MR-Compatible Motion Platform

Preliminary Report

BME 400

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Abstract

MRI phantoms are widely used today as a means to test and calibrate the functionality of MRI machines. Static phantoms are often used for this purpose, but these do not give a good representation of the dynamic movements the body makes during imaging. To resolve this issue, motion platforms have been developed to replicate anatomical movement during phantom imaging; however, current devices on the market are costly and limiting in their use. A new proposed design will allow imaging of a wide range of phantoms, be fabricated from off-the shelf components, and be cost effective such that it is applicable and accessible to other researchers. The preliminary design makes use of a piezoelectric motor, a microcontroller, and a rack and pinion.

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I. Introduction

A. Impact and Motivation

Quantitative magnetic resonance imaging (qMRI) is a new and developing MR technique that measures specified characteristics of the tissues being imaged [1]. Healthcare professionals can utilize qMRIs to assist in many functions such as detect tissue characteristic changes over time, diagnose and monitor diseases, and determine drug efficiency [2] [3]. Specifically, qMRIs of livers can quantifiably characterize fat and iron compositions within the liver. This information can assist in the noninvasive detection and early diagnosis of steatosis [4]. Steatosis, also known as fatty liver disease, is an excessive accumulation of fat in a patient's liver. Steasosis affects about 25% of the world's population, typically targeting obese patients [5]. If left untreated steatosis can lead to further liver damage, cancer, or cirrhosis [5]. It is imperative to have accurate and effective qMRI techniques so that patients with steatosis can be treated immediately.

B. Existing Designs/Treatments

Currently on the market there are some devices that are being used to produce motion within an MRI for testing of q-MRI protocols. In a study done by the Department of Radiology at University of Texas Southwestern Medical Center, researchers developed a one-dimensional MRI compatible motion platform. They used the platform in combination with an abdominal phantom to assess how movement during imaging affected the quality of images and the accuracy of quantitative metrics as shown below in Figure 1.

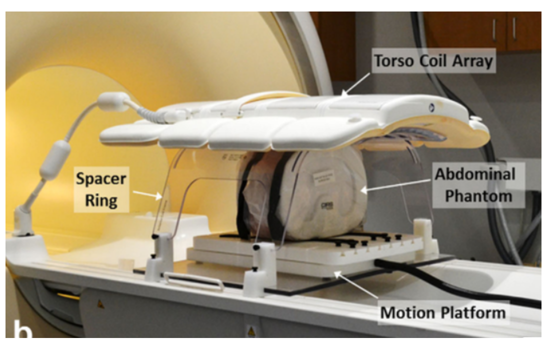

Figure 1. University of Texas Motion Platform [6]

This design consists of a motorized linear stage residing inside the MRI machine and driving electronics outside the MRI room. The motorized stage followed sinusoidal, harmonic, random, or user-defined trajectories. The device was used only for the study and is not on the market for outside use. Additionally this design was very costly, totaling around $19,000, and was specifically designed for an abdominal phantom [6].

Another competing design is the Vital Biomedical Technologies MRI Compatible Multi-Modality Motion Stage. This device is a programmable linear motion stage as shown below in Figure 2. This product is used in the bore of the MRI scanner and follows user-defined trajectories. The programmed trajectories are loaded onto the control system through a micro SD card.

Figure 2. Vital Biomedical Technologies MRI Compatible Motion Stage [7]

This product has a patent pending and there are a suite of other similar motion stages by this same company to address different anatomical motions [7]. Similar to the previous design this product is limited in phantom compatibility and cannot support the weight of a large phantom. Additionally, this product was also in the five figure range. Another drawback is that the motor is close to the phantom, which can create signal defects leading to inaccurate or imprecise q-MRI data.

The Quasar MRI Motion Phantom is an MR safe programmable phantom. In this device, the motion capable components are incorporated directly with the phantom as shown below in Figure 3.

