direct dynamic problem and inverse dynamic problem. The former is practical for computer simulation while the latter is the foundation for the model-based control of robots. The inverse dynamics of a robot is the problem of finding required torques/forces for a given trajectory of the end effector. The inverse dynamics of the 6RSS RAPR is required for the purpose of the model-based trajectory tracking control of the robot's mandible, which itself is needed for investigating the interaction of the RAPR's teeth and the food materials.

The additional actuator(s) in a RAPR make(s) its inverse dynamic problem more complicated than that of a nonredundant parallel robot. The inverse dynamics of a RAPR is an indeterminate problem since there are more unknowns than the number of the equations in this problem. Here, the number of unknowns is equal to the number of actuators and the number of equations is equal to the number of independent DOFs of the RAPR's end effector. However, this indeterminacy can allow alternative load distribution of the actuator torques/forces in RAPRs, which can be optimized for better performance. The most common optimization method is minimizing the Euclidian norm of the actuator torques/forces.

Conventional methods of solving the inverse dynamics of nonredundant parallel robots such as Lagrangian formulation, Newtown-Euler formulation, and the principle of virtual work can also be used to study the inverse dynamics of RAPRs. The Lagrangian formulation is more straightforward than the other two methods. In Lagrangian formulation, the potential and kinetic energies of the moving parts of the robot must be computed. However, in spatial robots with more complex structures, the Lagrangian formulation can impose computational burdens and is therefore time consuming. This complexity is due to the complicated rotational terms of the kinetic energy of the robot's legs. Assuming robot's legs masses as a point mass at the center of gravity of the legs alleviates this problem while retains an acceptable accuracy [24]. In the 6RSS RAPR, moving parts are the cranks, couplers, and mandible, see Fig. 1. As far as the 6RSS RAPR is concerned, the dynamics of the couplers result in intricate kinetic energy expressions. Therefore, the point mass assumption will be applied to the dynamics of the RAPR's couplers.

Lagrange's equations for the 6RSS RAPR can be formulated as,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = Q_{j_{n.c}} \qquad j = 1,2,3,4 \ . \qquad (2)$$

If K is the kinetic energy and P is the potential energy of the 6RSS RAPR, then $L=K-P$ is the Lagrangian of the RAPR. In (2), q_j and $\dot{q}_j$ are the j^{th} generalized coordinate and generalized velocity of the RAPR, respectively. $Q_{j_{n.c}}$ is the nonconservative generalized force corresponding to the j^{th} generalized coordinate. For the 6RSS RAPR, generalized coordinates are X, Y, β, and γ i.e. $\mathbf{q} = [X, Y, \beta, \gamma]^T$.

To have a more exact dynamic model of the chewing process for the model-based control of the RAPR, an approximation of the applied chewing forces to the molars will be evaluated. Measuring the chewing forces on incisors is neglected since they mostly contribute to the first bite, while a complete chewing process can have between 10 to 57 cycles [25]. FlexiForce B201 force sensor is proposed to evaluate the chewing forces on molars. This sensor is small enough to be used inside the oral cavity and has a paper-thin thickness. The FlexiForce B201 sensor is also flexible and water resistance, which are the required characteristics for being used inside the oral cavity. This sensor is available in different force sensing ranges including 0-4448N that covers the maximum biting forces between molars, which is in the range of 500-700N [1]. Because of the three dimensional surface of the molars, the sensors cannot be fixed to the occlusal surface of the molars directly. Therefore, the sensor will be bonded on a mouth guard and the human subject will be asked to chew the same food materials as those in the trajectory recording experiment while wearing the mouth guard. Therefore, an approximation of the normal chewing forces on the molars can be measured. These forces will be transferred to the coordinate system in which the generalized coordinates in (2) were measured, after which the components of these measured chewing forces will be added to the $Q_{j_{n.c}}$ in (2). Therefore, the components of the resultant mastication forces/torques corresponding to each generalized coordinate, Q_{j_R} , and therefore, the 4×1 vector of the resultant mastication forces/torques, $\mathbf{Q}_\mathrm{R}$, can be computed.

Using the principle of virtual work, the Jacobian matrix of a robot can relate the static forces/torques in the Cartesian space into the actuator forces/torques in the joint space. In the 6RSS RAPR, the 6×1 vector of required actuator torques and the $\mathbf{Q}_\mathrm{R}$ are related by,

$$\mathbf{Q}_\mathrm{R} = \boldsymbol{J}^\mathrm{T}\boldsymbol{\tau}\,, \tag{3}$$

where $\boldsymbol{J}$ is the 6×4 Jacobian matrix of the RAPR. Using (3), an optimization problem can be formulated to compute an optimal force distribution of the required actuator torques.

