Protecting Pilots: Designing a Variable Cervical Neck Brace to Mitigate Ejection Injuries

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Kathryn Leigh Ward

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Technical Project Team Members

Seth Berry

Brian Gilday

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Dr. Robert Salzar, Center for Applied Biomechanics

Abstract

Pilots in the United States military routinely face high gravitational forces that are applied directly to the spine. One in three pilots face neck injury from this force, and the higher threat of injury on smaller personnel bars most women from flying attack aircraft[1]. A neck brace that protects the cervical spine against injury would be a step forward in allowing smaller anthropometries into the cockpit of a fighter jet. The brace designed to protect the upper neck is a passive safety mechanism, as it inflates upon ejection. Three pressure chambers inflate to variable pressure based on a computational model of the spine when under the forces of ejection; injury criteria of vertical forces and forward rotation are minimized through the applied pressure from the brace. The computational model is based on literature surrounding the 50th percentile male anatomy, and can be further scaled to represent smaller anthropometries and helmet masses. The brace itself incorporates a portable gas source, piping system, and repurposed neck traction device that, when passive, sits unobtrusively around the neck and does not interfere with helmets or oxygen masks. Each individual airbag is connected to three pressure regulators, which are connected to a solenoid valve and carbon dioxide cartridge that serves as the source of pressurized gas for inflation. The feasibility of the brace's construction and design was validated through inflation tests first utilizing a manual inflation valve and subsequently with the solenoid valve. Before applying the brace to a militarized setting, further testing for injury mitigation and inflation time needs to be conducted.

Keywords: Acute Neck Trauma, Injury Prevention, Passive Safety Feature, Variable Pressure

Introduction

Reasoning

One in three pilots face injuries when ejecting from a fighter aircraft cockpit, coining the phrase, 'ejection in itself is a punishment[2].' In the 1950s, a standard hard helmet was issued to pilots in order to protect the head from impacts, but had the unfortunate effect of increasing the incidence of cervical spine stress during ejection[3]. As pilot helmets have become increasingly more intricate, they have also become heavier, producing a larger moment along the neck which has increased the number of injuries to the cervical spine to almost 30% of pilots who have to eject from an aircraft[4]. The new F-35 aircraft has produced an accompanying helmet that is much heavier than previous iterations and is highly likely to cause both acute and chronic neck trauma to the pilots who don them. The exact design specifications of the F-35 helmet are unknown to us at this time as that information is deemed classified by the Department of Defense. There are multiple steps that need to be taken to reduce the risks associated with ejecting in order to expand the military pilot job to a more diverse set of candidates: a brace that protects the upper neck and that is adjustable by anthropometry is simply the first in a series of necessary steps.

Previous Literature

The current applied research about ejection safety in the U.S. military centers around the 50th percentile male. Research has been conducted that further proves ejection is unsafe for smaller pilots, such as a NAVAIR study at Naval Air Station Patuxent River in 2006 that studied cervical spine risk of injury upon ejection, used to determine the minimum weight of pilots at 135 pounds[5]. The military has strict anthropometric standards when selecting personnel to pilot fighter aircraft, as the ejection force was designed to clear the 50th percentile male from the plane while not damaging his spine, and the designed force has disastrous effects on any anthropometries that differ significantly from the 50th percentile male. A 2009 study done by Dr. Robert Salzar at the University of Virginia Center for Applied Biomechanics for NAVAIR showed the 5th percentile female would crumple under the current ejection force, her lower spine folding past any survivable injury: further proving there was no reasonably safe option for smaller females to safely eject from fighter jets[4]. Cervical spine injury upon ejection was studied in a cadaver model published in a 2009 issue of Aviation Space and Environmental Medicine, and showed subfailure ligamentum flavum injuries within the cervical spine were most common upon ejection[6].

Goal of Research

The goal of this research is to design, develop and validate a cervical neck brace that will reduce incidence of acute trauma in jet pilots who must eject from their aircraft. This neck brace would be the first device to provide further protection against ejection related injuries, an aim which will be achieved by distributing the maximum force applied to any one section of the cervical spine based on modeling injury criteria. The computational modeling portion of this research serves to provide data on how stiffly to inflate the three vertically stacked sections of the neck brace: the model stiffness of the brace had to output a neck injury criterion under 22%. The acceleration based triggering system provides a hands-free inflation for the neck brace. This neck brace should provide protection of the cervical spine sufficient enough to offset the increased risk of injury associated with the new F-35 helmet and smaller anthropometries, making the fighter platform safer for all pilots.

Results

Computational Model

An MSC ADAMs lump mass model was constructed and tested under upper neck traces obtained from previous ejection research and compared to injury criteria to determine most effective 'stiffness' between cervical vertebrae that minimizes injury. The input of the model was a three-component force vector pulse over 340 ms constructed from fitting high degree polynomials to an ejection test done by the University of Virginia Center for Applied Biomechanics in 2009: the polynomials served to supply a time history of the ejection force found in the traces, and apply an accurate trend to the model force[4] (Figure S1). The model's stiffness between lump masses representing the cervical vertebrae was increased to represent a brace worn during the force of ejection; moment of the cervical vertebrae along the y-axis as well as compression along the-z axis were recorded and compared to USN/USAF neck injury criteria (Nij) (Equation 1) of the vertebral column, where neck injury criteria (Nij) is found using force on the z-axis and moment along the y-axis, and the initial values for both force and moment are pre-prescribed in literature, varying by size[5] (Tables 1 & 2). Stiffnesses that minimized injury risk below 22% were recorded for two parameters: the smaller female, and a heavy object (helmet) incorporated into the mass of the head. The optimized stiffnesses were then converted into pressures for the brace to inflate to upon ejection (Table 3).

$$Nij = \frac{F_Z}{F_{Zint}} + \frac{M_Y}{M_{Yint}} \quad [1]$$

Stiffness	Vertebrae	Fz Int (N)	Fz (N)	My Int (Nm)	My (NM)	Nij
0.097	Head:C1	4500	99.83	310	35.63	0.1371199
0.124	C1:C2	4500	126	310	51.44	0.1939355
0.178	C2:C3	4500	120.4	310	28.26	0.1179168

Table 1. Neck Injury Criteria for male with helmet. The far-left column is the additional stiffness added to the anatomical stiffness to represent the brace. Nij in the far-right column does not exceed 0.22.

