Novel Design of an MR-safe Pneumatic Stepper Motor for MRI-guided Robotic Interventions

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INTRODUCTION

Magnetic resonance imaging (MRI) superiority is well-known by providing non-ionizing radiation, non-invasive and high-contrast imaging in particular for soft tissues [1]. These advantages have prompted MRI for the various application in surgical interventions ranging from neurosurgery, cardiac ablation to prostate biopsies. However, MR-safe mechatronics is still confronted by the fundamental challenge, namely to maintain zero interference of its imaging operation during the MRI navigation.

Currently, four types of MRI actuations have been explored at different MR-safety conditions [2]: 1) electric actuators, e.g. piezoelectric motors and ultrasonic motors; 2) fluid-power motors; 3) MR-powered actuators. In terms of adaptability in general hospital setup, image quality and MR-safety, pneumatic actuators are advantageous in both material and energetics considerations. The material of pneumatic actuators could be non-magnetic and non-conducting, minimizing the effects on inhomogeneity of magnetic field. Pressured clean air as power supply is commonly available in MRI scanner rooms. This ensures zero image artifacts caused by the electromagnetic (EM) waves of electricity. Such pneumatic stepper actuators with the capability of generating accurate stepwise motion have been introduced recently. Stoianovici et al. [3] invented the first MR-safe pneumatic stepper motor that comprises three actuated diaphragms driving a hoop gear. Several pneumatic stepper motors [4-6] have been sequentially developed and their performances (e.g. torque-speed) have been demonstrated. However, many technical challenges still have not been addressed in these motors, e.g. typically large in motor size, high cost for the complicated fabrication and sterilization, dissatisfactory signal-to-noise ratio (SNR), as well as image distortion induced by the proximal electronics and valves of motor drivers.

In this paper, we propose a novel MR-safe pneumatic stepper motor, whose design could be relatively compact, flexibly customized for various actuation requirements. Such a motor can be made of a homogeneous material for ease of minimization and reconfiguration. One set of design parameters are selected for the experimental evaluation. Self-locking and high speed (up to 160RPM) is achieved in both rotation directions. Steady torque within a wide range of speed can also be preserved. Low imaging interference has been experimentally demonstrated while operating the motor inside the MRI scanner. Regarding these specifications, this motor is potential to be incorporated into an MRI-compatible robot for needle manipulation during intra-operative procedures, e.g. prostate surgery.

MATERIALS AND METHODS

The presented motor is compactly designed in cylindrical structure within the dimension of Ø35×88mm. It weighs 70g only. **Fig. 1** shows the motor assembly offering flexibility for design of a small-size and light-weight robot for MRI-guided interventions. The assembly can be completed manually and rapidly. The starting point of this mechanism is based on the design of Chen et al. [5], by merging such two uni-directional units together to achieve bi-directional rotation and continuous torque-speed performance.

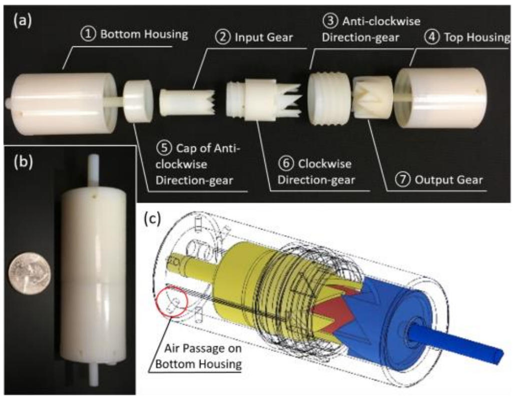

Fig. 1 (a) Exploded component view, (b) dimension and (c) CAD model of the stepper motor.

All the components made of an acrylic compounds material (VeroWhitePlus, Stratasys, USA) are fabricated by a rapid prototyping machine (Objet260 Connex, Stratasys, USA), constructing a rigid structure of the motor. Smooth surface of the 3D printout also ensures rather low friction coefficient (μ=0.157, obtained from pre-experiments). The completion time in printing one prototype is approximately 4 hours. Additionally small amount of semisolid lubricant could satisfactorily further smoothen the motion. Very little heat is dissipated accredited to the less friction, ensuring its durable uses and reliable performance after long repeatable run.