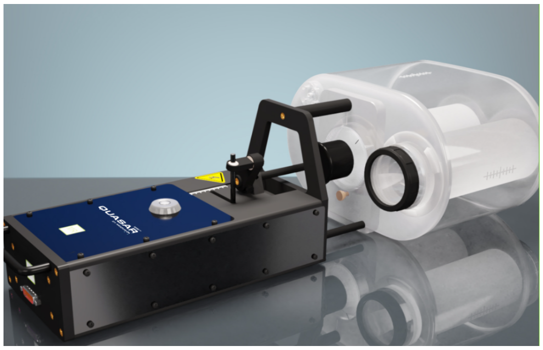

Figure 3. Quasar MRI Motion Phantom [8]

This design uses piezoelectric motors to create desired motions. It is intended to be used to test deep inspiration breath hold protocols. It is unclear how useful this product would be in protocols that require normal respiratory movement rather than breath holding [8]. This was the most expensive of the three competing designs as the client received a quote near $50,000. In addition to the cost, this design limits what phantoms can be used as it can only hold specific cartridges provided by the company. This design also has motor components close to the phantom, which raises concerns about signal interference similar to the design by Vital Biomedical Technologies.

C. Problem Statement

Tissue phantoms used to test and calibrate qMRIs are often static models of the human body. These static models do not effectively represent the constant motion created from natural processes such as respiratory and digestive functions. To solve this, an MR-compatible device that can hold a phantom and simulate the physiological movements will be created for qMRI evaluations.

II. Background

A. Physiology and Biology

Quantitative MRIs map physiological characteristics by correlating the pixel intensity to a measurement of the specified physiological property. Examples of quantifiable characteristics that qMRIs can measure are nuclear magnetic resonance, relaxation times T1 and T2, diffusion and perfusion rates, fat and water fractions, iron fraction, elastic properties of tissue, temperature, chemical composition, and chemical exchange [9]. Figure 4, row B shows the qMRI map of liver fat fractions. This image compares a healthy liver (far left) to a steatotic liver (far right). Row C shows the percent fat in each liver with the steatotic liver being 75% composed of fat [4]. As you can see in the figure, the qMRI map uses different color gradients to represent different fat concentrations across the liver sample.

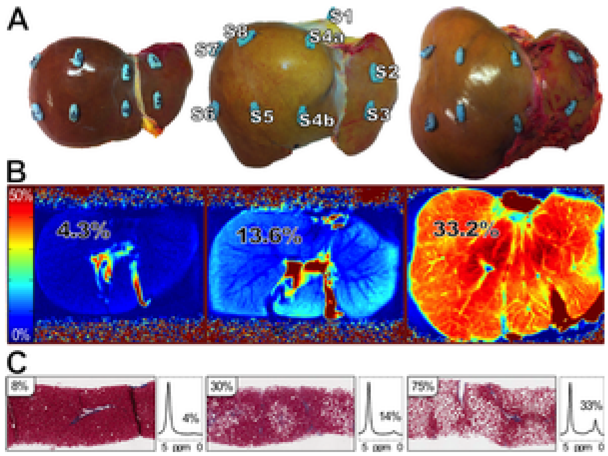

Figure 4. qMRI comparing health liver to steatotic liver [4]

Movement during MRI scans can lead to motion artifacts which can cause inaccurate and imprecise data. Currently qMRIs rely on breath holding techniques to mitigate this. While these breath holding techniques can be very successful, they are not suitable for all patient populations. Some patient groups, such as severely ill, elderly and pediatric patients, are not always able to adequately perform these necessary breath holds [10]. Developing qMRI protocols that can account for respiratory motion could allow for more accurate and comfortable diagnosis of liver conditions. Studies have been performed to track the movement of internal organs due to respirations using external signals [11]. Based on this data, liver moment due to respiration has been shown to be sinusoidal [11].

B. <u>Ultrasonic Motors and Torque</u>

Figure 5 shows the nonmagnetic piezoelectric ultrasonic motor that will be used to create the motions of the phantom-holding platform. Unfortunately, the ultrasonic motor can interfere with the radiofrequency field of the MRI magnet and produce image artifacts on the resulting image [12]. Therefore, the motor will have to be displaced the length of the MRI bed to the platform to reduce these artifacts..

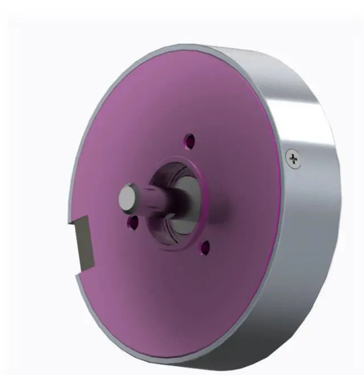

Figure 5. Nonmagnetic piezoelectric ultrasonic motor [13]

The fundamental equation of torque, $\tau = rFsin\theta$, can be applied to find a maximum axial radius of the shaft [13]. Knowing the motor has a maximum torque of 1.2 Nm and assuming the whole assembly is 9 kg or under, the axial radius is 1.4 cm in the shaft connecting the motor to the platform.