Stiffness	Vertebrae	Fz Int (N)	Fz (N)	My Int (Nm)	My (Nm)	Nij
0.157	Head:C1	3370	63.41	155	23.22	0.1686225
0.178	C1:C2	3370	51.59	155	31.13	0.2161473
0.193	C2:C2	3370	60.94	155	17.17	0.1288573

Table 2. Neck Injury Criteria for small female. Similar to Table 1, the far-left column is the additional stiffness added to the anatomical stiffness to represent the brace and Nij in the far-right column does not exceed 0.22.

Vertebrae (Helmet Model)	Stiffness (N/mm^2)	PSI
Head:C1	.097	14.01
C1:C2	.124	17.98
C2:C3	.178	25.82
Vertebrae (Female Model)	**Stiffness (N/mm^2)**	**PSI**
Head:C1	.157	22.77
C1:C2	.178	25.82
C2:C3	.193	27.99

Table 3. Optimized Stiffnesses. Added stiffness in the rotational and translations springs converted into PSI for the brace. PSI given for each vertebral connection from head to C3.

Brace Assembly

The final prototype for the variable neck brace principally consists of a three-tiered airbag repurposed from a commercial neck traction device originally designed for pain relief. The airbag is compact and low profile, enabling a high degree of mobility for its users, particularly in a compact environment like a fighter jet cockpit. Each tier of the airbag is an isolated pressure system with separate intake ports to provide for variable, well-distributed pressurization. Rubber tubing from each of the three intake ports directly connects the airbags to individual pressure regulators via straight, push-to-connect tube fitting adapters. The pressure regulators themselves are relieving with analog gauges and knobs for manual adjustment of pressure settings based on the anthropometric measurements of the user. Each pressure regulator connects to a system of threaded steel and iron piping, which ultimately feeds into a single inflow port for the pressurized gas source. The metal piping provides a durable, robust method of containing the pressurized gas with threading that is easily connectable to both the pressure regulators and the gas source. In keeping with the design constraints of a brace that must be both compact and wearable by the user, the pressurized gas source is a single use, 3.375in x 0.875in 16g carbon dioxide cartridge that connects to the intake port of the piping system via an aluminum and steel alloy inflator and a brass Schrader valve. The airbag can be rapidly deployed by the user via a manual knob on the inflator valve prior to activating the ejection lever in their cockpit. Below in Figure 1 are images of the brace's inflation capabilities and include each of the prototype components connected to the carbon dioxide cartridge.

Fig. 1. **Final Prototype Assembly.** The two images display the airbags inflated to various pressures, connected to pressure regulators, piping system, manual inflator valve and gas cartridge.

<u>Discussion</u>

Accomplishments

An original computational model for ejection was created in MSC ADAMs that is versatile to both the F-35 helmet weight and smaller anthropometries, giving insight to how the cervical neck should be protected based on cervical spine size and the working mass of a head with a helmet. The model can be used to further research the stiffness of the cervical and how it relates to injury, injury mitigation devices, and ejection forces on a range of anthropometries. Additionally, a prototype for the neck brace was assembled and successfully inflated, validating proof of concept for the project and its feasibility to progress from an idea to a functioning device. Another accomplishment was the production of a simple manual switch connected to a solenoid valve from the materials available. The main component of the switch uses a MOSFET that provides a 24V signal to the valve when the state of the MOSFET is altered.

Constraints

The brace was validated by a manual inflator valve, shown above, which has the ability to inflate with carbon dioxide cartridges to given pressures taken from the computational model. However, the brace was not tested in a lab setting, and thus, the passive trigger mechanism remains untested. The manual switch is not viable in an ejection seat situation, as the pilot does not have time to pull the trigger: the accelerometer triggering mechanism serves as the continuation of the trigger toward a functioning, acceleration triggered system that is sufficient for proof of concept and validation testing. Further, the brace itself is bulky and not wearable, as it serves as a prototype. The valves are made of steel, and would have to be softened to both make the brace wearable and not intrusive on a pilot's range of motion and negate further injury risks from the hard steel construction.

Continuations

The next steps in the design of the brace including testing with a drop tower, as shown by the drawings in Figure 2. Drop tower tests would validate the accelerometer triggering mechanism, and could incorporate biofidelic dummies to test the brace's injury mitigation outside of the computational model.