V. Control of 6RSS RAPR and food-teeth interaction

Controlling the RAPR's end effector to mimic a human being's chewing pattern is a key point to in-vitro investigation of the interaction between food and teeth. The actual dynamic response during the chewing process are affected by the shape, size, and angle of the teeth; interactions between the food and soft tissues such as tongue and cheeks; and changing food properties due to temperature changes and addition of saliva. The resulting unmodeled dynamics gives rise to uncertainties in model-based control algorithms. These uncertainties can be considered as disturbances. In general, for a measureable disturbance, a feedforward strategy can alleviate the effect of the disturbance [26]. However, in this study, the disturbance also included unmodeled dynamics of the 6RSS RAPR and the food, which are not measurable. Estimating the disturbance from measurable variables, and then, taking a control action based on the estimated disturbance to compensate for the effects of the disturbance is a strategy to deal with the unmodeled dynamics. This strategy is referred as disturbance/uncertainty estimation and attenuation (DUEA) approach in the literature [26]. Although the traditional feedback control was proposed to attenuate the influence of the disturbances, its intrinsic constraints restrict its application for compensating the disturbances [26]. For example, in the traditional feedback control, there is a trade-off between tracking and disturbance rejection. The DUEA approach can be used to resolve such constraints. Disturbance-observer-based control (DOBC) is a common DUEA method which is proposed for trajectory tracking control of the 6RSS RAPR's mandible. The DOBC consists of a feedback controller part and a feedforward controller part. The feedback part performs the tracking control, while the feedforward part compensates the disturbances and uncertainties [27]. A conceptual block diagram for the DOBC is depicted in Fig. 5, where y_r represents the reference signal, y is the system output, x is the state, u_{fb} is the feedback control output, u_{ff} is the feedforward control output, u is the control input, d is the disturbance, and $\hat{d}$ is the disturbance estimation. A review of the DOBC is presented in [26].

After the RAPR mimics the complex human-like chewing process accurately, the interaction of the RAPR's teeth with the food can be studied. For this purpose, load cells are proposed to measure the chewing forces exerted on the molars from the food materials during simulation of mastication by the RAPR. An ultra-compact UNCDW-500N load cell will be mounted under the molars of the 6RSS RAPR's maxilla for this purpose. This sensor is small enough to be mounted under the RAPR's molars and measure the normal component of chewing forces. These chewing forces are more exact than measured forces by FlexiForce B201 force sensors bonded on a mouth guard in the proposed experiment in Section IV. Measuring the chewing forces by the RAPR allows for including the interaction of the occlusal surface of the molars with the food materials.

In our natural chewing process, the chewing pattern changes continuously to achieve an effective trajectory to break down the food materials. Also, based on the muscle capabilities, there are limits on the maximum chewing force beyond which, the chewing trajectory is adjusted and the process is iterated. The DOBC is proposed for the model-based trajectory tracking control of the RAPR's mandible to reproduce the human-like chewing pattern. While the robot is mimicking the human being's chewing trajectory, the applied forces to the molars will be measured and compared with forces measured by sensors in motion capturing experiment. The chewing pattern will be changed based on the applied forces to the molars. When a new range of chewing forces is detected by the sensors, the RAPR will shift to another chewing trajectory compatible with the new range of chewing force on the molars. The chewing process will be continued until a minimum chewing force on the molars is detected. This minimum chewing force indicates that the food has been chewed sufficiently. This control strategy allows for continuous adaption of the chewing pattern to food materials based on the interactions between the food and the teeth. After the chewing process is completed, the size of the chewed food materials can be measured to evaluate the chewing efficiency.

VI. Significance of 6RSS RAPR investigations on food-teeth interaction

The 6RSS RAPR can be employed for the bio-mimicking simulation of the mastication process to study in-vitro interaction between different food items and teeth.

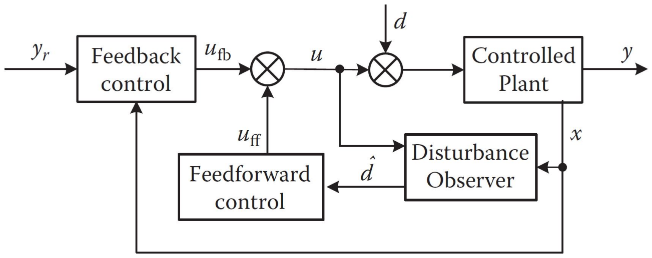

Fig. 5. Conceptual block diagram of DOBC [27].

This study is practical for dental material testing and design of dentures, reliability testing for implants, dental training, and study of chewing efficiency. Studying the physical properties and texture of the food materials is a requirement for the food industry that can also be performed by investigating the interaction of teeth and foods.

Texture plays an important role in customer preference for a particular food item. For example, people are unwilling to eat a mashed pizza, and changing the texture of wheat grains to bread loaves can command higher prices. It can similarly be argued that meat based proteins command higher prices compare to plant based proteins because of its pleasant texture. Therefore, analyzing the texture of the foods is beneficial for the food industry.

