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# Modelling and quality control of robot-assisted gastrointestinal assembly

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ABSTRACT

Surgical soft tissue assembly is characterized by the hyperelasticity, bio-compatibility of the parts to be joined and the specific medical evaluation criteria which differs from traditional mechanical assembly. The minimally invasive surgical (MIS) robot equipped with a functional end-effector is an effective platform for the complicated surgical task. This paper presents a mechanical model of robot-assisted gastrointestinal assembly and the use of such model in the control of assembly quality. The finite element method (FEM) simulation illustrates the stress distribution and joint formation process. The geometrical parameters of the assembled B-shaped staple are used to optimize variables in the mechanical model.

## 1. Introduction

Soft tissue assembly during surgeries, such as enterorrhaphy and angiorrhaphy, differs from traditional mechanical assembly such as single-sided piercing riveting (SSPR) and self-piercing riveting (SPR) which are essentially cold forming operation [1]. It is closely related to the hyperelastic property of soft tissue, the bio-compatibility of the parts to be joined and the specific medical evaluation criteria. The creation of gastrointestinal stapled anastomosis greatly improved those surgical procedures. Steichen and Ravitch introduced stapling instruments in the 1960s [2], and automatic stapling instruments have continued to be improved. In this surgical approach, two or three rows of U-shaped staples penetrate the bilevel gastrointestinal tract in parallel, and ultimately form B-shaped staples on the anvil, fixing two layers of the tissue tightly. Although this effective approach has been shown to be reliable and safe, significant complications, such as anastomosis leakage, stenosis and postoperative bleeding that affect the long-term quality of life (QOL) of patients, cannot be completely avoided [3,4].

Methods for analysing the impact of staples on the tissue and the basic mechanics of stapled anastomosis have been the subject of research. Compressive behaviour of various soft tissues including intestines was recently addressed by De and Rosen [5]. Hu et al. experimentally investigated the characteristic responses of biological soft tissues to cutting [6]. Both geometric parameters and material properties vary significantly along the gastrointestinal tract [7]. Novacek et al. evaluated the influence of various parameters on the mechanical performance of a stapled colorectal anastomosis [8]. However, there are only a few researches concerning the numerical simulation of stapling intestinal tissues.

The process of penetrating into the gastrointestinal tract can be approximatively characterized as a soft tissue cutting problem regarding the pushing and puncturing [9]. Although the gastrointestinal tract is a complex multilayer structure. The intestinal wall is simplistically modelled as one layer material due to the lack of appropriate data identified for separate layers [7,10]. With this mechanical model, the gastrointestinal anastomosis quality can be related to certain controllable design parameters including the leg chamfer, the shape of the anvil, the contact friction among staple, anvil and tissue, and the shooting speed. As a result, optimum control of these parameters for the desired shape formation can be applied to improve the quality of gastrointestinal anastomosis. Minimally invasive surgical (MIS) robot equipped with the stapling instrument is an effective platform for the complicated surgical task [11]. Compared with the manual instrument, MIS robot could provide improved viewing angles and more flexible endowrist manipulation. Moreover, the robot-assisted MIS is superior in precise kinematics control by scaling down motion and filtering out hand tremor, and especially the ability to smoothly control the individual motor-driven wheels actuated by cable-based transmission system, inducing a stable shooting speed.

Based on the developed ‘MicroHand S’ robot-assisted MIS system which is in clinical trial, this study investigates the mechanical model of robot-assisted gastrointestinal assembly and the use of such models for the control of assembly quality.

## 2. Modelling of soft tissue assembly

### 2.1. Robot-assisted stapler

An experimental prototype of the robot-assisted stapler is shown in Fig. 1. This robot has an operation console for surgeons and a slave console engaged with patients respectively. The robot-assisted stapler used for gastrointestinal anastomosis is composed of a sterile surgical adaptor, a transmission mechanism and an end-effector. The end-effector has two DOFs, namely the clamping

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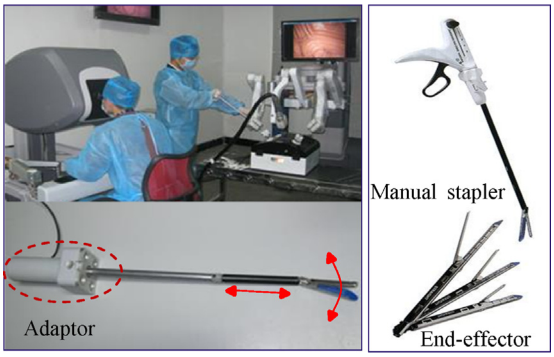

**Fig. 1.** The robot-assisted stapler experimental prototype and the manual stapler.

movement using the maxillary and mandibular effector and the feeding movement of the staple pusher. In this way, additional actuator is not needed in the system. Motors have been chosen to provide a sufficient torque to clamp the two layers of the gastrointestinal tissue tightly and to fix them together by B-shaped staples. Harmonic drive 2250-BX4 AES motors (FAULHABER) with a 45 reduction ratio have been selected. The motors are equipped with incremental encoders and their velocities are controlled by built-in control loops running on servo controllers.

Due to its geometrical configuration and the driving mode that the stapler knob is usually loaded on the pulsive instantaneous thrust, the shooting speed of the manual stapler is obviously unstable. In contrast, relying on the kinematic closed-loop control system, the shooting speed of robot-assisted stapler is ideally stable and controllable, as shown in Fig. 2.