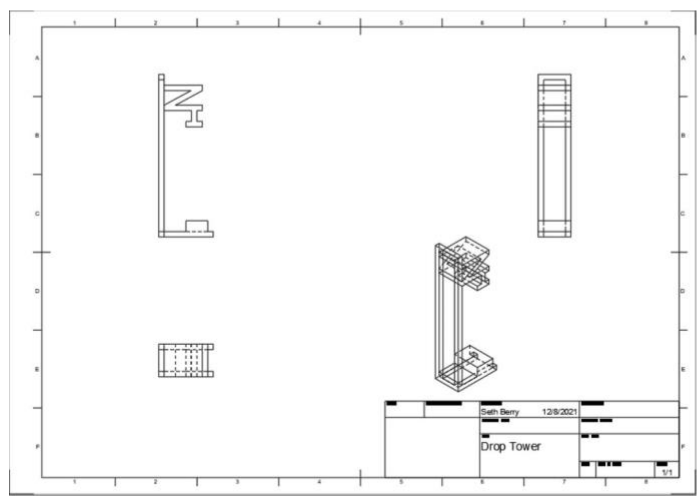

Fig. 2. Schematic of a Drop Tower. The Hybrid III dummy head would be affixed to the z shaped brace towards the front, directly over the part that protrudes down from this brace. The part protruding out from the bottom of the z shaped brace is meant to come into contact with honeycombed metal that flattens out the force applied to the head on impact.

The brace does not inflate quickly enough to deploy upon ejection, and the next series of prototypes would need to incorporate more efficient tubing or closer quarter tubing to achieve the desired result of instantaneous ejection, much like a car airbag. The brace material and structural components would need to be optimized to best fit the upper neck: a cost/benefit analysis of plausible materials and design should be conducted to determine the construction, as well as further modeling in both MSC ADAMs and biofidelic models to achieve high levels of injury mitigation. Should the brace be used to accomplish the specific aim of protecting smaller anthropometries, it would need to have multiple size variations to best fit the cervical spine of larger and smaller pilots.

Triggering Mechanism Design

The brace setup used a valve that remained in a closed position until 24V were supplied to it, which would cause the valve to open, allowing carbon dioxide to rush into and inflate the brace. These 24V were supplied using a metal-oxide-semiconductor field effect transistor (MOSFET), an accelerometer, and a microcontroller. The accelerometer reacts to changes in acceleration, where maximum acceleration in the negative direction is 0V and maximum acceleration in the positive direction is 3.3V. This voltage is sent to the Arduino microcontroller where it is subsequently turned into a bit integer on the range of 0 to 1024, exclusive. The accelerometer returns integers in the middle of this range, which is approximately 512, for the x and y directions, but the resting integer is higher for the z-axis since it can detect gravity as shown in Figure 3. In order to use the accelerometer as a triggering mechanism a specific acceleration must be settled upon as the threshold acceleration, which will be the minimum acceleration the accelerometer must detect before the microcontroller will send a signal to the MOSFET. In the graph on the left there is no force being applied to the accelerometer and so the resulting integer is a flat line, whereas simply shaking the accelerometer, shown to the right, results in spikes of acceleration in the z direction and relatively low amounts of noise in the x and y directions. It is imperative that the threshold acceleration used to send a signal to the MOSFET is tested and improved, since too low a threshold acceleration will result in false positives, causing the neck brace to activate unnecessarily, and too high a threshold acceleration will result in false negatives, where the neck brace does not deploy at all.

Once the threshold acceleration has been met the microcontroller will send a 3.3V signal to the control pin on the MOSFET. The MOSFET is a p type MOSFET meaning that it is active when it receives a sufficiently large signal; the MOSFET consists of three pins, a source, a drain, and a control. The source pin receives a 25V signal from a larger power supply, the drain pin leads directly into the valve, but will only pass along the 25V from the power supply when the control pin receives a signal. The microcontroller provides this signal to the MOSFET only when a sufficient threshold acceleration is detected by the accelerometer. Once the 25V signal is passed along from the MOSFET to the valve, the valve snaps open and carbon dioxide can begin filling the brace. In order to get the triggering system working the accelerometer, microcontroller, MOSFET, and valve must all be able to communicate with each other. The accelerometer and microcontroller worked together but the MOSFET was unable to react to the signal provided by the microcontroller.

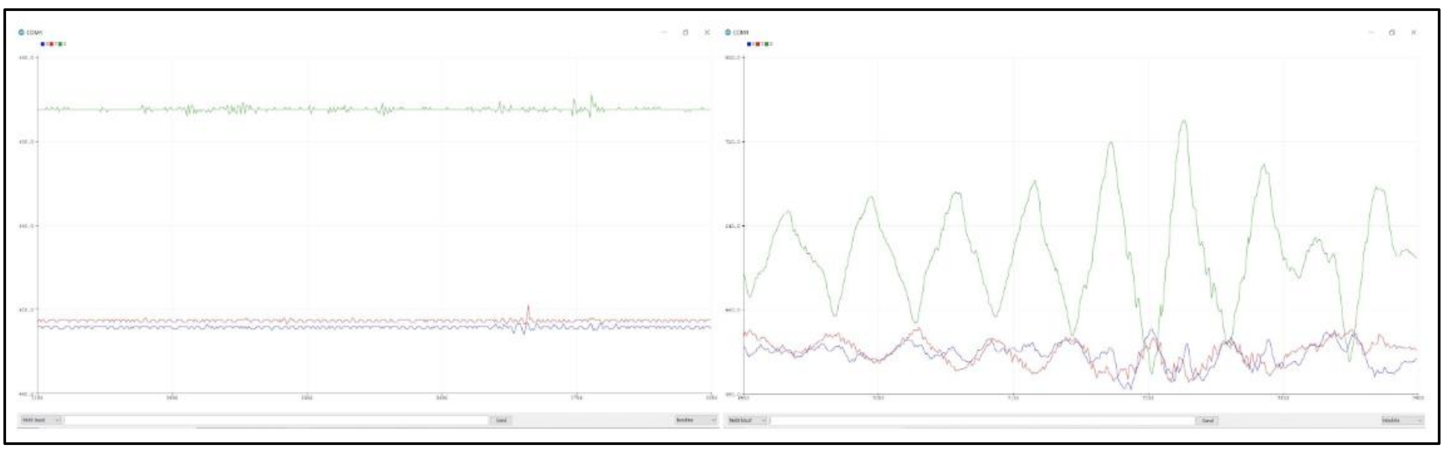

Fig. 3. Accelerometer Force Detection. The graphs show the forces recorded with the y-axis displaying the forces in terms of a 32 bit integer and the x axis displaying time. The graph on the left shows the accelerometer at rest, and the graph on the right shows the accelerometer moving up and down in the z direction (towards and away from the ground).

