

Feedback control system for safe and accurate control of a fully MRI-compatible hydraulic treadmill

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Introduction: Controlling devices within the MRI environment poses unique challenges because ferromagnetic materials and electrical components which can introduce noise into the images are unsuitable for use in the MRI room. A fully MRI-compatible water hydraulic treadmill was developed to enable exercise stress testing of cardiac patients immediately adjacent to the MRI table. This system requires continuous feedback control of speed and incline, requiring sensing to be performed directly on the treadmill while the sensing electronics and the control PC must be positioned outside of the MRI room. In addition to signal detection and transmission, another challenge is to ensure safe operation by keeping the belt speed and incline within specified safety limits. For example, a failure in the speed sensor would result in zero feedback, causing the system to over-compensate and increase the belt speed to dangerous levels for a patient. The control system development and testing will be the focus of this abstract.

Purpose: To develop a feedback control system for an MRI-compatible hydraulic treadmill and test its performance up to the speed of 5.5 miles/hr and the incline of 11.3°, corresponding to stage 6 of the standard Bruce treadmill protocol widely used in cardiac stress testing.

Materials and Methods: The hydraulic treadmill system schematic is shown in Figure 1. An electric motor located outside the MRI room drives a hydraulic pump which sends water into a hydraulic motor located on the treadmill, causing the belt to move. The incline is changed by altering the stroke of a lift cylinder on the treadmill. In order to address the challenge of remote sensing, fiber optic sensors were selected using visible light transmission at 660 nm. Figure 2 shows the hydraulic motor, the lift cylinder, and the transmitting and receiving fibers for sensing speed and incline, which pass through a waveguide to connect to the sensing electronics outside the MRI room. The speed is measured using an “optical chopper” mounted on the flywheel between the transmitting and receiving fibers, such that the number of detected pulses can be converted to flywheel frequency and belt speed. The incline is determined by sensing the cylinder stroke based on the light intensity between the transmitting and receiving fibers mounted on

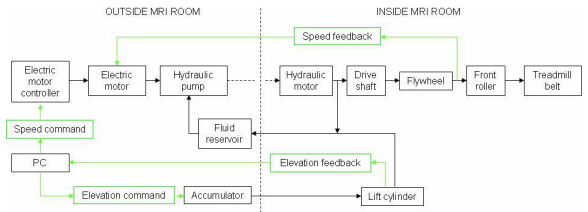


Figure 1: Schematic of the MRI-compatible treadmill system

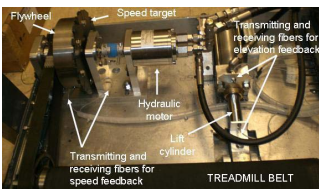


Figure 2: Front of the MRI-compatible treadmill, indicating the fiber optic cables for sensing speed and incline

two ends of the lift cylinder. A greater separation reduces the received light intensity and thus the sensor voltage output. Calibration coefficients that were previously obtained using an electrical inclinometer relate the voltage output to an angle in degrees.

The control program was written in LabVIEW, and operates from a PC located outside the MRI room. Proportional-integral (PI) control of flywheel speed is performed through an electric motor controller (PowerFlex 70 Variable Frequency AC Drive, Rockwell Automation, Inc.) using the default settings of $K_p = 1$ and $T_i = 2$ sec. When the belt speed is below desired, the motor controller causes the electric motor and thus the hydraulic motor to speed up, and vice versa. The incline control is performed by activating two solenoid valves which control the cylinder stroke by adjusting the volume of water in the lift cylinder. The solenoid valves are controlled from LabVIEW using 4 Hz pulse width modulation with a 24% duty cycle. In addition to an emergency stop button located on the treadmill, additional safety features have been implemented in LabVIEW to automatically send a stop command to the electric motor and thus the treadmill belt if the speed or incline fell outside of safety limits of ± 0.6 mph from desired for speed and $\pm 1.1^\circ$ from desired for incline.

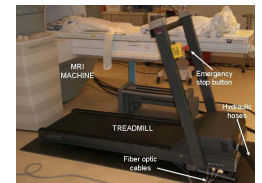


Figure 3: Treadmill placed immediately adjacent to the MRI

The control system performance was evaluated with the treadmill placed immediately adjacent to the MRI table (Figure 3) using a pulse tachometer to measure the average belt speed over 30 second intervals, and an electrical inclinometer to measure the incline. The measurements were performed at 6 levels corresponding to 6 stages of the Bruce protocol in 3 subjects with weights of 125 lbs, 177 lbs, and 244 lbs. In addition, the safety features were tested over a range of conditions such as power loss to sensing electronics or obstruction in fiber optic transmission.

Results: The results of the control system performance testing inside the MRI room are shown in Table 1 for speed and Table 2 for incline across the 3 weights. The maximum difference from the target at any weight was 1.60% for speed and 1.91% for incline, in both cases at stage 1. This good agreement shows that the control system operated accurately within the MRI environment. Furthermore, the safety tests were successful and resulted in the treadmill belt automatically stopping if any of the safety limits were breached.

Conclusions: We developed the feedback control system for a fully MRI-compatible hydraulic treadmill with no ferromagnetic or electrical components within the MRI room, which is capable of executing the full range of speeds and inclines up to stage 6 of the Bruce protocol. We have demonstrated that the fully MRI-compatible treadmill operates accurately and safely when it is positioned immediately adjacent to the MRI table, thus enabling treadmill exercise stress MRI.

Table 1: Speed performance of the treadmill inside the MRI room

Stage	Target (mph)	125 Lbs (%)	177 Lbs (%)	203 Lbs (%)
1	1.7	0.02	1.60	1.60
2	2.5	-0.68	-0.68	-0.68
3	3.4	0.81	0.02	-0.78
4	4.2	-1.04	0.24	-1.04
5	5	-0.68	-0.14	-1.22
6	5.5	-0.39	-0.39	-0.39

Table 2: Incline performance of the treadmill inside the MRI room

Stage	Target (deg)	125 Lbs (%)	177 Lbs (%)	203 Lbs (%)
1	5.7	0.90	1.79	1.91
2	6.8	1.49	-1.58	-1.42
3	8	0.15	-0.74	-0.94
4	9.1	-1.34	-1.04	-0.09
5	10.2	0.18	-0.36	-0.47
6	11.3	-0.03	0.04	-0.13