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Evaluation of MRI-compatible pneumatic muscle stepper motors

Abstract: The automation of instruments and tools (e.g. bone drill) or robotic devices (e.g. needle positioning robot for prostate surgery) for use in interventional MRI (iMRI) is still challenging due to a lack of accurate, affordable and completely metal-free actuators and motors. Inspired by biological muscles, a bionic equivalent known as the fluid muscle actuator (which can be operated pneumatically or hydraulically) is well-known in the mechanical engineering industry. Fluid muscle actuators have multiple beneficial characteristics: they are simple, self-returning, low-friction and can produce relatively high actuation forces at low diameters and pressures.

We present two novel designs for metal-free, pneumatic stepper motors for potential application in iMRI. Our stepper motors are powered by simple pneumatic muscles, which are assembled from low-cost off-the-shelf components. Besides, the components of the stepper motor demonstrators were 3D-printed using a stereolithographic additive manufacturing process (SLA printing).

We evaluate the effect of pneumatic muscle length on contractile force and length. Our results demonstrated the functional feasibility of the pneumatic muscle-powered and fully MRI-compatible stepper motor designs. In a next step, we will optimize the motor's design, characterize their performance and reliability, and use the stepper motors to power a micropositioning device in iMRI-phantom tests.

Keywords: Stepper motor, pneumatic motor, pneumatic muscle, MR compatible, robotic interventional MRI

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1 Background

Interventional Magnetic Resonance Imaging (iMRI) is useful for accurate targeting e.g. in stereotactic neurosurgery such as brain biopsy and electrode implantation because of its superior soft-tissue contrast compared to X-ray Computed Tomography (CT). The strong magnetic fields involved in MRI prohibit the use of conventional electric motor-driven robots. Surgeries must therefore be performed with bulky stereotactic frames or completely freehand in the narrow MRI tunnel [1].

To provide automated positioning for tools (such as biopsy needles and electrodes) and robotic devices, an MRI-compatible motorized platform is needed. For precise alignments, e.g. in remotely controlled robotic devices, stepper motors are desirable due to their incremental and precisely controllable rotational motion.

In this paper, we present an evaluation of two pneumatic muscle-based stepper motor designs made for remotely controlled operation. Since pneumatic muscles are inherently air-tight (unlike pneumatic cylinders), they are beneficial for iMRI application, as they do not exhaust potentially contaminated air to the local environment. The pneumatic motors, a unidirectional impulse stepper motor and a bidirectional sequential stepper motor, were evaluated to determine which one is most appropriate to match the requirements of iMRI robotics.

2 Materials and Methods

Any installation of metallic objects in the vicinity of the MRI tunnel can be a safety hazard to the patient. Ferromagnetic components can be accelerated by the magnetic field and cause injury or damage to equipment. Conductive but non-magnetic objects are at risk from induced currents. Loops of a resonant size can be dangerously heated by the high-frequency shifting magnetic fields. Apart from safety, the major concern with regard to metallic and electronic devices is image degradation. To completely avoid image degradation,

electric motors were substituted with piezoelectric motors in many MRI-compatible surgical robots [2–4].

On the downside, piezoelectric motors still require conductive cables for their operation. Alternatively, systems which generate power (pneumatic fluid pressure) remotely and transmit it through metal-free tubes to completely MRI-compatible motors in the MRI room avoid conductors entirely. Accordingly, these motors are hydraulic or pneumatic. A large number of different pneumatic motor designs have been applied to MRI-guided surgical robots [5–10]. Maximum MRI compatibility is achieved when these motors are made entirely from nonmetallic materials.