Materials and Methods

Computational Modeling

A lump mass model was created to model the cervical spine and cervical spine connections, as shown in Figure 4. The masses of the modeled vertebrae were based on pre-existing

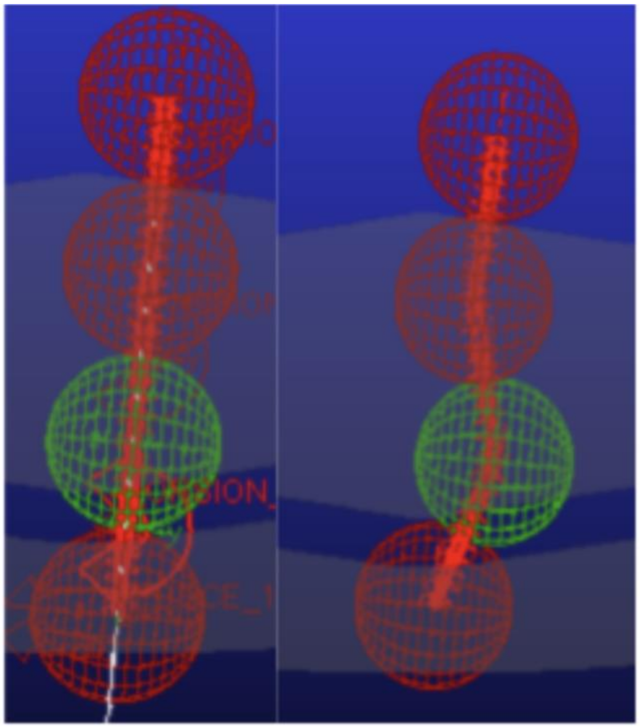

Fig. 4. Cervical Spine Model. On the left, the spine is uninjured after ejection force, while on the right, injury the the second vertebrae has occurred with a high Nij.

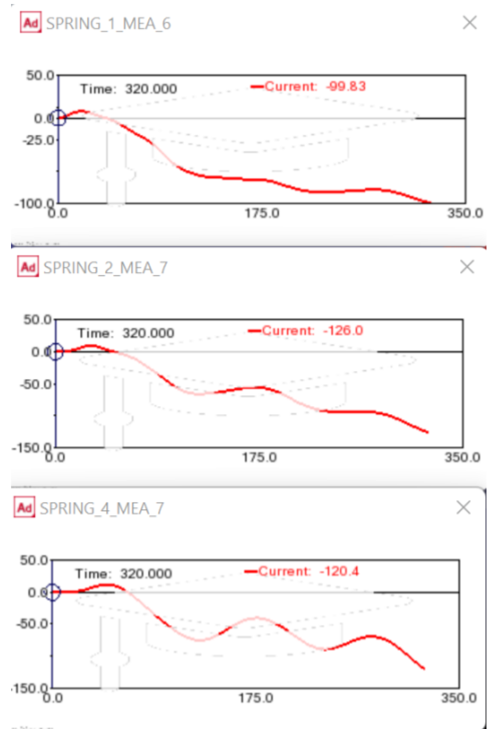

Fig. 5. Male with Helmet Model. Compression force on z-axis between Head and C1, C1 and C2, and C2 and C3, respectively, over 340 ms.

literature, and the ejection force was modeled using a 2009 study of ejection traces on the upper neck[7,4]. The lump masses were connected to each other by a rotational spring along the z-axis and a translational spring along the y-axis. The translational spring served to model the translation of force from the bottom vertebrae in the model (C3) up to the top lump mass (the head). The rotational springs modeled the stiffness of the spine, and the stiffness (k) was set to the coefficient found in the Dibbs 2009 tension study, with the baseline values of translational stiffness at 71.6 N/mm^2, and rotation stiffness 94.1 N/mm^2.

To model the brace, the stiffnesses of the rotational and translational springs was increased incrementally to represent additional stabilizing pressure, and the model was run under the ejection force: the resultant forces in between the vertebral bodies along the z-axis as well as the moments along the y-axis were recorded and compared to USN/USAF injury criteria. Finally, the coefficient of stiffness is measured in N/mm^2, which was converted into PSI, and set as the pressure for which the brace should inflate to. The entire process was repeated on variations of the model: one variation was scaled down by 35% to represent a smaller, female cervical vertebrae, and the other variation increased the mass of the top lump model to model a heavier helmet worn by an F-35 pilot.

