CT Feet Holder

Midsemester Report

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Abstract

The ankle and foot are commonly scanned using Computed Tomography scanning machines, but there is currently no working device that will hold the feet and provide a measurable load during the scan. The goal of this project is to design and build a foot holder for a General Electric (GE) CT scanner that fulfills the requirements of the client and will not interfere with the imaging capability. Three designs were developed and analyzed to see which would be most effective for use with a CT scan. A final design was chosen, and a prototype will be made and tested to make sure that the design is in working condition for actual use.

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I. Problem Statement

The ankle and foot are commonly scanned using Computed Tomography (CT) machines. There is currently no device for both positioning the feet and applying a measurable load on them during a CT scan. The goal of this project is to design and build a foot holder for a General Electric (GE) CT scanner that contains no metal or radiopaque materials within the scanning field, allows the patient's feet to be held in a standardized neutral position, is easily cleaned and disinfected, and is lightweight for easy transportation around the facility. The foot holder must also be securely attached to the CT scanning table. Additionally, it must provide a method to apply and measure a force against the feet so that the force simulates a weight-bearing image.

II. Background Information

Computed Tomography consists of x-ray imaging from many different angles in a 360º range. The CT scanner takes many images and reconstructs the whole image using a computer program. The basis of X-ray imaging is that different materials or tissues provide a different X-ray attenuation. X-ray attenuation is the fraction of a beam that gets scattered or absorbed by the material per unit thickness. Therefore as the attenuation coefficient increases the amount of energy that can pass through the material decreases. Bones have a much higher coefficient than soft material this is why it is much more distinguishable on an X-ray.

CT uses this ideology and images the object from all different angles and then is interfaced with a computer. A diagram of this process is shown in Figure 1. The computer then generates a reconstruction of this image based on the X-ray attenuation of each tissue. An example of a CT reconstruction of an ankle can be viewed in Figure 2.

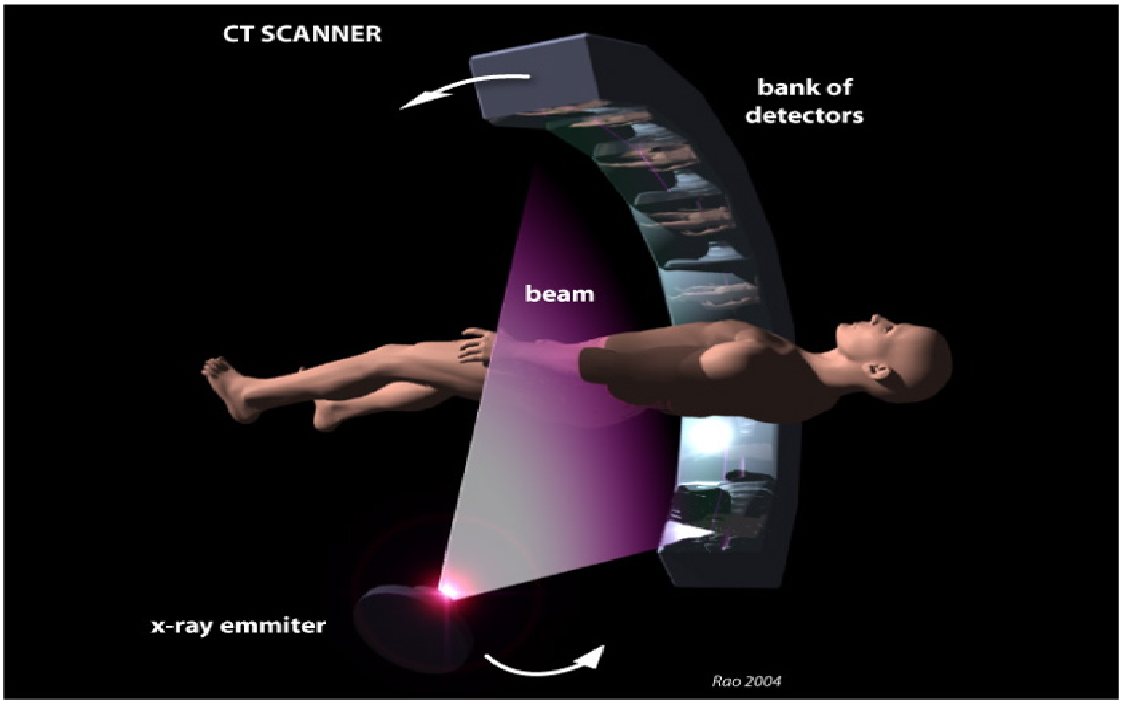


Figure 1
Image shows the rotation occurring in a CT scan as well as the beam angle.
http://www.mscd.edu/~biology/3000course/webportfolio/webportfolio-Pages/Image17.html

