An *in silico* Approach to Understanding Pain Associated with the Chest Tube

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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

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An *in silico* Approach to Understanding Pain Associated with the Chest Tube

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Abstract

Initial management of chest tubes influence the efficiency of fluid drainage, course of disease recovery, and length of hospital stay. Thus, improving the current standard of care and reducing its associated pain is one common goal among patients, healthcare providers (HCPs), insurance companies, and public health officials. The central purpose of this study was to determine the origin of pain using an *in silico* modeling approach. A survey was distributed to medical professionals in order to gauge their opinions on the current standard of care and associated pain with the chest tube. Over 85% of providers believed that chest tubes or chest tube dressings needed improvements (n = 71), and 90% of these HCPs were willing to adopt a new protocol (n = 61). On average, providers ranked the pain associated with the chest tube as a 4.75 ± 1.58 (mean ± s.e.m) on the standard pain scale. Furthermore, over half of them believed that pain originated from the intercostal space or pleural cavity. Subsequently, a multi-layer, computer-aided design (CAD) model of the thoracic cavity was developed. A chest tube, along with its associated sutures, were included in the model in order to simulate the chest tube-chest wall junction. Static stress finite element analysis simulations were conducted to determine the stresses, strains, and deformations present in each connective tissue when external loads were applied to the chest tube. Results suggest that the majority of stress lies on the intercostal muscles and ribs, whereas the majority of strain and deformation lies on the skin and adipose tissue. These simulation results – coupled with the survey finding that 85% of HCPs want the standard of care improved – indicate that a true clinical need exists in the realm of pain management following thoracotomy and sternotomy procedures.

Keywords: Chest tube, pain, thoracic cavity connective tissues, finite element analysis

Introduction

In the United States, doctors perform approximately 1 million chest tube (CT) insertions each year.[1] Common indications for a chest tube thoracostomy include a pneumothorax, hemothorax, pleural effusion, pyothorax, and chylothorax.[2] Oftentimes, pleural chest tubes are used to drain excess fluid or air from the pleural cavity that results from thoracic injury or trauma. Trauma, specifically, is the leading cause of fatality for younger individuals, with approximately 25% of those cases being attributed to primary thoracic injuries alone.[3] Some estimate that chest tubes inserted after thoracic trauma comprise over 10% of all chest tubes thoracostomies.[1] On the other hand, mediastinal CTs are commonly used after open heart surgery in order to drain postoperative blood and fluid from the mediastinum.[4] It is estimated that around half of all chest tube insertions occur in the context of thoracic surgery.[1]

After a chest tube is inserted into the pleural space or into the mediastinum, the incision is sutured on both sides of the tube, and the remaining skin flaps are stitched up the sides of the tube base. The suture thread is then wrapped around the tube several times and knotted.[2] An occlusive gauze or dressing is placed around the chest tube to stabilize it, keep the wound dry, and ensure that no air leaks are present.

Typically, a chest tube is kept in a patient until the draining fluids and air fall below a certain threshold. This usually lasts anywhere between two to 14 days. Initial management of chest tubes and chest tube dressings influence the efficiency of fluid drainage and intensity of pain; both of these factors play major roles in dictating hospital stay duration and associated medical costs.[5,6] Thus, there exist ethical, medical, and economic incentives to improve the current standard of care.

Two main concerns with the chest tube itself are those of pain management and tube kinking and occlusion. Studies show that small-bore chest tubes (≤14 French) are less painful than large-bore drains, yet bigger tubes are often necessary for larger pneumothoraces or to drain highly viscous fluid from the pleural cavity.[7,8] These drains are also sturdier and less likely to become inadvertently occluded. Survey findings from Shalli et al., reveal that although pain is worse with large-bore tubes, “physicians generally err on the side of caution to avoid clogging and insert tubes with larger diameters.”[9] Thus, there exists an inherent tradeoff between risk of occlusion and pain associated with these drainage systems.