Brace Design and Construction

Initial conceptualization of the brace incorporated the employment of a fabric or material that stiffens when an electrical current is passed through it, based on data collected from a gravitational force sensor throughout various flight maneuvers, not just upon ejection of the pilot from the cockpit. This would optimally protect the cervical spine from both acute trauma associated with ejections as well as chronic trauma that develops after repeated, aggressive flight maneuvers over time. Due to overall project time constraints, this design was simplified to one that centers around an adjustable airbag that exclusively focused on acute cervical spine trauma and deployed only upon pilot ejection from the cockpit. The airbag itself was taken from a commercially available cervical neck traction device that was originally intended for therapeutic use and chosen due to its compactness, comfortability, and three-tiered design. The original neck traction device had individual ports on each of its three tiers, connected to a single manual squeeze pump via 8mm flexible rubber tubing. While lack of strength and durability were the primary initial concerns with regards to the flexible rubber tubing, it was determined that utilizing push-to-connect tube fitting adapters on the ends of each tube rather than completely removing them from the intake ports would mitigate potential sources of error with respect to gas leaks.

The threaded tube fitting adapters were then directly connected to three separate relieving pressure regulators, each composed of an analog gauge and knob for manual adjustment. Based on the optimal stiffnesses between cervical vertebrae of the user as determined by computational modeling, each regulator, and in turn each airbag, could be adjusted to variable pressure settings that most effectively protect the user from excessive vertical loading scenarios (ejections). Manual pressure regulators were chosen primarily to demonstrate proof of concept, but further development and prototype iterations should incorporate digital pressure regulators to minimize pressure setting errors. From the pressure regulators, 2.5 in steel threaded pipes connect to a single intake port for the gas source using a series of pipe fitting connectors. The threading of each component of the piping system was standardized at ¼ NPT and is illustrated in Figures S2-8, along with all other brace components.

Preliminary designs for the gas source involved the utilization of a large, multi-use gas tank for iterative testing and troubleshooting for leakage within the tubing and piping. This was bypassed by attaching a Schrader valve and manual inflator valve to the piping system intake port for use with smaller gas cartridges that could be more effectively stored and tested in motion. The 16g single-use cartridges chosen to test the inflation capabilities of the prototype have a maximum pressure of 130 psi, well within what would be needed for a proof of concept, and provide a reliable yet inexpensive source of pressurized gas.

Triggering and Testing

The manual triggering mechanism opens the valve using a simple design consisting of a breadboard, jumper wire, and the valve itself. This simple design has a power source shown at the bottom left that is tied to the source side of the MOSFET, a wire tied from the voltage source to the control pin of the MOSFET, and a wire connecting the drain pin of the MOSFET to the valve. For proof of concept the manual triggering mechanism is a sufficient solution, but for further lab testing an accelerometer actuated triggering mechanism would be a significant improvement. Real world design application will most likely require that the triggering mechanism be tied to the ejection mechanism so that they occur simultaneously, ensuring the neck brace has ample time to deploy. Since accelerometers track orientation and pilots are routinely subjected to high forces during flight, the accelerometer would likely not be appropriate for real world application for fear that the brace would deploy at inappropriate times, hampering the pilots' abilities.

End Matter

Author Contributions and Notes

S.T.B., B.M.G., and K.L.W. formalized proposal, S.T.B., B.M.G., and K.L.W. performed research, K.L.W. formulated and applied computer modeling, B.M.G. designed and constructed prototype; S.T.B. built and integrated triggering mechanism; and S.T.B., B.M.G., and K.L.W. prepared report.

The authors declare no conflict of interest.

