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Design of mastication robot with life-sized linear actuator of human muscle and load cells for measuring force distribution on teeth[☆]

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ABSTRACT

In this paper, we present a design of mastication robot for texture analysis of foods in similar environment of human masticatory process respect to the following two things: First, subminiature load cells were installed at each artificial tooth of the upper jaw in order to directly measure interaction forces between the each tooth and foods. Collecting the sensor signals on each tooth, we can see which of teeth dominantly interacts with foods and analyze different patterns of the interaction forces among the incisor, cuspid and molar teeth. Second, we developed linear actuators for human masticatory muscles, which size, acting force, and coordination of attachment match with human counterpart. By appropriately coordinating the linear actuators, the resultant jaw motion can replicate the human chewing motion; thus, it generates similar patterns of the interaction forces between human teeth and foods. Two experiments for realization of the chewing motion and analysis of interaction forces between each tooth and food samples were conducted to evaluate the effectiveness of the developed mastication robots.

1. Introduction

Texture of foods is “sensory and functional manifestation of the structural, mechanical and surface properties of food detected though the senses of vision, hearing, touch, kinesthetics” [1]. The mechanical characteristics of the texture such as hardness, cohesiveness, viscosity, elasticity, and adhesiveness can be quantified by commercial texture analyzers (e.g. Inc. Stable Micro Systems), and those analytical results can be used in assessment of food development.

The procedure of the analytical method is measuring interaction force between foods and probes with simple shape such as cylinder, pin, corn, and blade during the once or twice bites. However, the experimental environment is quite different from that of human masticatory process; thus, it seems that the results do not accurately reflect the human sense. For the more advanced texture analysis, therefore, it is necessary to make the experiment environment maximally similar to that of the human masticatory process in the following two things: 1) The interaction forces between the human teeth and foods should be measured. 2) Development of a mastication robot to replicate the human chewing behavior is needed in order to generate the similar pattern of the interaction forces between the human teeth and foods.

As the research of the first one, the authors of [2] used the artificial teeth probes of upper and lower jaw, and installed a pressure sensor under a molar tooth, in which a biting experiment was conducted with 1-D chewing trajectory. In [3], ring-shaped array of molar teeth for upper and lower jaw was used and 2-D chewing motion was enabled by vertical translation and rotation. The crushing force of lower jaw was estimated from current of actuators. In [4], the 2-D chewing motion was realized by six-bar linkage robot, and a load cell are installed under the molar teeth to measure the interacting forces between the molar teeth and foods. In [5,6], the artificial teeth probes was embedded in the commercial texture analyzer and the clenching motion of jaw was enabled and the overall biting force was measured by a load cell incorporated in the texture analyzer.

The research of the mastication robot has initially conducted in purpose of dentistry. In [7–9], Waseda–Yamanashi (WY) series of robots have been developed for dental training of jaw disorder patients. Although WY-5 and WY-6 which are the most advanced versions have 6 degrees of freedom (DOF), the detailed design does not match the human counterpart except the movable range. In [2,10–12], Waseda Jaw (WJ) series of robots have been developed in order to analyze relationship between a patient’s jaw movement and resistance forces due to temporomandibular joint (TMJ) dysfunction, for which total 9 masticatory muscles were implemented by tendon mechanism.

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However, the maximum DOF of the WJ robot is only 3 DOF. The research group of [13–15] presented a conceptual design of the mastication robot for the texture analysis of foods. In this design, the masticatory muscles are modeled as a linear actuator, and 6 DOF of the lower jaw is enabled by bi-directional actuation of total 6 linear actuators. Furthermore, their lengths and attachment coordinates were design by biomechanical findings of jaw structure and characteristics of the masticatory muscles [16], which results in accordance of force direction between the linear actuators and the masticatory muscles. However, to the best our knowledge, the linear actuators with the same length and contracting force to human muscles have not been yet developed.

The contributions of this paper are as follows: First, our masticatory robot can measure the interaction forces between each human tooth and foods by installing subminiature load cells at each artificial tooth of the upper jaw. It is notable that the authors of [2–4] considered only the molar teeth; thus, the texture analysis such as biting a cookie with incisor and cuspid teeth is not enabled. The biting force measured in [5,6] is resulted from interaction with the incisor and cuspid teeth as well as the molar teeth; however, the effects of those teeth cannot be distinguished. In this paper, the interaction force of each tooth can be independently measured; thus, we can analyze the different force pattern of the incisor, cuspid, and molar teeth separately, and we can identify which of teeth dominantly interacts with foods.