Common methods to measure the texture of foods can be classified into sensory and instrumental methods. In sensory method, human panels perform the measurement and report what they perceive by their senses through texture vocabularies such as smooth, crunchy, juicy, chewy, hard, soft, etc. Sensory method is subjective, its results vary for different panels and there is no consistent standard for this method. Even for the same panel this method can yield different results at different times, because of issues like the favorite textures for breakfast and lunch are different. People tend to use soft, creamy, and smooth foods in the morning while tougher foods are favorable for the lunch. On the other hand, in instrumental methods, mechanical machines are used to measure the mechanical properties of the food and the results are reported through stress-strain or force-deformation graphs.

Common instrumental tests are uniaxial tensile, compression, and bending. Instrumental tests, despite all the consideration for an accurate experiment, may lead to incorrect results for evaluation of the mechanical properties of the food items mainly due to the following reasons:

1) In these tests, materials are assumed isotropic and homogenous while most of the foods are anisotropic and heterogeneous.

2) Foods are mostly composite materials and the mechanical properties of them depend on the ingredients.

3) The tests are performed in constant velocities, while the rates of chewing cycles are different during the mastication of a food. Mechanical properties of food samples can be changed by the speed at which the load is applied. For example, at a low speed, a food material might behave as a ductile material, while higher speed could make it brittle.

Moreover, instrumental methods merely study the mechanical (procedure-independent) properties of the foods, while there are nonmechanical (procedure-dependent) properties involved in chewing process. Mastication is a dynamic process, the physical properties of foods change during the chewing cycles due to different interactions inside the oral cavity such as mixing the food materials with saliva. Therefore, instrumental methods can represent only a small part of the texture of foods.

Based on the discussion presented in this section, it can be concluded that new physical experiments are required to study the texture of the foods. The 6RSS RAPR can facilitate such experiments by studying the chewing process and the interaction between different food items and the RAPR's teeth.

VII. Conclusion

In this paper, the roadmap for experimental investigation of interaction between the teeth and foods during mastication is developed. A 4-DOF 6RSS RAPR is introduced and proposed as the robotic platform for performing the experiments in vitro. The technical challenges in conducting the proposed experiments are presented and proper solutions for them are proposed. Finally, application and necessity of the proposed concept in the food industry are discussed.

References

[1] W. L. Xu, J. E. Bronlund, J. Potgieter, K. D. Foster, O. Röhrle, A. J. Pullan, and J. A. Kieser, "Review of the human masticatory system and masticatory robotics," *Mech. Mach. Theory*, vol. 43, no. 11, pp. 1353–1375, 2008.

[2] W. L. Xu, J. D. Torrance, B. Q. Chen, J. Potgieter, J. E. Bronlund, and J. S. Pap, "Kinematics and experiments of a life-sized masticatory robot for characterizing food texture," *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 2121–2132, 2008.

[3] L. HUANG, W. L. XU, J. TORRANCE, and J. E. BRONLUND, "Design of a Position and Force Control Scheme for 6Rss Parallel Robots and Its Application in Chewing Robots," *Int. J. Humanoid Robot.*, vol. 7, no. 3, pp. 477–489, 2010.

[4] W. L. Xu, D. Lewis, J. E. Bronlund, and M. P. Morgenstern, "Mechanism, design and motion control of a linkage chewing device for food evaluation," *Mech. Mach. Theory*, vol. 43, no. 3, pp. 376–389, 2008.

[5] C. Sun, W. L. Xu, J. E. Bronlund, and M. Morgenstern, "Dynamics and compliance control of a linkage robot for food chewing," *IEEE Trans. Ind. Electron.*, vol. 61, no. 1, pp. 377–386, 2014.

[6] J. H. Koolstra, T. M. G. J. van Eijden, P. H. van Spronsen, W. A. Weijs, and J. Valk, "Computer-assisted estimation of lines of action of human masticatory muscles reconstructed in vivo by means of magnetic resonance imaging of parallel sections," *Arch. Oral Biol.*, vol. 35, no. 7, pp. 549–556, 1990.

[7] H. Takanobu, A. Takanishi, and I. Kato, "Control of a mastication robot for reduction of jaw joint force focusing on musculus temporalis," *IEEE/RSJ/GI Int. Conf. Intell. Robot. Syst.*, vol. 3, pp. 1824–1831, 1994.

[8] A. Takanishi, T. Tanase, M. Kumei, and I. Kato, "Development of 3 DOF Jaw Robot WJ-2 as a Human's Mastication Simulator," *Fifth International Conference on Advanced Robotics (ICAR)* . pp. 277–282, 1991.