C. Design Specifications

The most important specification of the design is that it is MR-compatible to assure it is safe to use in the MRI room as well as minimize signal interference to ensure accurate imaging results. The client has provided an initial budget of $1000 with more funds available if necessary. The client has emphasized making the design accessible and easy to replicate. Therefore, when possible, the motion platform should be designed using non-complex fabrication techniques and commercially available parts. This way other researchers and scientists, especially in places with limited funding, can analyze their own phantoms. In order to be compatible with liver phantoms, the platform should be able to support at least 4 kg and it must be larger than 25 cm by 35 cm [14]. In terms of motion capabilities, the product should be able to mimic physiologically realistic breathing patterns, which would be approximately 8 cycles per min with an amplitude of 3 cm [15]. The motion must be consistent for 10-15 minutes and within a standard deviation of 5% from the desired waveform [16]. For further specifications refer to Appendix A.

D. Client Information

Mr. Jiayi Tang is a PhD student at UW-Madison in the Department of Medical Physics as well as a research assistant in the Quantitative Imaging Methods Lab. His studies are focused on the implementation, evaluation, and improvement of motion-robust qMRI sequences on liver phantoms.

III. Preliminary Designs

A. Lead Screw

The first design will utilize a lead screw to translate the rotational motion of the motor into the linear motion of the platform. As the motor rotates, the threads of the lead screw engage with a threaded attachment which either moves it forward or backward depending on the motor's direction. The lead screw in this design will be approximately 2 meters so the motor can be far from the platform to reduce image noise.

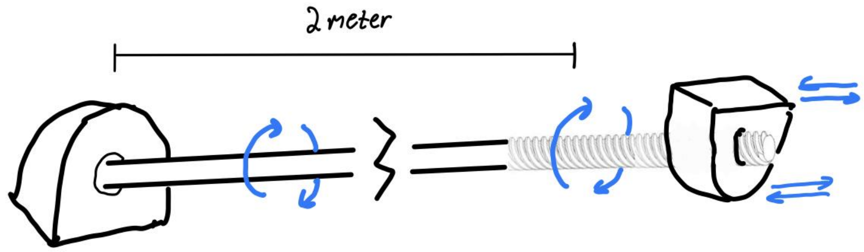

Figure 6. Lead Screw Design

Some benefits to this design include variable efficiency as you vary the helix angle of the screw. A higher helix angle allows for smoother motion, which reduces friction and improves the efficiency of power transfer, however, it also does require more torque [17]. Another benefit is that this mechanism works well for light loads, which is within the specifications outlined in the PDS (Appendix A). A drawback of this design is that the screw may wear out unevenly, causing a need for more frequent maintenance and replacement [17].

B. <u>Scotch Yoke</u>

The second design utilizes a scotch yoke to translate the rotational motion of the motor into the linear motion of the platform. As the motor rotates, the circular disc translates the motion into a back and forth movement, which is purely sinusoidal over time. The direction and distance of the linear motion are determined by the position of the pin along the radius of the disk. In order to get sufficient distance between the motor and the imaging platform, a set of bevel gears and a drive shaft will be used to translate the rotational motion 2 meters.

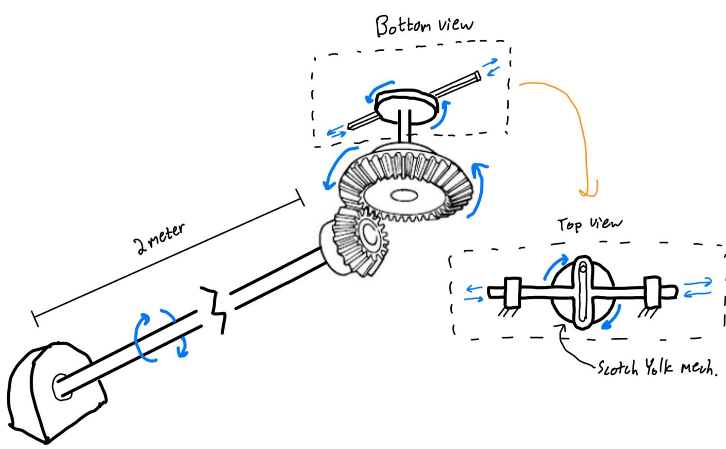

Figure 7. Scotch Yoke Design, including 2 bevel gears and a drive shaft

A benefit of this overall design is that it has variable torque depending on the angular position of the arm. The arm is longest at both ends of travel, which generates the most torque, and shortest at the midpoint, which generates the least torque [18]. This also has an inverse relationship with the speed of the linear motion. A drawback of this design is that the slot can wear out quickly due to friction and contact pressure [19].