RESULTS

Output torque and speed are two key metrics to characterize performance of various motors. Apart from design parameters, the maximum output torque is dependent on the exerted pressure and actuation frequency. **Fig. 2** illustrates torque-speed performance curves varied with applied pressure from 0.30 MPa to 0.51 MPa in sampling interval of 0.03 MPa. Under the lower level of pressure <4.2MPa, it is evident that torque can maintain at a stable level within a relatively wide range of speed (0-60 RPM). Stronger correlation is found between torque and speed when speed is over 60 RPM, in which torque is declining gently with the speed rising. This is because the disturbances between pulses become severe. Insufficient time for air diffusion may just provide very limited momentum for pressurized air to drive the gears, thus resulting in the decreasing torque. Overall the maximum power is 46.5 mW achieved at 0.48MPa, 140 RPM.

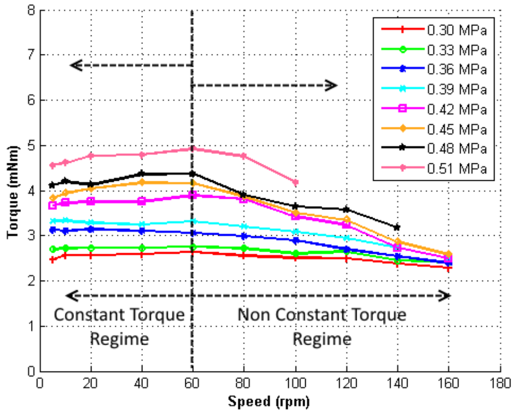

Fig. 2 Output torque varying with motor speed at the eight levels of pressure.

To quantify the MRI-compatibility, experiments with motor running under MRI have been conducted. The motor was placed closely to a commercial MRI phantom cylinder (#452213095955, CadMed+, USA), which was located at the isocenter of the scanner. The experimental setup is as shown in **Fig. 3**. Related electronic is all placed outside the MRI room, thus no extra shielding is required. To measure SNR and the maximum width of image artifacts, two common image sequences, T2-weighted Turbo Spin Echo (TSE) and T1- weighted Fast Field Echo (FFE) were applied to generate images of the phantom under different motor operation settings (as in **Fig. 3**), showing that the proposed stepper motor does not cause significant SNR loss. No image artifact is observable even within the delicate structures inside the phantom.

DISCUSSION

We presented a novel design of an MR-safe pneumatic stepper motor, which comprises only seven components made of homogeneous material. Not only does this significantly simplify the design process, but it also reduces the manufacturing cost. The motor can be disposable for single-use, without having to deal with complicated sterilization. The maximum torque and highest speed of our preliminary design was measured at 4.92 mNm and 160 RPM respectively, under the pressure up to 0.51 MPa. Validation through the operation under MRI has demonstrated its impressive MR-compatibility, thus supporting its practical use in many MRI-guided intervention assisted by robot.

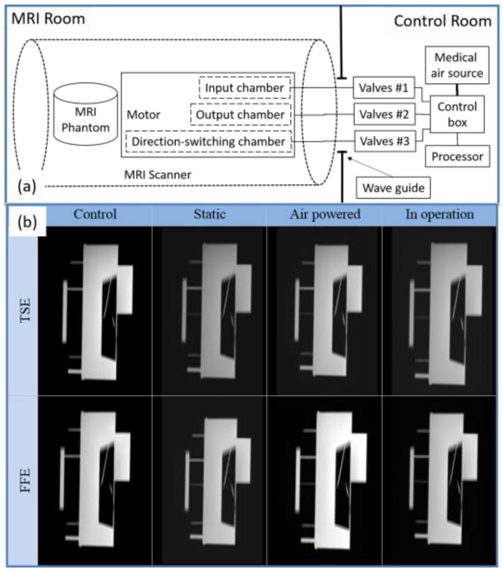

Fig. 3 (a) Motor evaluation setup with pneumatic components for the MRI-compatibility test. (b) MR images of the phantom with two sequences T2-weighted TSE and T1-weighted FFE images under different scenarios.

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