Figure 2
Computer reconstruction of a CT scan of an ankle
http://www.ablesw.com/3d-doctor/images.html

Previously, Dr. Schreibman of the University of Wisconsin (UW) Medical School Radiology Department had assigned a team to create a feet holder for use in ankle CT scans, which is Dr. Schreibman's focus. This feet holder, made of Plexiglas, had a weak connection and broke after a few uses. He had several ideas for a better design and considered giving the project to a company outside UW-Madison, but has instead given it to the Biomedical Engineering Department. After consulting with Dr. Schreibman, the criteria for an improved feet holder design were laid out as described in the problem statement.

III. Materials

Several criteria were considered when selecting materials.

1. X-ray attenuation: any material in the scanning field had to be radiolucent to avoid interfering with CT imaging.
2. Strength: had to withstand reaction forces from load on feet.
3. Weight: lightweight materials were required to improve portability.
4. Cost: low cost materials were preferred.

A material's X-ray attenuation varies with the energy of the X-rays passing through it. Dr. Schreibman conducts his ankle CT exams at 120-140 keV and 100-400 mA. For these energy levels, the Hounsfield scale, using units of HU, quantifies the radiodensity, or relative transparency of a material to X-rays [2]. The standard defines air as -1000 HU and water at 0 HU. A material's HU value is also referred to as its CT number. Figure 3 displays the CT numbers for various materials [3]:

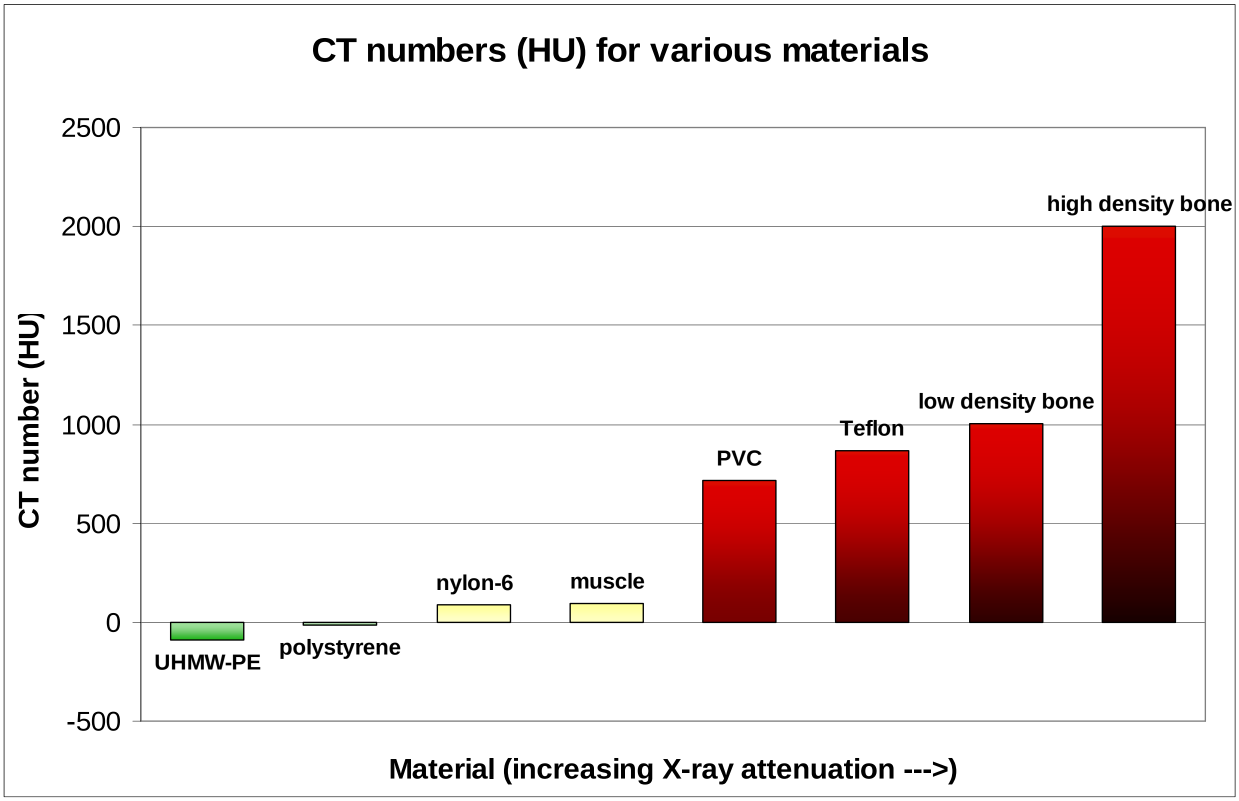


Figure 3
Diagram shows HU for various materials
*Bone ranges from 1000 to 3000 HU, depending on its density [4].

As seen in Figure 3, polyethylene has a very low CT number of –89. This is 16.8% lower than muscle and approximately 43.9% lower than bone. It has the lowest out of the other common thermoplastics on the graph. Once it was known that polyethylene has exceptionally low X-ray attenuation, its other properties were investigated.

Specifications for polyethylene were obtained online from McMaster-Carr [1], a large supplier of hardware and raw materials. They offered several varieties of polyethylene. The specifications for each variety are displayed in Figure 4:

Polyethylene Type	Impact strength	Tensile strength (psi)	Cost*	Specifications met
Low-density (LDPE)	Will not break per ASTM D256	1600	$7.17	FDA, UL
High-density (HDPE)	2.3 ft.-lbs./in.	4000	$7.24	FDA, UL
Ultra High Molecular Weight (UHMW)	Unbreakable by notched Izod test	3050	$8.48	FDA

Figure 4
This table provides the different varieties of polyethylene available from McMaster-Carr [1].
*Cost and weight are given for 12"x12"x3/8" sheet.

All three varieties of polyethylene have a similar density so it was assumed that all three had a CT number approximately equal to that given for polyethylene [3]. Since all three were lightweight, the decision was based on the tensile and impact strengths. The UHMW variety provided exceptional tensile strength (3050 psi) and was unbreakable by a notched Izod impact test. According to McMaster's product description, standard grade UHMW is "ideal for applications that require chemical, friction, and impact resistance" [1]. With all of this information taken into account, UHMW polyethylene was selected as the material for all structural parts, both inside and outside of the X-ray scanning field. Nylon was chosen for fasteners as it the most commonly available plastic for screws and still has a relatively low CT number of 86 HU. Nylon was also the material of choice for the threaded rod of the screw design, as it was the only plastic material found for that component.