Second, we first present a mechanism for the linear actuators which fully satisfies the requirements of [13–15] such as size, acting force, coordination of attachment of the masticatory muscles. It is notable that there have been two mechanisms that mimic the linear motion of the masticatory muscles: a revolute-spherical-spherical(RSS) parallel mechanism which is similar to crank mechanism [17] and a prismatic-universal-spherical(PUS) parallel mechanism [18]. However, both mechanisms are not linear actuators in a strict sense, and the position of the origin of muscle in both mechanisms is moved by rotation of crank and movement of prismatic slider, respectively. As a result, the direction of acting force of both the mechanism does not coincide with that of the human muscle. Furthermore, in view of kinematics, our robot system provides simpler inverse kinematics, which results in easier calculation of length of each linear actuator.

The remaining part of the paper is organized as follows. In Section 2, detailed hardware design of the mastication robot in this paper is presented. In Section 3, the design of control system for human masticatory motion and its implementation are presented. In Section 4, two experiments for realization of the human masticatory motion and texture analysis in the realized masticatory process are presented. In Section 5, we conclude this paper.

2. Hardware design

2.1. Mechanical device of life-sized linear actuator for human masticatory muscles

As mentioned in introduction section, the linear actuators with the human muscle length and contracting force have not been developed in a strict sense. In this paper, however, we propose a mechanical device for the linear actuator which fully satisfies the requirements of the conceptual design such as size, motion speed, acting force, and coordinates of attachment of the human masticatory muscles. Fig. 1(a) describes mechanism for the proposed linear actuator. Main body of the linear actuator is a certain slider (M-4), which length is determined by the linear motion between the upper and lower parts of the slider. Muscle origin and insertion are modeled as ball joints (M-1). Because the ball joint enables any rotational motion between the jaw and the connected slider, the direction of actuation of the linear actuator always coincides with that of the resultant muscular force. The principle of the linear actuation is same to that of a block and tackle system. One end of a steel wire (M-2) is attached to the pulley (M-3) which is connected to the motor axis. The wire is guided along V groove which is engraved along circumference of the slider, and is attached to the upper part of the slider with screw (M-5). When the wire is wound by the motor, the lower part of the slider moves in contracting direction. When the wire is released, on the contrary, the slider recovers its length by spring (M-6) which is installed inside of the slider. The pin (M-7) shown in Fig. 1(b) prevents the lower part of slider from breaking away from its upper part by the spring force.

Fig. 2 shows dimensions of the linear actuators and their operational ranges and Table 1 shows the attachment coordinates of the linear actuators which are represented as the origin and insertion of the corresponding masticatory muscles in the closed-mouth position, which data are referred from [15]. Note that there is modification that the coordinates of y axis of Masseter translate outward to 3 mm in order to avoid collision between the linear actuator of Masseter and the lower jaw. However, the direction of the linear actuator of Masseter is unchanged because y-coordinate of both origin and insertion are translated with the same degree. The operation range of each linear actuator is designed as shown in Table 1.

2.2. Design of spring installed in the linear actuators

The successful development of the proposed linear actuator critically depends on design of the spring installed in the device. The spring should generate sufficient recovering force as well as guarantee fatigue life. Increasing coil diameter of the spring results in increase of the recovering force; however, the fatigue life decreases. In order to guarantee the fatigue life, outer diameter of spring should also be increased. However, the increased diameter causes size problem of the linear actuator and collision of the linear actuator with other parts. Therefore, there is trade-off between the size and the fatigue life of spring.

In this paper, we obtain the smallest outer diameter of spring guaranteeing both force capability and fatigue life via numerical optimization. In the optimization problem, the design parameters are the mean diameter of spring D_m, the coil diameter d, the free height H_f, and the effective turns N_e. The constants are the required length of stroke L_m, the preloaded height H_p, the required minimum spring force P_{min}, the required maximum spring force P_{max}, shear Modulus G, and tensile strength S_u. The material of spring is music wire (ASTM A228) and its shear Modulus and tensile strength are $G = 8000$ kgf/mm^2 and $S_u = 215$ kgf/mm^2, respectively. The followings are equations and requirements for spring designs [19]: The pitch of spring p is

$$p = (L_f - 1.5d)/N_e.$$

According to design guidance, the pitch should be bounded as

$$p \leq 0.5D_m. \tag{1}$$

The maximally allowable stroke length L_a is

$$L_a = H_f - H_s$$

where $H_s = N_t d$ is the solid height and $N_t = N_e + 2$ is the total turns. For the linear operation of the spring, the actual stroke length should be within 85% of L_a, i.e.,

$$(H_f - H_p) + L_m \leq 0.85L_a \tag{2}$$

The spring constant K is

$$K = \frac{Gd^4}{8N_e D^3},$$

and the corresponding spring force F becomes

$$F = KL.$$

The minimum (pre-loaded) force F_{min} and the maximum force F_{max} become when $L = H_f - H_p$ and $L = (H_f - H_p) + L_m$, respectively. For the given values of P_{min} and P_{max}, it is required that