C. Rack and Pinion

The third design utilizes a rack and pinion to translate the rotational motion of the motor into the linear motion of the platform. As the motor rotates, the gears of the fixed pinion engage with the teeth on the rack, causing it to move back and forth depending on the direction of the motor. Similar to the second design, a set of bevel gears and a drive shaft will be used to translate the rotational motion 2 meters.

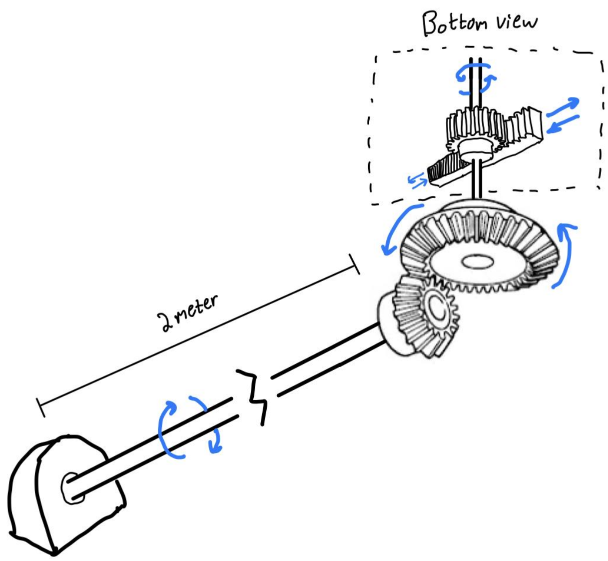

Figure 7. Rack and Pinion Design, including 2 bevel gears and a drive shaft

A benefit of this overall design is that it has efficiencies of up to 98.5%, allowing for smooth and accurate motion [20]. This mechanism is flexible to fit well with most applications by varying parameters such as pinion size, gear ratio, and damping levels [20]. A drawback of this design is it requires constant motor directional change, which leads to stress on the motor. Furthermore, any misalignment can damage parts and cause failures, so it is imperative to manufacture the components well [20].

IV. Preliminary Design Evaluation

A. Design Matrix

Table 1. Design Matrix of the three prototypes discussed above. Criteria are outlined on the left with the category winner highlighted in light green and the winning design highlighted in dark green.

Categories	Lead Screw		Scotch Yoke		Rack & Pinion	
Efficiency (25)	2/5	10	4/5	20	5/5	25
Accuracy (20)	5/5	20	3/5	12	4/5	16
Ease of Fabrication (15)	2/5	6	4/5	12	3/5	9
Cost (15)	4/5	12	3/5	9	2/5	6
Adjustability (10)	5/5	10	2/5	4	4/5	8
Safety (10)	4/5	8	2/5	4	4/5	8
Durability (5)	1/5	1	4/5	4	4/5	4
Total (100)		67		65		**76**

Once the product design specifications were fully developed, design criteria were generated to evaluate the effectiveness of the proposed designs. The designs were evaluated using the following criteria: Efficiency (25), Accuracy (20), Ease of Fabrication (15), Cost (15), Adjustability (10), Safety (10), and Durability (5).

Efficiency:

Currently the speed and shape of the waveforms produced by the design is greatly limited by the speed and torque produced by the piezoelectric motor. To accommodate this, the conversion of rotational motion to linear motion has to be done efficiently, hence its high weight in the design matrix. The Rack and Pinion design is the most efficient mechanism out of the three, which gives it the highest rating in this category. The Scotch Yoke design will inherently have more friction in its conversion, which lowers its rating. The Lead Screw design by far has the most friction and is the least efficient in its conversion. This high friction causes the Lead Screw to have the lowest ranking of the three devices.