The success of this “high stakes, low-frequency" procedure depends on the skill level of the healthcare provider; those with little experience or exposure to the procedure often have trouble with insertion and properly securing the tube to the body.[8,10] Although simulation training laboratories exist to teach future physicians on the chest tube thoracostomy and median sternotomy techniques, they are often inadequate. A survey found that only 14.3% of medical students who completed one of these training programs actually felt confident in their skillset.[11] Additionally, none of the digital training programs have been widely implemented into a curriculum, leaving students with little to no “hands-on” practice.[12] Most of the programs that have been incorporated into to the curriculum focus on placement of the tube after trauma, rather than surgical entry into the chest wall or closing the wound around the tube after placement.

There also exists very minimal literature and documentation on training programs and simulations for cardiothoracic surgeons who implant CTs after cardiovascular surgery. Since a thoracotomy typically accompanies a larger, more complex procedure, simulations and models are often generated to focus on improving the actual surgical operation, rather than the mechanism for merely opening the chest wall. For example, Yamada et al., generated a computer model of the heart to train physicians on minimally invasive techniques to repair the mitral valve, yet they ignore the chest cavity entirely.[13] Furthermore, it seems that even when the thoracic cavity is constructed in a CAD software, the ultimate goal is to print the model for hands-on use, rather than conducting finite element analysis for mechanical simulations. For example, Bergquist et al., describes a technique to model and print a personalized chest wall in order to inform the best approach for thoracic cavity reconstruction surgery.[14] This model, however, focuses mainly on the ribs and intercostal space; it falls short in accounting for the connective tissue layers of the chest wall. There currently exists no free, accurate, and publicly available model of the chest cavity that includes the ribs, muscle, adipose tissue, and skin.

As previously mentioned, the pain associated with chest tubes has been acknowledged, yet there exists little information on this exact unmet clinical problem. Thus, the current research component of the project seeks to survey healthcare providers to determine specific location, cause, and severity of pain associated with the chest tube. The design component aims to utilize a finite element analysis method to analyze stress, strain, and deformation on the thoracic cavity when external loads are applied to a chest tube. This second component of the project operates under the assumption that pain following a thoracotomy is due to nociceptive somatic afferents, which initiate the sensation of pain and are activated by mechanical stimuli.[15,16] The third and final goal of the current project aims to assess whether the thoracic cavity model and finite element analysis is predictive of clinical observations of pain associated with chest tubes.

We hypothesized that the largest source of pain is due to the forces impingent on the subcutaneous suture and that an accurate thoracic cavity model will show large stress, strains, or deformations at the suture-skin junction.

Materials and Methods

Survey on Pain Associated with the Chest Tube (Protocol #4075)

The current study was approved by the University of Virginia’s Institutional Review Board for the Social and Behavioral Sciences (IRB-SBS), and all healthcare providers gave informed consent prior to the study. Between January 27, 2021 and April 19, 2021, a *Survey on Pain Associated with the Chest Tube* was distributed to 1,202 different HCPs at 17 different institutions across the United States. Doctors, nurses, physician assistants (PAs), and respiratory therapists were surveyed from the following institutions: Virginia Commonwealth University, the University of Virginia, Duke University, the University of North Carolina at Chapel Hill, University of Pittsburg, Stanford University, Emory University, University of Colorado at Boulder, University of California in Los

Angeles, Vanderbilt University, University of Washington, University of Wisconsin, Medical College of Georgia, University of Southern California, University of Maryland at College Park, and the University of Arizona.

The survey was largely interested in uncovering consensus regarding pain intensity and location from the provider's standpoint. In one section of the analysis, the average pain scale rating was broken down for each location using Equation 1:

$$Average\ Rating = \frac{\sum_{i=0}^{10} i(n_{i,l})}{n_l} \qquad [1]$$

where i refers to the pain scale rating, n refers to the number of providers selecting that origin as one source of pain, and l corresponds to the location.

Autodesk Fusion 360: Computer-Aided Design

Our thoracic cavity model was developed in CAD and includes the skin, adipose tissue, intercostal muscles, and two ribs. All of these components were made from forms, which are T-spline representations of bodies that are highly useful for sculpting and molding. The final design is shown in Figure 1.