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Supplementary Figures

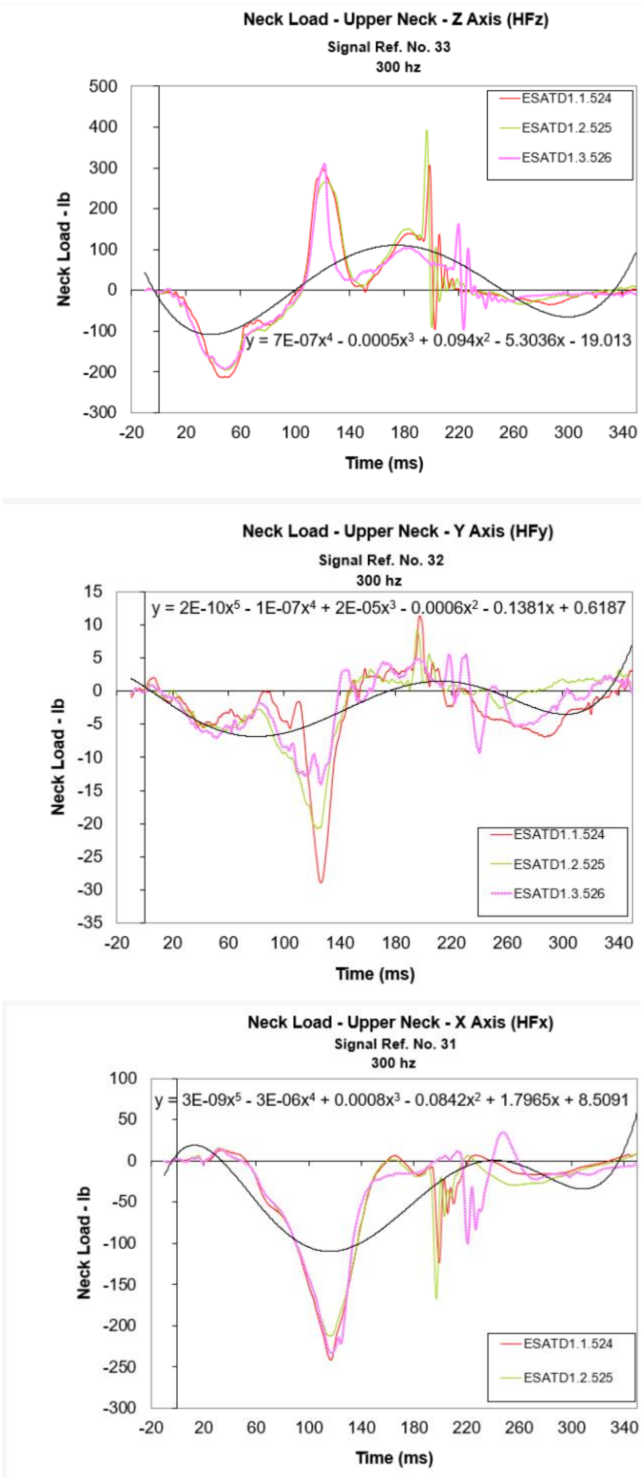

Fig. S1. Neck Load Testing. Ejection force traces on the lower neck done by a study in 2009 by Dr. Robert Salzar at the University of Virginia Center for Applied Biomechanics.[4] High degree polynomials were fit to the curves and modeled in ADAMs MSC and a three-component ejection pulse.