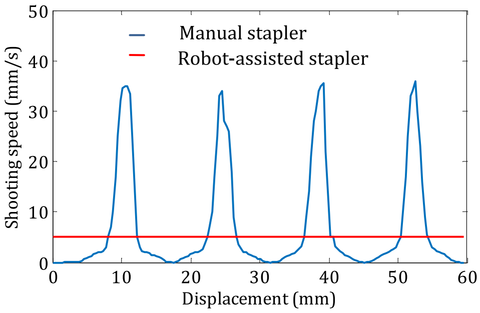

**Fig. 2.** Comparison of shooting speed between manual stapler and robot-assisted stapler.

### 2.2. Mechanical model

The stapled anastomosis is somewhat similar to the single-sided piercing riveting (SSPR), one kind of mechanical assembly, as shown in Fig. 3. SSPR is proposed for fixing and controlling the gap between the sheet panels during adhesive bonding of vehicle body assembly [12,13]. The SSPR and the stapled anastomosis are both used for joining two sheet parts by driving a U-shaped rivet using an impact force.

But significant differences exist: (1) The SSPR process of aluminium workpieces is a process of local large plastic deformation with material separation, which are modelled as bilinear elastic–plastic; while the anastomosis process of the bilevel gastrointestinal tract is characterized as a soft tissue extruding and cutting problem. (2) The riveting speed in SSPR is higher than that in gastrointestinal anastomosis up to four orders of magnitude. (3) The gap between the metal workpieces is used as the evaluation parameter in SSPR, while the performance of B-shaped staple is evaluated in gastrointestinal anastomosis for the assembly quality determination.

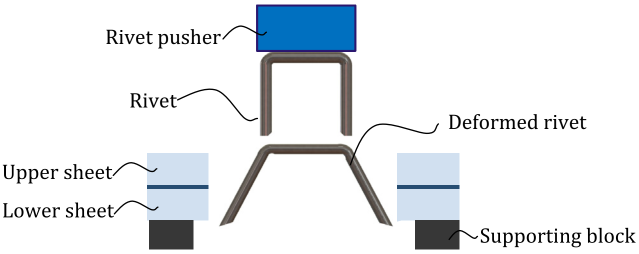

**Fig. 3.** Mechanical model of SSPR.

In the stapled anastomosis technique, the staple is placed between the staple pusher and the upper soft tissue surface. The equivalent mechanical model of the gastrointestinal anastomosis process is shown in Fig. 4. The anvil and staples are modelled as linearly elastic bodies made of steel and/or titanium. The tissue is modelled as incompressible hyperelastic 3rd order Ogden material [14,15]. In the Ogden model, the strain–energy density $W$ is a function of principle stretches $\lambda_i$, $i = 1, 2, 3$:

$$W = W(\lambda_1, \lambda_2, \lambda_3) = \sum_{p=1}^{N} \frac{\mu_p}{a_p}(\lambda_1^{a_p} + \lambda_2^{a_p} + \lambda_3^{a_p} - 3) \quad (1)$$

with the consistency condition $2\mu = \sum_{p=1}^{N} \mu_p a_p$, where $\mu_p$ and $a_p$ are material constants, $\mu$ is the shear modulus of the material and $N$ is the number of terms in the strain–energy function, respectively; here $N = 3$ is chosen. Material coefficients of the tissue were identified from experiments performed in vitro on porcine colorectal tissues by Novacek et al. [8]. A type of normal staple was used in gastrointestinal anastomosis, with 0.28 mm in diameter and 3.5 mm in length.

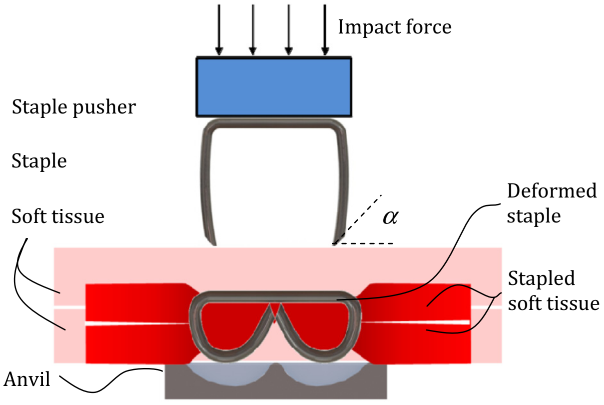

**Fig. 4.** Mechanical model of gastrointestinal anastomosis process.

The maxillary and mandibular effector compresses the bilevel gastrointestinal tract. By plugging motors directly on the staple pusher, the staple penetrates into the compressed tissue with a leg chamfer $\alpha$ and a shooting speed $v$, and finally bends a B-shaped staple on the anvil with a continuous pressure on the staple. The leg chamfer and the shooting speed are two controllable parameters in this model. Both parameters have impact on the anastomosis quality.

### 2.3. FEM model and validation

Gastrointestinal tracts undergo large deformation and local fracture in the anastomosis operation. Based on the mechanical model, the gastrointestinal anastomosis processes are simulated using ABAQUES [16] to obtain the formation of the staple assembly, including the impact force, the deformed shape of the staple. An FEM model of the stapling process is built. In the FEM simulation, the staple pusher and the anvil are considered as analytical rigid and the material of the staple is TA2. Gastrointestinal tissue material follows the principle of incompressible hyperelastic 3rd order Ogden model described before. The element type is selected as C3D8R with reduced integration and hourglass control. The leg chamfer is 45°and the shooting speed is 5 mm/s. The deformed shape of the staple and the impact force via FEM

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