[9] H. Takanobu, a. Takanishi, and I. Kato, "Design of a mastication robot mechanism using a human skull model," *Proc. 1993 IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS '93)*, vol. 1, no. C, pp. 203–208, 1993.

[10] H. Takanobu, T. Tanase, a. Takanishi, and I. Kato, "Adaptive masticatory jaw motion using jaw position and biting force\ninformation," *Proc. 1994 IEEE Int. Conf. MFI '94. Multisens. Fusion Integr. Intell. Syst.*, pp. 360–365, 1994.

[11] H. Takanobu, T. Yajima, and A. Takanishi, "Development of a mastication robot using nonlinear viscoelastic mechanism," in *Proceedings of the 1997 IEEE/RSJ International Conference on Intelligent Robot and Systems. Innovative Robotics for Real-World Applications. IROS '97*, 1997, vol. 3, pp. 1527–1532.

[12] H. Takanobu, T. Yajima, M. Nakazawa, a. Takanishi, K. Ohtsuki, and M. Ohnishi, "Quantification of masticatory efficiency with a mastication robot," *Proceedings. 1998 IEEE Int. Conf. Robot. Autom. (Cat. No.98CH36146)*, vol. 2, no. May, 1998.

[13] H. Takanobu, T. Maruyama, A. Takanishi, K. Ohtsuki, and M. Ohnishi, "Mouth opening and closing training with 6-DOF parallel robot," *Robot. Autom. 2000. Proceedings. ICRA '00. IEEE Int. Conf.*, vol. 2, no. April, pp. 1384–1389 vol.2, 2000.

[14] H. Takanobu, T. Akizuki, A. Takanishi, K. Ohtsuki, D. Ozawa, M. Ohnishi, and A. Okino, "Jaw training robot that manipulates patient's jaw to sideway," in *IEEE/RSJ International Conference on Intelligent Robots and System*, 2002, vol. 2, no. October, pp. 1463–1468.

[15] A. Okino, T. Inoue, H. Takanobu, A. Takanishi, K. Ohtsuki, M. Ohnishi, and Y. Nakano, "A Clinical Jaw Movement Training Robot for Lateral Movement Training," *IEEE Int. Conf. Robot. Autom.* , vol. 1, no. 6, pp. 244–249, 2003.

[16] J. S. Pap, W. L. Xu, and J. Bronlund, "A robotic human masticatory system: kinematics simulations," *Int. J. Intell. Syst. Technol. Appl.*, vol. 1, p. 3, 2005.

[17] J. Bronlund and J. Kieser, "Choosing New Ways to Chew," *IEEE Robot. Autom. Mag.*, no. June, 2005.

[18] B. Daumas, W. L. Xu, and J. Bronlund, "Jaw mechanism modeling and simulation," *Mech. Mach. Theory*, vol. 40, no. 7, pp. 821–833, 2005.

[19] W. L. Xu, J. S. Pap, and J. Bronlund, "Design of a biologically inspired parallel robot for foods chewing," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 832–841, 2008.

[20] H. Wen, W. Xu, and M. Cong, "Kinematic Model and Analysis of an Actuation Redundant Parallel Robot With Higher Kinematic Pairs for Jaw Movement," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1590–1598, Mar. 2015.

[21] C. Cheng, W. Xu, and J. Shang, "Distributed-Torque-Based Independent Joint Tracking Control of a Redundantly Actuated Parallel Robot with Two Higher Kinematic Pairs," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1062–1070, 2016.

[22] O. Röhrle, J. N. Waddell, K. D. Foster, H. Saini, and A. J. Pullan, "Using a motion-capture system to record dynamic articulation for application in CAD/CAM software," *J. Prosthodont.*, vol. 18, no. 8, pp. 703–710, 2009.

[23] D. Raabe, A. Harrison, K. Alemzadeh, A. Ireland, and J. Sandy, "Capturing motions and forces of the human masticatory system to replicate chewing and to perform dental wear experiments," *Proc. - IEEE Symp. Comput. Med. Syst.*, 2011.

[24] N. Mostashiri, A. Akbarzadeh, J. Dhupia, A. Verl, and W. Xu, "A comprehensive inverse dynamics problem of a Stewart platform by means of Lagrangian formulation," in *Proceedings of the ASME 2017 Dynamic Systems and Control Conference, in press.*

[25] M. C. BOURNE, "Is rheology enough for food texture measurement?," *J. Texture Stud.*, vol. 6, no. 2, pp. 259–262, Jun. 1975.

[26] W. Chen, J. Yang, L. Guo, and S. Li, "Disturbance-Observer-Based Control and Related Methods-An Overview," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1083–1095, Feb. 2016.

[27] S. Li, J. Yang, W. H. Chen, and X. Chen, *Disturbance Observer-Based Control: Methods and Applications*. CRC press, 2014.