Accuracy:

As the design is hindered by the speed and torque of the piezoelectric motor, it is important to assure that the accuracy of the waveforms produced is not sacrificed at the cost of the efficiency of the device. The device has to be capable of producing a multitude of different waveforms that are easily differentiable from one another. The Lead Screw can be designed with a pitch that allows for high accuracy in the produced waveforms, this makes the Lead Screw the highest scoring design for accuracy. The Rack and Pinion can be designed with a high density of gear teeth, which will allow for increased precision and accuracy in the waveform produced. With increased gear teeth density, the Rack and Pinion becomes the second highest scoring design for accuracy. The waveform produced by the Scotch Yoke is limited by the location of the pin. This limitation of the waveform produced lowers the accuracy of the design overall and makes it the lowest ranking design in this criterion.

Ease of Fabrication:

The client highlighted the need for the device to be easy to fabricate. Many labs could benefit from having a device such as this, so its fabrication must be relatively easy to allow this design to be fabricated by others. Of the three preliminary designs, the Lead Screw design would likely be the hardest to fabricate. The Lead Screw of this design would likely have to be 3D-printed. For improved print quality, the screw would have to be printed vertically. The vertical height limit of 3D-printers would limit the overall length of the Lead Screw in the design. This process to develop the Lead Screw causes its design to be the lowest ranking of the three. The fabrication of the Scotch Yoke and Rack and Pinion designs would be relatively similar to each other. All components of both designs would be 3D-printed, so the Scotch Yoke design ranked as the best design in this criterion due to it requiring less material.

Cost:

Similar to ease of fabrication, the client wants this device to be easily accessible to labs. Therefore, the cost of the device should be as low as possible. All three designs utilize the same piezoelectric motor, and the rest of the components will be 3D-printed. This leads to the only cost differential between the three designs to be due to the amount of material each will consume to print. The Lead Screw design will consume the least amount of material to print, hence it was rated the best design in this category. The Scotch Yoke design would consume less material than the Rack and Pinion, leading to these designs being ranked 2nd and 3rd respectively.

Adjustability:

The device has to be capable of producing a multitude of different waveforms. It is important for this device to be easy to adjust to these different waveforms. This criterion measures how easy it is for the user to change what waveform is being output to the phantom bed of the design. The Lead Screw design rated the highest of the designs in this category due to its only limitation coming from the length of the screw. Any waveform with a magnitude within the length of the Lead Screw can be translated to the phantom bed. The Rack and Pinion design is similar in this respect, as it is also limited in its producible magnitude by the length of the rack. The Rack and Pinion design, however, is also limited by the required gearing ratio to transfer planes of rotation within the bevel gear box. This additional limitation makes this design the second highest scoring. The Scotch Yoke design is heavily limited by the radius at which the pin is located on the design. To change the sinusoidal waveform produced by this design, the pin on the Scotch Yoke would have to be physically moved by the user. This requirement makes the Scotch Yoke design undesirable when it comes to this criterion, and causes it to be ranked the lowest.

Safety:

This device must be able to fully function within an MRI and do so safely. Due to the high intensity magnetic fields being present within an MRI, it is vitally important that safety be considered when evaluating these designs. All three of these designs minimize the use of metal components to the same extent, so the only difference lies in how these devices might interact with the user. The Lead Screw and Rack and Pinion design both have minimal moving components and present the lowest pinch risk for the user when handling. Given this, the Lead Screw and Rack and Pinion design tied for best design for safety. The Scotch Yoke design has more moving components than the other two, leading to its lower ranking.

Durability:

This device is meant to be easy to fabricate and cost efficient. These two criteria tend to have an inverse relationship with durability, so it's important to consider this as a criterion as well. Durability, however, is not as vital of an aspect to this design as the others, so it has a lower weight. The Rack and Pinion design and the Scotch Yoke design both reduce friction to a great extent without the need of lubrication. This leads to these two designs being tied for the best in durability. The Lead Screw design inherently has a lot of friction in its mechanism, and would likely require periodic lubrication to prevent wear. Due to the high friction within the system, the Lead Screw design ranked the lowest for durability.

B. Proposed Final Design

Based on the design criteria above, the Rack and Pinion design emerged as the best overall design. This design ranked the best in efficiency and tied for best in safety and durability. It ranked second in accuracy, ease of fabrication, and adjustability, but last in cost. With all the benefits this design presents, it will be used moving forward.

V. Fabrication/Development Process

A. Materials

The prototype will primarily be 3D-printed with PLA plastic to reduce interference with the MRI. Additionally, once these components are assembled, they will be connected to a piezoelectric motor and a microcontroller that will be positioned an appropriate distance away from the machine. For appropriate function and longer shelf life, all components will be non-conductive and non-metallic/magnetic.