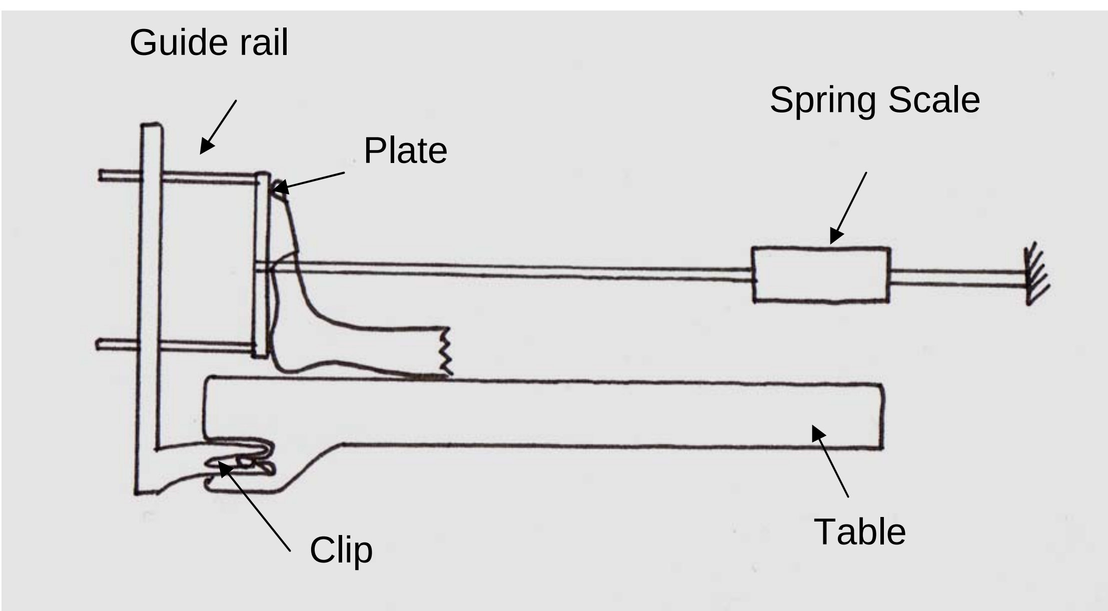
IV. Designs

A. Force Measurement

All three of the proposed designs use a load plate to apply a force to the feet. For the first prototype, the load plate will be a common bathroom scale. While the scale may interfere with CT imaging, it simplifies the force measurement portion of the design and allows the other mechanical components to be focused on. Later prototypes will use a strain gauge-based solution mounted to a UHWM polyethylene load plate. This will provide more accurate force measurement and will be designed to avoid interfering with CT imaging.

B. Cable

The cable design, shown in Figure 5, pulls the feet to apply a force via two cables attached to either side of a plate against which the feet rest. As the technician tightens the cables, they pull the plate, thereby applying a force to the feet. The cables are attached to a shoulder piece, not shown in the diagram below and held down by the weight of the patient. The force will be measured using a spring scale on each cable. This will let the technician know whether or not the tensions in the cables are equal, so an equal force will be acting on the feet.



A **Figure 5**
A sketch of the cable design

- metal free
- accurate force measurement
- easy to adjust force

Disadvantages:

- takes up a lot of space
- imposing to patient
- time consuming to position patient
- more parts to clean

C. Pneumatic

This design consists of the same framework as the screw design, but uses an inflatable air bag and a pump, either manual or electric, to produce the force on the plate and feet, shown in Figure 6. The air bag will be attached between frame and the movable plate, with a tube running from the air bag, through the frame, and connecting to the pump. To make use of this design, the patient will lie on the table with his or her feet strapped against the plate, and the technician will use the pump to inflate the air bag, which will then push the plate against the feet, thereby applying a force to the feet. Manual air pumps cost approximately eight dollars. One such pump, the Small Bellows Foot Pump, model 204IB, is 1.5 lbs, 3 liters, 9.25 in x 6.5 in, and 5.5 psi. According to Amazon.com the price on this is $7.95.

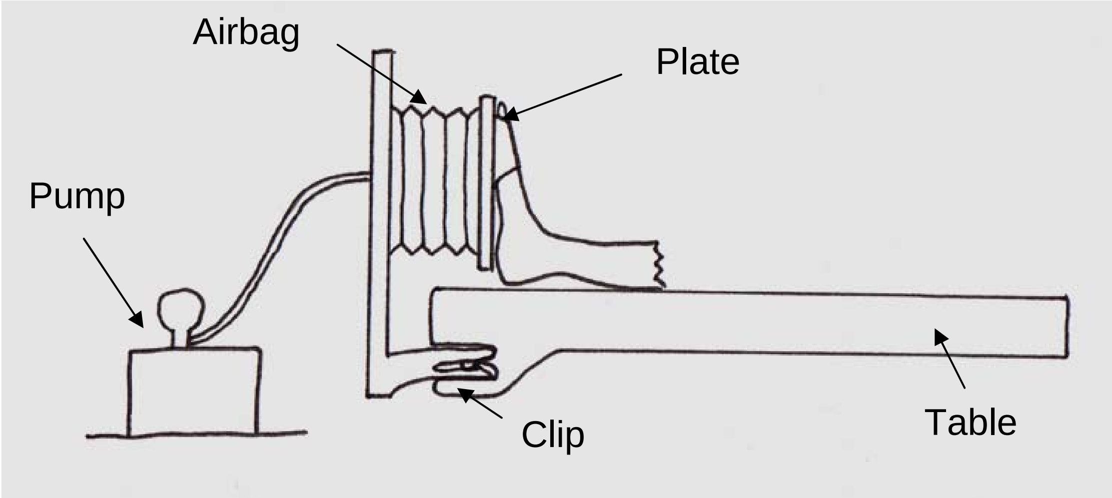


Figure 6
Sketch of the Pneumatic design

Advantages:

- metal free
- minimal strength required to operate design
- lightweight
- relatively easy to adjust force
- accurate force measurement
- manual pump – relatively cost effective
- electric pump – easy to inflate air bag

Disadvantages:

- air bag may be slow to deflate
- manual pump – takes a while to inflate air bag
- electric pump – less cost effective, consumes electrical power

D. Screw

Figure 7 displays the screw design, named for its use of a screw to drive a plate against the patient's feet. The screw is a large threaded rod with 1"-8 threads. A rod with a 1" diameter was chosen to ensure that it would be able to withstand the reaction forces from the load plate. The rod is driven by a long handle distal to the load plate. It was desirable to have a long handle to allow the operator to generate greater torque. A detailed list of the screw design's components and their functions can be seen in Figure 8.

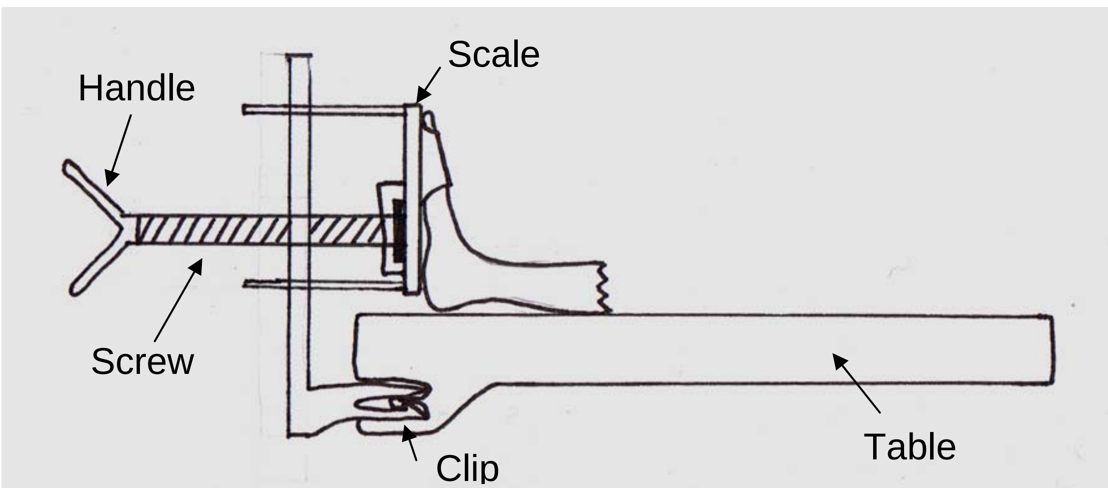


Figure 7
Sketch of the screw design.

Component	Function	Material	Weight (lbs.)	Approximate Cost ($)
Load plate	Applies load to feet.	UHMW-PE	1.81	9.00
Threaded rod	Pushes load plate against feet by converting handle rotation to linear motion.	Nylon 6-6	.81	25.00
Handle	Technician rotates handle to drive the threaded rod.	Steel	Approx 1	35.00
Straps	Hold feet securely in proper position.	Unspecified	Negligible	Unknown
Mounting plate	Anchors device to CT table	UHMW-PE	1.81	9.00
Threaded insert	Has internal 1"-8 threads that prevent threaded rod from being pushed back under load.	Unspecified	Negligible	1.00
Guide rails	Help keep load plate properly aligned.	UHMW-PE	.3	4.00
Retention assembly	Keeps threaded rod connected to load plate to allow the plate to be pulled back.	UHMW-PE	.3	11.00
Disc	Plastic-welded to end of threaded rod to allow plate to be pulled back by pushing against retention assembly.	UHMW-PE	Negligible	1.00
		Total	5.22 pounds	70 dollars (excluding device to measure force)

Figure 8
Table describes each component in the screw design and compiles the weight and cost.

Advantages

1. *Safety* – the technician has immediate manual control of the load on the feet. If the patient experiences pain, the handle can be quickly reversed to remove the load.
2. *Portable* – it contains a small number of parts that are all lightweight. With an estimated approximate total weight of 5.22lbs, obtained from Figure 8. This weight is important because it should be easily movable by one technician.