2.1 Pneumatic muscle

A pneumatic air muscles (PAM) consists of an inflatable bladder, and a braided sleeve. When the bladder is inflated, it presses against the sleeve. The sleeve contracts axially as it expands radially, thus forcefully contracting the muscle. Compared to pneumatic cylinders, PAMs have more reliable sealing, since the sealing parts near the edges are static rather than dynamic (i.e. the two edges of the seal do not move relative to each other). They have an elastic and compliant structure, as opposed to the rigidity of a pneumatic cylinder. At small diameters and lower operating pressures, they have potentially more output force than pneumatic cylinders. However, at larger diameters pneumatic cylinders output more force, and the solid walls of pneumatic cylinders can survive much higher pressures than the thin, flexible bladders inside PAMs. Unlike pneumatic cylinders, PAMs can only generate contractile force: they can pull, but not push. The length of contraction is limited to a fraction of the PAM's overall length. Because the bladder itself resists deformation, the characteristics of the muscle are determined not only by its inner diameter (ID) like a pneumatic cylinder, but also by its outer diameter (OD).

2.2 Impulse stepper motor

The impulse stepper motor comprises a lower push rod driven by the pneumatic muscle to engage an upper push rod and compress a rubber spring. The push rods both terminate in a number of discretely rotationally-symmetric sliding planes, with which they engage each other; the case also has a set of sliding planes (the basic design principle was derived from the design presented by Guo et al. [5]). The discrete increment of rotational symmetry in the case is equal to one step; the push rods have sliding planes every other step. At rest, the case constrains the push rods, preventing them from rotating. At the

Figure 1: Cross-section views of the impulse stepper motor without PAM and spring (left and center) showing the lower push rod (1) and the upper push rod (2) that convert the translational motion into incremental rotational motion and the rotating output shaft (3). (Right) Assembled demonstrator with PAM.

top of its stroke, the upper push rod is freed from the rotational constraint of the case, and rotates slightly as the spring forces its sliding planes to slide over those of the lower push rod, which is still prevented from rotating by the case. As the upper push rod continues to be forced away from the top of its stroke by the spring, its sliding planes engage with those of the case, continuing the rotation. This rotation is carried through an attached output shaft, which is rotationally locked to the upper push rod with a pin and slot, and constrained in the axial direction by the case. The output shaft also holds the rubber spring. By the end of the stroke, the upper push rod has settled into a new position, which is level with its previous position and once again rotationally constrained by the case, but rotated by a fixed step. The push rods terminate with equal sliding protrusions with a slope of 45° from horizontal; providing unidirectional motion, see Figure 1.

2.3 Sequential stepper motor

To take advantage of the pneumatic air muscle's high force at small diameters, and having sufficient mounting room in the axial direction to accommodate their length, the sequential stepper motor is built to actuate three sets of driving teeth with a trio of air muscles (ID 5 mm and OD 6 mm silicone tubing, effective length 20 mm). The driving teeth are aligned around one concentric output gear. To minimize size, the motor's diameter is built around the spacing of the trio of muscles, which are to be placed as closely as possible together without actually colliding. The three muscles are actuated sequentially and only one muscle is inflated at a time. The motor case is built as a rounded triangle to accommodate the inflated state of all three muscles. In order to be aligned with only one set of driving teeth but not the other two, the number of teeth on the rotating gear must not be a multiple of three, e.g. 16 teeth, see Figure 2. With a specific actuation sequence

of the three PAMs and driving teeth, the rotation direction of the sequential stepper motor can be adjusted.

All custom made components for the pneumatic muscles, the impulse stepper motor and the sequential stepper motor were printed on a stereolithographic 3D printer [Form 2, Formlabs, Somerville, USA].

Figure 2, Left: The output gear (red) is aligned with the top set of driving teeth (green), so the slight misalignment with the other two sets, which allows rotation in either direction when those sets are pulled against the output gear, is visible. **Center:** Transparently sectioned case and cover. Internal PAMs are not shown. **Right:** Demonstrator assembled without case or cap, to display air muscles, output gear, and driving teeth. The rigidity of metal fasteners was necessary to hold the motor together without its case; with the case included, the motor is assembled with plastic fasteners.