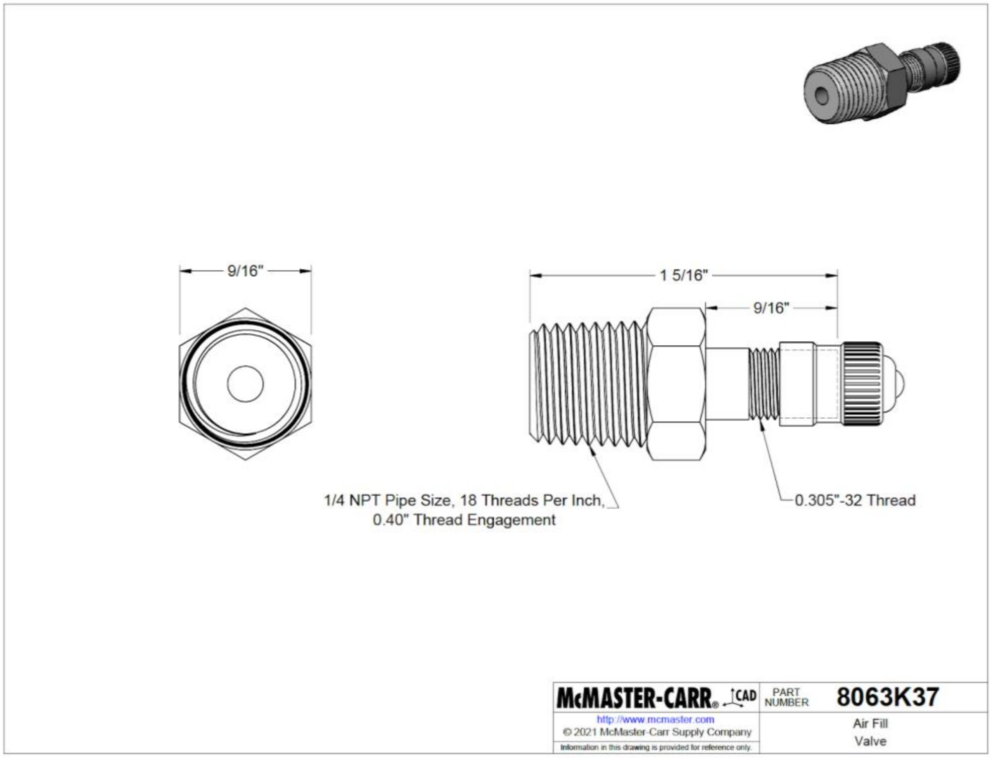

Fig. S2. Air Fill Valve

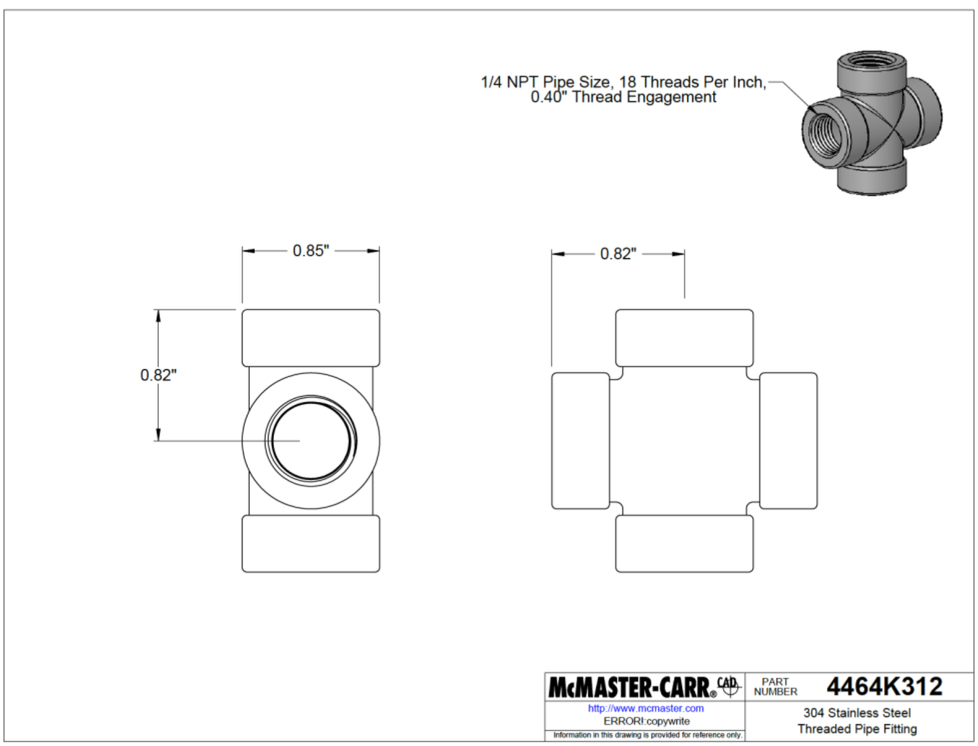

Fig. S3. Cross Pipe Fitting

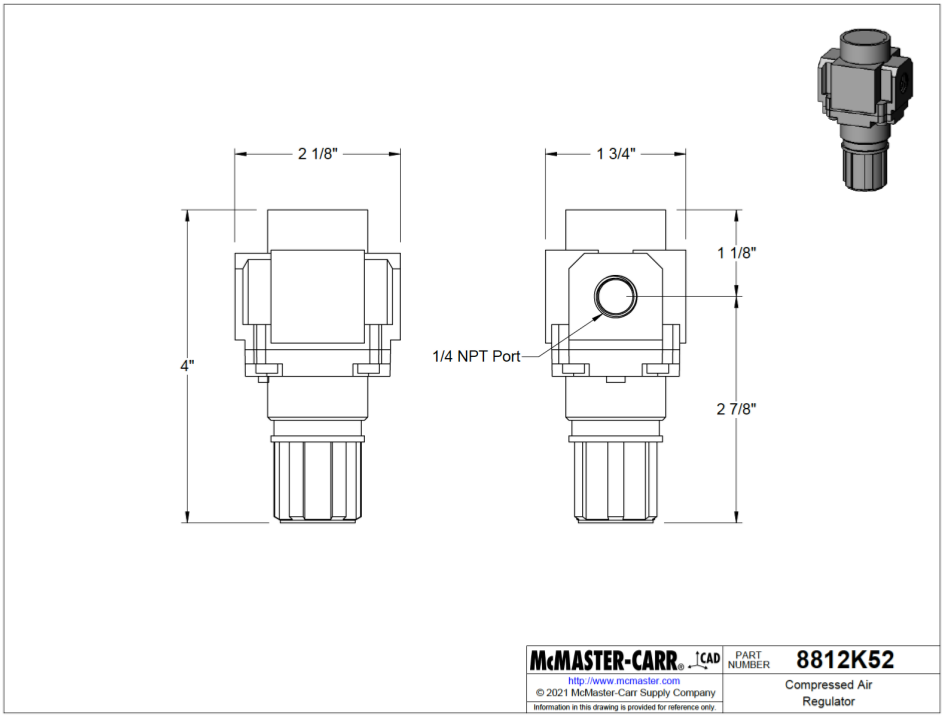

Fig. S4. Relieving Pressure Regulator

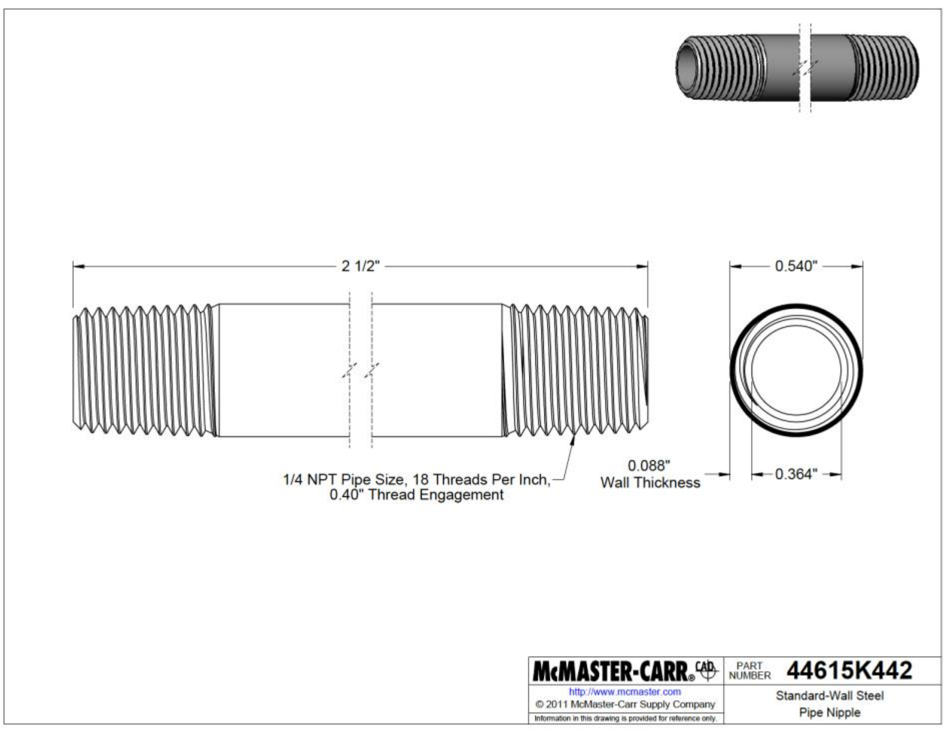

