Chapter 5
Mastication Robot of a Crank-Slider Linkage*

Abstract. This chapter outlines the development of a linkage-based masticatory device for use in food evaluation that is capable of performing a range of standardised chewing trajectories. The robot design was required to match the trajectory of the first molar and the forces applied on the foods as measured during human chewing experiments performed in-vivo. A four-bar linkage was synthesized to achieve a lateral chewing trajectory of the molar. By adjustment of the ground link length, any trajectory between lateral (grinding) and vertical (crushing) chewing motions was possible. A six-bar crank-slider linkage was then designed in order to guide the movement of the mandible in a set orientation whilst maintaining the chewing trajectory produced by the four-bar linkage. The chewing device based on the six-bar linkage was constructed inclusive of: anatomically correct teeth for reducing the food particle size, a food retention device for collection of the food particles being chewed and a shock absorber for preventing the application of excessive chewing forces. The linkage chewing device was evaluated by way of kinematics and dynamics simulations together with a comparative analysis of the actual measurements of the trajectory and chewing force. The chewing velocity along the trajectory was profiled for both the occlusal and opening/closing phases of the chewing process and used for the set points for motion control. Variations to account for differences in chewing cycle velocity profiles were made to be adjustable through a graphical user interface developed in LabView. The masticatory device was validated against experimentation involving the chewing of example food systems and comparison of the resultant particle size within the bolus produced by the device and those produced by human subjects for the same food stuffs.

5.1 Why a Linkage Mechanism for Mastication

The human masticatory system is a complex system that comprises of an upper and a lower jaw, both of which have teeth. The system also includes a tongue,

cheek and saliva production capability. When mastication is performed, the lower jaw (mandible) is moved by muscles that are attached between it and the upper jaw [1]. The chewing movement begins with the mandible opening, thereby creating a space between the teeth located on the skull and the mandible. The tongue then relocates food particles that require chewing to the molars on one side of the mouth. The mandible then closes and breaks up these food particles. The particles then fall off the teeth back on to the tongue enabling repositioning during the next chewing cycle [2]. The opening movement of the mouth during the chewing cycle is approximately vertical [3]. The speed with which the mandible moves during the opening phase is initially slow and increases as the mouth opens. When the mouth starts to close, the mandible moves laterally outward, initially it closes quickly as it comes back towards the teeth, and then slows for occlusion.

In the frontal plane, the trajectories of the teeth during chewing vary substantially for different food types, but, are very close to a straight line in the sagittal plane [4]. This line may vary from a vertical line, where the teeth come together at a $0^\circ$ angle, and a line where the teeth come together at a $30^\circ$ angle. The trajectories used to chew different food particles differ depending upon both the shape and the texture of the food particles, thus generating a different chewing action for different foods. If a vertical chewing motion is used, the cusps of the teeth are used in order to fracture food particles. In comparison, when a more lateral chewing motion is employed, the sharp edges of the teeth are used and function as blades and allow food particles to be cut up into pieces [5].

As food properties affect the chewing trajectories, a considerable amount of work has been done to determine chewing movements in food sciences [3, 4, 5]. Measurements of these various chewing movements have been made continuously over the masticatory process, and include the following parameters: frequency, length of chewing time, tracking of jaw movement, force distribution, application of compression and shear forces on the food together with the particle size and structure of the bolus just prior to swallowing. Results vary between subjects (e.g. due to differences in jaw geometry, teeth shape and sensitivity to pain) and across various food textures (e.g. elasticity, hardness, adhesion especially to dentures etc.).

There are a variety of instruments or devices available for evaluating food properties. However, such devices usually use a simple straight motion (mostly food compression) and are not capable of simulating the entire suite of complex functions and movements involved during human mastication. Since the early 1990s, there have been various attempts at developing masticatory robots for food texture assessment (as reviewed in Chapter 1). While robotic chewing devices that possess multiple DOFs are able to reproduce chewing behaviour in a 3D space, a single DOF linkage device for chewing is the objective in this Chapter. A linkage device is simple in both structure and motion control and is more reliable than more complex systems in terms of its operation. The presence of a straight line trajectory in the sagittal plane presents the opportunity to approximate human chewing motion in 2D using a simple linkage device.