The skin, shown as the mustard-colored layer in Figure 1, includes the epidermis and dermis in a combined layer that was sketched to be 4 millimeters thick.17 This conflation of skin layers was possible owing to their highly similar biomechanical properties. Research from Storchle et al., found that the mean subcutaneous fat thickness on the anterior and posterior trunk was around 4 millimeters for males whose body mass index (BMI) falls below 28.5 kg/m2 (n = 10).18 It is important to note, however, that this soft tissue layer is the most variable between people and genders. Lastly, Yoshida et al., measured the intercostal muscle thickness with ultrasound imaging during rest and maximal breathing.19 Results from their study indicate that the intercostal muscles are around 3 millimeters thick at rest and around 5 millimeters thick at maximal breathing. Thus, the intercostal muscle layer, which includes the external, internal, and innermost intercostal muscles, was set to be 4 millimeters thick.

The two ribs were modeled off Slobodan Simić's representation of a female's 4th and 5th rib. His CAD model was initially created from segmented digital imaging communications in medicine (DICOM) files that were obtained from the University of Iowa's Human Visual Project.20 The ribs used in our thoracic cavity model were made by sculpting a cylindrical form around the ribs found in Simić's CAD model.

Since CAD does not have built-in materials that represent biological tissues, certain biomechanical properties, including as Young's Modulus, Poisson's Ratio, shear strength, density, damping coefficient, yield strength,