Fig. S5. Threaded Steel Pipe

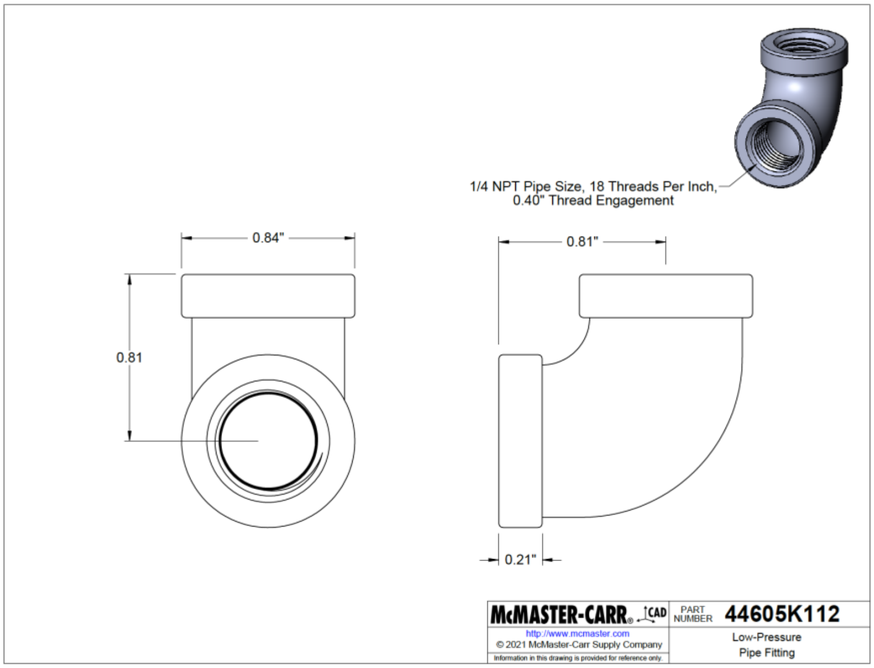

Fig. S6. Steel Pipe Elbow Fitting

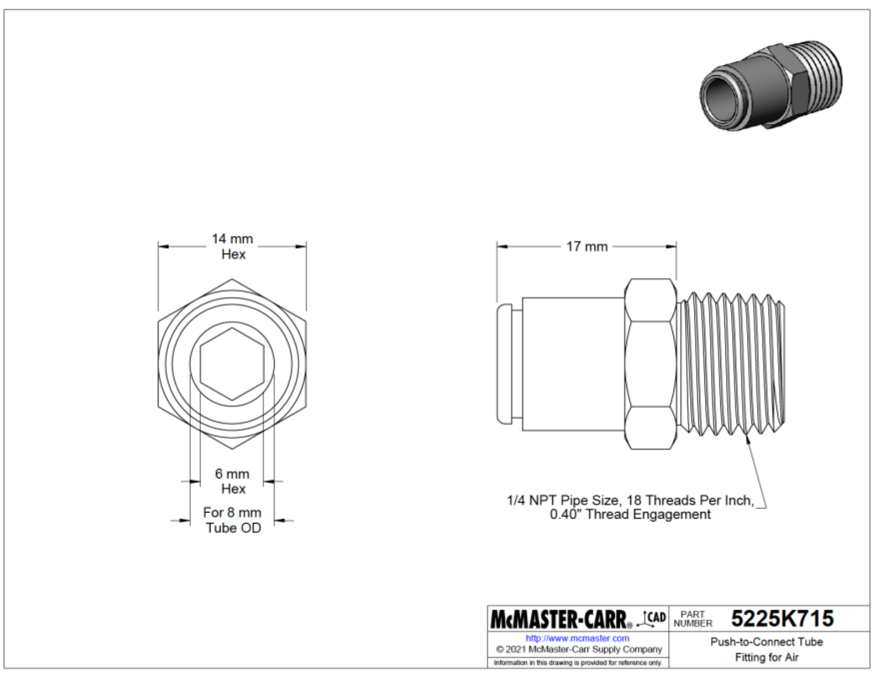

Fig. S7. Push-To-Connect Tube Fitting

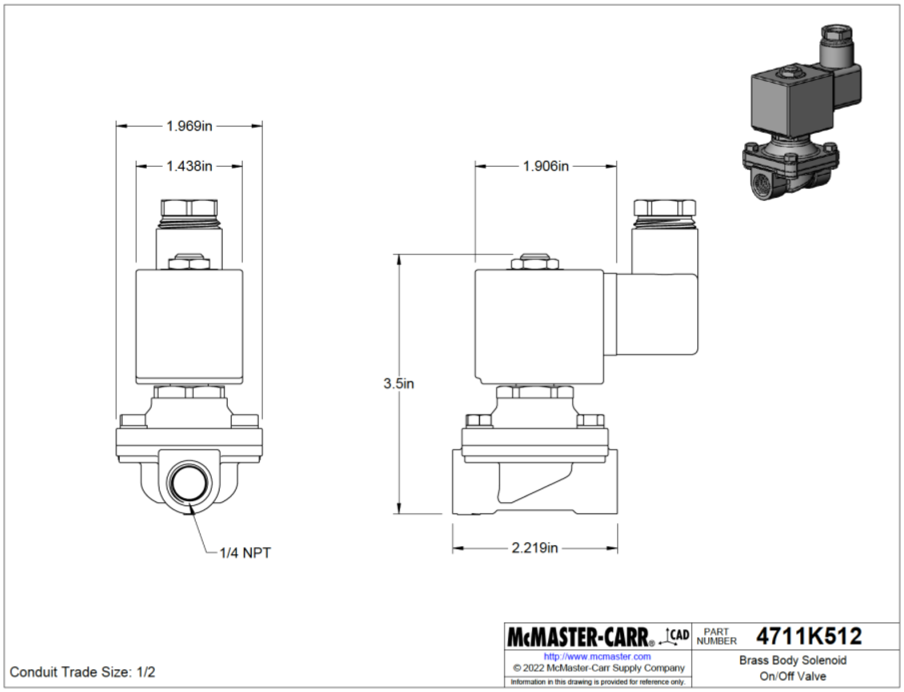

Fig. S8. Solenoid Valve