3. *Durability* – all parts are wear-resistant and the UHMW-PE parts have high impact strength, minimizing damage to the device if dropped.
4. *Accuracy* – the load is directly measurable at high accuracy and precision by either a strain gauge-based device or a simple scale.
5. *Simple mechanics* – it has no complex parts and should be relatively easy to manufacture and clean.
6. *Cost* – the total estimated cost of this design is 70 dollars, this is excluding the price for the force measuring mechanism.

Disadvantages

1. *Ease of use* –
    a. The handle is manually operated and may require excessive force to use. Quantification of the operating force requires testing.
    b. The amount of rotation necessary to apply a considerable load on the feet is unknown but likely small. If the rotation is very small, such as 45 degrees or less, gearing may be required to allow for finer adjustment.
    c. Space is also a concern, as the handle may not be easy to reach due to the proximity of the CT scanner.

V. Design Evaluation

A design matrix was created to evaluate each design. The three designs were compared based on several weighted criteria. The criteria were discussed, defined, and weighted by the team before creating the matrix.

Criteria	Weight	Definition
Patient Safety	20	Patient safety was weighted the highest without question. A safe device would allow the load to be adjusted or removed quickly if the patient experiences pain.
Portability	20	Our client stressed that it was very important that the device be easily movable by one technician. It should be lightweight and easy to carry to another CT table.
Ease of use	15	The device must be easy to operate by one technician. It should not require excessive force or much effort to timely reach the desired load.
Accuracy	15	The load must be able to be accurately measured to within ± 0.5 lbs.
Durability	10	The device must be wear and impact resistant in order to last
Comfort	10	The device should not be imposing to the impatient or create any additional discomfort.
Cost	5	Cost of all components should be minimized. Less than $300 is required.
Complexity	5	A less complex design is one that uses less few parts, has less things that can go wrong, and is easier to manufacture.

Figure 9
Table describes the components by which each design was rated against.

Each team member individually generated a comparison matrix and the averages were used for the final matrix, as can be seen in Figure 10.

Criteria	Weight	Screw	Pneumatic	Cable
Patient Safety	20	19.25	17.75	15.5
Portability	20	19	14.5	11.75
Ease of use	15	12	12.25	9.5
Accuracy	15	14	14	14
Durability	10	9	9	8.25
Comfort	10	9	9	3.25
Cost	5	4.75	3.5	3.5
Complexity	5	4.75	3.25	2.75
Total	**100**	**91.75**	**83.25**	**68.5**

Figure 10
Table of the design matrix

As seen in the matrix, the screw design scored highest and was selected as the final design. With its simple manual control, patient safety was rated the highest. It is also estimated to weigh only 5.22lbs., so should be easy to carry from table to table. It scored high in all categories, with the only concern being ease of use. These difficulties were previously highlighted in the disadvantages section of the screw design description and will be addressed and worked around if needed after testing. The pneumatic design scored high as well and will be continually developed as a backup to the screw design. The cable design had several significant disadvantages that contributed to its low score and will no longer be considered as an option.

VI. Future Work

As can be seen from the design matrix, the Screw Design met the criteria best and was the chosen design to work with for the rest of the semester. As the Pneumatic Design had a somewhat close score to the Screw Design, it was kept as a backup in case the screw design does not work. The materials for the prototype will be bought so that the screw design can be constructed. Before the prototype is completely constructed, IRB approval is needed in order to do any kind of testing on volunteers. Once approval is granted, testing of the prototype will commence, and the design will be refined as needed to ensure that the prototype is in working condition.

References

1. Polyethylene Material. *McMaster-Carr* **2006**, 1 (2006) http://www.mcmaster.com/.

2. Hounsfield scale. *Wikipedia* **2006**, 1 (2006) http://en.wikipedia.org/wiki/Hounsfield_scale.

3. Schneider, U., Pedroni, E. & Lomax, A. The calibration of CT Hounsfield units for radiotherapy treatment planning. *Phys. Med. Biol.* **41**, 111-124 (1996).

4. Smith, H. Computed tomography. *GE Healthcare Medcyclopaedia* **2006**, 3 (2006) http://www.medcyclopaedia.com/library/radiology/chapter04/4_2.aspx.