B. Methods

The prototype components will be designed in SOLIDWORKS and 3D-printed in the Makerspace. After fabrication, each 3D-printed component will be assessed on rigidity and weight. Once each component successfully passes each assessment, the prototype will be assembled starting with the PLA plastic components. The piezoelectric motor and microcontroller will be connected an appropriate distance away from the platform. If additional mobility is needed, a lubricant may be applied with no risk to the motor.

VI. Testing

The assembled prototype will undergo three main functionality tests. The first test is designed to assess component proficiency, specifically the movement of gears and teeth needed to optimally move the platform. This test will be conducted without additional weight. There will be at least 10 trials measuring the amount of rotations and the full time to travel the track. The data will be compared against each other.

The second test involves load bearing variance. This test is designed to assess the performance of the prototype in carrying different loads. A set weight will be placed on the platform and will be recorded on video for at least 10 trials for each weight. Once at least 10 trials for a weight have been completed the next increment of weight will be placed on the platform until the maximum load specified by the client is reached. Each video will be compared to a video of the prototype carrying no load.

The third test is designed for velocity variance. At programmed speeds the prototype will be assessed to how accurate the physical speed is compared to the expected speed. At least 10 trials will be conducted for each set speed. The load will be constant throughout the trials.

VII. Results

As of October 11th, 2023, there are no results regarding the final prototype since no tests have been performed. After testing is completed, data will be statistically analyzed based on the product design specifications (Appendix A) and observations will be recorded here.

VIII. Discussion

The implications of the results will be discussed here once testing is completed. There are no ethical concerns regarding the testing or future use of this device as it will be intended for use in a research setting. Sources of error and changes to testing procedures will be discussed in the future.

IX. Conclusions

The client for this project is Mr. Jiayi Tang, a PhD student at UW-Madison in the Department of Medical Physics. He has proposed that developing a MR-compatible motion platform that is more cost effective and accessible would allow researchers to more accurately evaluate qMRI protocols. Currently products that are designed for this function are limited to specific phantoms and are extremely expensive. This technology would improve diagnostic capabilities for patients currently unable to perform current image artifact mitigation procedures such as deep inspiration breath hold protocols.

While there are different modalities for producing linear motion, a design that features a rack and pinion allows for precise control, high power conversion efficiency, and high durability. The next steps in the design process include fabrication and testing. The platform will be fabricated in MR-compatible materials, then assembled together with the existing motor, electronic circuitry, microcontroller, and sliding rails. Code, given by the client, will be used to generate the waveform motion that will move the platform. The testing plans include evaluating the assembly function and control. After the prototype has been evaluated, it can be tested in an MRI and accuracy can be determined using liver phantoms with known fat concentrations.

X. References

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XI. Appendix

A. Product Design Specifications

MRI Compatible Motion Platform - BME 400

Product Design Specifications
September 22nd, 2023

Client:	Mr. Jiayi Tang
Advisor:	Dr. James Trevathan
Team:	Maxwell Naslund - Team Leader Kendra Besser - Communicator Amber Schneider - BWIG Jamie Flogel - BPAG Caspar Uy - BSAC

Function

MRI phantoms are often static models of the human body that are used to test and calibrate MRI's. Natural process' such as respiration and digestion create constant motion within the human body. Static phantoms used to calibrate MRI's do not properly represent this motion. This demonstrates a need for an MR compatible device that holds a phantom and is capable of simulating the movements found within the human body.

Client requirements:

- MR Compatible
- Moves back and forth
- Minimize the use of electronics inside the room
- Potentially incorporate materials currently available from the client
- Create a prototype with a budget of $1000
- Utilize commercially available parts
- Avoid complex fabrication methods

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements*: The product will be a magnetic resonance compatible platform that provides a periodic waveform motion. The waveform motion will have a frequency of 8 cycles/min and amplitude of 3 cm to represent physiological breathing patterns. The motion will be consistent for 10-15 minutes and is allotted a standard deviation of 5% from the desired waveform. The product must withstand the size and weight of a phantom liver for testing purposes.

b. *Safety*: The device will be entirely made of MR compatible material and will pose no safety risk within the MR environment. The device's magnetically induced displacement and torque forces will be tested to assure these forces are below their gravitational equivalents. The device will also be evaluated for RF heating, eddy currents, gradient induced vibrations, and gradient induced extrinsic electrical potential risks, as also recommended by the FDA [1]. As this device will utilize electronics, it is classified as an active medical device and will follow FDA 21 CFR part 801 and ASTM F2503 labeling requirements.