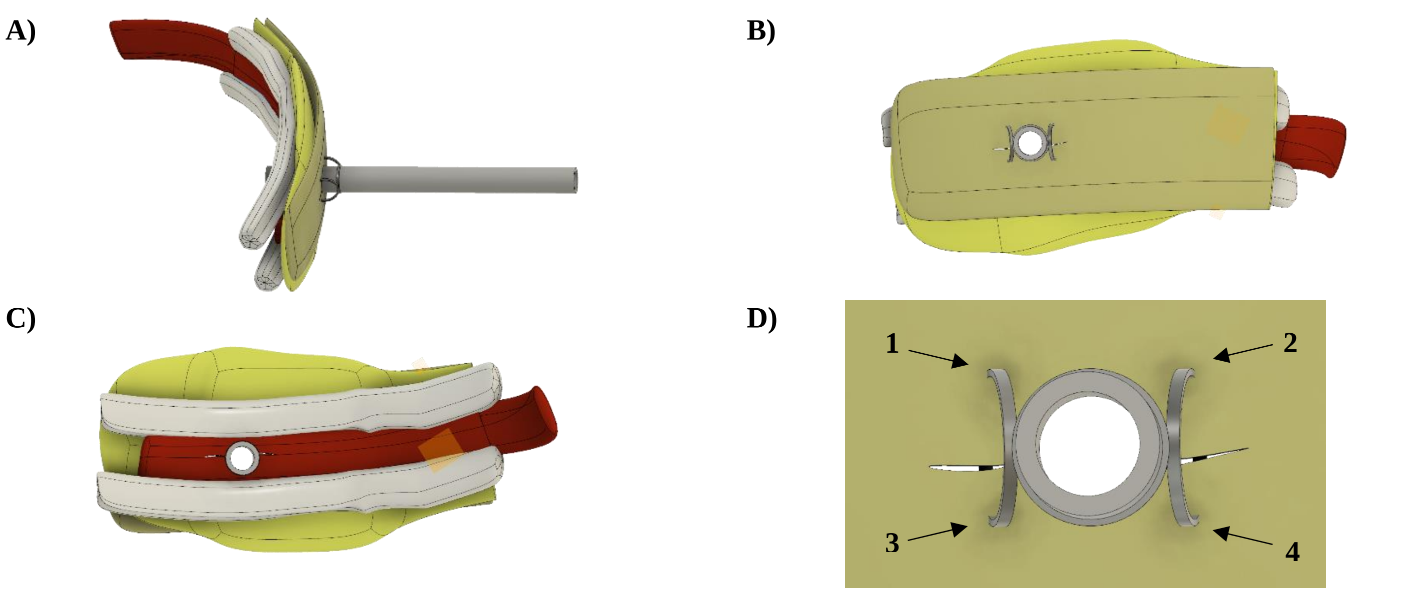

Fig. 1. 7th-iteration thoracic cavity model. (A) Front view of the thoracic cavity model. (B) Side view of the thoracic cavity model. (C) Underside view of the thoracic cavity model. (D) Close-up view of the suture. Numbers refer to specific suture-skin junctions. One corresponds to the anterior superior suture position. Two corresponds to the posterior superior suture position. Three corresponds to the anterior inferior suture position, and four corresponds to the posterior inferior suture position.

and tensile strength, were found for each connective tissue type. These parameters – listed in Supplementary Table 1 -- were used to create CAD materials for the final simulation.

An "incision," measuring 19.3 millimeters in length, was made through the skin, fat, and muscle layers. The incision was aligned parallel with the ribs, and a hole for the chest tube was created directly in the middle of the incision.

The dimensions of the chest tube were based on a typical 26 French (Fr) gauge tube; it had an external diameter of 8.7 millimeters and a wall thickness of 1.2 millimeters. The chest tube was modeled from flexible polyvinyl chloride (PVC), which is a material widely used in the clinic.

Sutures of Nylon 6/6, were modeled to go through the skin incision on both sides of the tube, effectively "closing" the openings. A close-up of the suture is shown in Figure 1D. A separate "ring-like" form represented the suture-tube junction. Although the sutures are not a perfect representation of the way clinicians close the thoracostomy or sternotomy incision, it seemed to be a sufficient representation of the tube-skin connection, which is further elaborated upon in the results section.

Finite Element Analysis

Two final simulations were settled upon to represent the forces and stresses that could impinge on the tube. Both simulations used a 45 Newton (N) force; this corresponds to roughly 10 pounds. The Pleur-evac A-8000 chest drain system weighs 3.2 pounds when empty and 8.8 pounds when full.[21] Thus 10 pounds was selected in order to account for any tugging on the tube due to the drainage system, chest tube, or other movements. The first simulation was intended to represent "pulling" on the tube and was applied perpendicularly, away from the body. This type of outward force would likely be present when a person would stand upright, or when a person is lying supine in bed with the tube pulling down toward the ground. In the second simulation, the force was applied in the positive normal direction to the end of the tube and was intended to represent existing forces that may push on the tube, which would occur if a patient rolled onto the side where with the tube.

For both simulations, rough contact sets were made between the tube and each of the tissues it penetrates. This was necessary to ensure that the tube itself neither welded nor slipped through the layers of the thoracic model. The ribs were constrained so that they would not move in simulation space. Additionally, the far edges of the skin, fat, and muscle layers were constrained, since the edges in the model were arbitrarily decided upon and were far enough away from the incision site. In a real body, the muscle would extend beyond the arbitrary end-point chosen and be attached to a different tissue or organ.

After successfully executing the simulations, the maximum stress, displacement, and strains were measured for each tissue.

<u>Differentiating Stress, Strains, and Deformations Within the Skin</u>

Probe sets were created at various points in order to investigate the differences in stress and strains at the incision site versus the suture-skin junction. Specifically, the stress, strains, and deformations at eight points surrounding the insertion site and four points corresponding to each suture-skin junction were recorded and compared.

Results

Survey of Healthcare Providers

Between January 27, 2021 and April 19, 2021, a *Survey on Pain Associated with the Chest Tube* was distributed to 1,202 different healthcare providers at 17 different institutions across the United States.

A total of 71 healthcare responders completed the survey; this corresponds to a 5.9% response rate. Physicians constituted 65% of the responder pool, nurses constituted 27% of the responder pool, and physician assistants (PA) comprised 7% of the responding HCPs. The further breakdown of doctors and nurses is illustrated in Supplementary Figure 1. Lastly, one of the responders, denoted as "other," was a respiratory therapist. They have been included in the aggregated data results, yet this group was not used in any statistical analysis when investigating differences in responses based on healthcare profession or title.