2.4 Test setup

To better understand how the length and the membrane wall thickness affect the force and length of contraction of a pneumatic muscle, an initial series of tests was performed on muscles made with the materials procured for conceptual design construction. Since the calculation of these characteristics is depending on multiple characteristics such as elastic storage of energy in the bladder, initial braid angle, and noncylindrical tip effects, as well as basic muscle geometry, it is critical to know the muscle length required to ensure that a sufficient force and length of contraction can be achieved. By physically building and testing multiple different muscles, these parameters are known with a higher certainty than by calculation alone. Four muscles were constructed for testing, all using 12 mm OD silicone rubber tubing as the bladder. Three muscles used 2 mm-thick (inner diameter 8 mm) tubing, and were made to approximately 25 mm, 50 mm, and 100 mm effective length, to cover a plausible range of muscle lengths once proportional size reduction is considered.

In order to measure the motors' torque output, we built a test frame using a force gauge and a redirection wheel to convert torque into linear force. The motors' output shaft was connected to the redirection wheel. A non-stretchable monofilament was wrapped around the wheel and connected to the force gauge. By measuring the pulling force at a known

radius, the torque about an axis can be determined. In addition to the critical metrics of torque, the motor demonstrators were evaluated with respect to precision, speed and reliability.

3 Results

3.1 Pneumatic muscle

Testing of the actuation force of each pneumatic muscle showed the expected linear relation between pressure and force. The relation between length and force, however, matched a logarithmic regression. This indicates that longer muscles do generate more force, but with a diminishing-returns trend as length increases, see Figure 3.

Figure 3: PAM length vs blocked force, ID 8/OD 12 mm tubing. The predicted logarithmic relationship between length and blocked force is illustrated with lines fitted tests at 0.4, 0.3, and 0.2 MPa (4, 3, and 2 bar).

3.2 Pneumatic motors

When measured statically, the impulse stepper motor outputs a minimum of 85 mN·m of torque, while the sequential stepper motor outputs a minimum of 15 mN·m.

Both stepper motors have a fixed step distance which underlays an uncertain residual precision (e.g. due to tolerance gaps or precision of printed parts): The impulse stepper motor has a step size of 45° and a design clearance of 2.5° in either direction, with an additional 2.5° possible from print tolerance. Even with only 16 teeth on the output gear (step size 7.5°) the sequential stepper motor still has a higher degree of precision and a design clearance of 1.0°.

When the speed of the impulse stepper motor was determined with manual actuation instead of the air muscle, 30 actuations could be made in 10 seconds, yielding a speed of 22.5 RPM given that one full revolution needed eight actuations. For the sequential stepper motor an approximate value for the actuation frequency was estimated at 10 Hz. With a step size of 7.5°, this translates to a rotational speed of 12.5 RPM.

The operational reliability was assessed based on the number of failures observed during a series of actuations after all manual post-processing of 3D-printed objects was complete. The impulse stepper did not jam during the free actuation, but did jam three times when tested under payload. In contrast, the sequential stepper was never seen to jam. Because of its low torque, the sequential stepper could not be tested with any payload. Instead, it was subjected to 100 muscle actuations. No stoppages were observed during any of these actuations.

4 Conclusion

The objective of this work was to develop and evaluate two different designs for pneumatically actuated stepper motors under the requirements for potential use in tools and robotic devices applied in iMRI. Demonstrators of the two concepts were built from MRI-compatible materials to confirm their suitability to the requirements such as a direct positioning inside the field of view. As a source of motive power, pneumatic air muscles were evaluated with respect to contraction force and length. Since the pneumatic air muscles do not exhaust any air, which is a common issue from pneumatic setups in iMRI, the sterility goal is met optimally. The motors do not require any electronic components inside the MRI theatre; the controller and valve units can be located outside the scanner room, with pneumatic lines passed through e.g. a waveguide.

In future work, MRI-compatible fiber-optic encoders will be developed and attached to the output shafts of the motors to measure the rotary displacement and thereby determine the current position. In addition, the unidirectional stepper motor can be coupled with a forward-reverse-gearbox to provide bidirectional motion. One dissatisfactory aspect of the test setup was that it measured torque only in a static position. Dynamic characterization of the motor is advantageous for determining its suitability for clinical iMRI applications.

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