c. *Accuracy and Reliability*: The device must be able to produce repeatable patterns of movements within 2mm. The components of the device must not decrease the signal to noise ratio of the calibration phantom being tested. The device must be able to reliably repeat MR scans with minimal decrease in image quality between scans.

d. *Life in Service*: The device must operate for up to 60 minutes at a time as that is the time an MRI may take to produce an image of a medium-sized area [2]. A non-magnetic motor should last 20,000 hours under normal operating conditions [3]. Overall the device should last as long as an MRI scanner, which is approximately 10 years [4].

e. *Shelf Life*: Based on the motor components it should be stored in -40 to 70 °C temperatures with humidity 0 to 80% non condensing [2].

f. *Operating Environment*: The device must be able to withstand upwards of 3 tesla for 1 hour [5]. The device must be able to withstand potential RF heating, eddy currents, gradient induced vibrations, and gradient induced extrinsic electrical potential risks associated with devices within strong magnetic fields [1].

g. *Ergonomics*: The platform should have a height that is comfortable and safe for people to interact with when placed in the MRI. No force should be applied by a person to the motor or any moving parts during operation. An emergency stop feature should be implemented to allow users to immediately stop the motion platform in case of any issues or safety concerns.

h. *Size*: The platform will be no smaller than 25cm x 35cm in order to hold a range of phantom liver samples [6]. The platform will be rectangular shaped.

i. *Weight*: In order for the user to install and uninstall the platform during each segment of testing, the weight should not exceed 10kg. The platform must be able to withstand 4kg [7].

j. *Materials*: The product will be composed of MRI compatible materials. Ferrous and magnetic metals will not be used; other metals, such as brass and aluminum, will be limited to minimize the possibility of induced currents. A nonmagnetic ultrasonic piezoelectric motor will be used to provide platform motion. Nonmetalic sliding rails and bearings will be used to guide the platform through the MRI machine.

k. *Aesthetics*, *Appearance, and Finish*: Color, shape, form, texture of finish should be specified where possible (get opinions from as many sources as possible).

2. Production Characteristics

a. *Quantity*: Produce one motion controlled platform.

b. *Target Product Cost*: The budget for this project is $1000 with many of the components already provided including some motors, rails, software, and hardware. Existing MRI compatible designs cost around $9700 excluding the cost of the phantom used [7].

3. Miscellaneous

a. *Standards and Specifications*: MRI systems and accessories must follow the multiple sets of standards designed by the organizations like the FDA involving forms of testing the functionality of the machine including any additional accessories. Accessory parts should allow appropriate function in testing MRI displacement force ASTM F2052, torque ASTM F2213, RF heating ASTM F2182, and image artifact ASTM F2119 [8].

b. *Customer*: Preferences on stability and levelness will assist users in creating more genuine images. Reducing additional noise from both the platform and machine would be beneficial to more optimal usage.

c. *Patient-related concerns*: The device would need to be appropriately cleaned and disinfected for each use as instructed with the associated manufacturer. Appropriate dimensions levelness of the platform will need to be monitored to help with specimen/subject safety. Additionally cleanliness of the machine is an important consideration as the device should not leak motor oil or other fluids on the MRI bed.

d. Competition:

- Vital Biomedical Technologies MRI Compatible Multi-Modality Motion Stage is a programmable linear motion stage. This product is used in the bore of the MRI scanner and follows user-defined trajectories. The programmed trajectories are loaded onto the control system through a micro SD card. This product has a patent pending and there are a suite of other similar motion stages by this same company to address different anatomical motions [9].
- For a study done by the Department of Radiology at University of Texas

Southwestern Medical Center researchers developed a one-dimensional MRI compatible motion platform. They used this in combination with an abdominal phantom to assess how movement during imaging affected the quality of images and the accuracy of quantitative metrics. This design consisted of a motorized linear stage residing inside the MRI machine and driving electronics outside the MRI room. The motorized stage followed sinusoidal, harmonic, random or user-defined trajectories. The device was used for the study and is not on the market for outside use [7].

- The Quasar MRI Motion Phantom is a completely MR safe programmable phantom. In this device the motion capable components are incorporated directly with the phantom. This design uses piezoelectric motors to create desired motions. It is intended to be used to test deep inspiration breath hold protocols. It is unclear how useful this product would be in protocols that require normal respiratory movement rather than breath holding [10].

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