<u>The Chest Tube Needs Improvements</u>

Respondents were first asked whether they believed the chest tube or chest tube dressing needed improvements. In total, 61 out of 71 responders (>85%) believed that the chest tube needed some form of improvement. Of those providers that thought adjustments were necessary, 77% believed that the tube only needed minor changes, while the remaining 23% thought that a major revamp was necessary. Subsequent statistical analysis revealed that doctors were more likely to believe that the chest tube need improvements when compared to nurses (two-tailed, Fisher's exact test, $p = 0.0146$). The detailed breakdown of survey responses is shown in Supplementary Figure 2.

The 61 healthcare providers, who desired

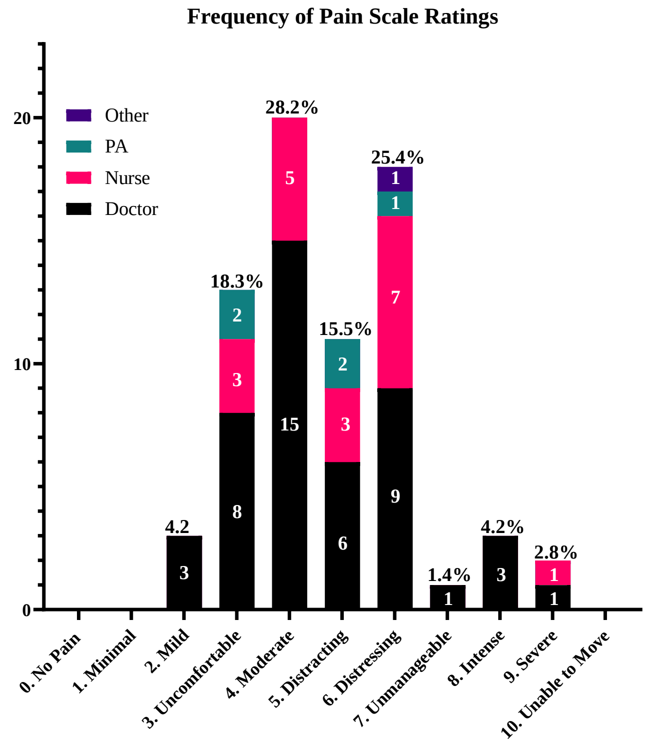

Fig. 2. Frequency of Pain Scale Ratings given by healthcare providers when estimating the average pain that a chest tube patient endures (n = 71).

improvements, were later asked whether they were likely to adopt a new protocol that addressed issues regarding the chest tube. The detailed survey responses are shown in Supplementary Table 2, but overall, 90% of these HCPs admitted to being either somewhat or extremely likely to adopt a new protocol.

<u>The Primary Goal of a New Chest Tube Dressing Should be to Minimize Pain</u>

HCPs were also asked to rank the order of importance for changes that should be made to the chest tube dressing. The three options consisted of: minimizing pain, reducing kinking/occluding, and increasing dressing absorbency. Of the healthcare providers that believed chest tubes should be improved, 43% of them ranked "having a mechanism to minimize pain" as the most important change, while 38% thought "reducing kinking and occlusions" should be the top priority. Lastly, only 19% of responders thought that an increased absorbency should be the main focus.

The results from this ordinal ranking question were then broken down based on healthcare provider. The results are shown in Supplementary Table 3. Interestingly enough, slightly more physicians thought the top priority should be to reduce kinking than to minimize pain. On the other hand, nurses showed the opposite trend, with 66% of them desiring a less painful chest tube and only 25% of them believing kinking to be the main issue. Although these two findings seem to conflict, a device that stabilizes the chest tube to reduce its associated pain will likely address the kinking and bending issue that occurs with this drainage system as well.

<u>Intensity and Origination of Pain</u>

All responding healthcare providers were asked to estimate how painful chest tubes are for patients, using the standard pain scale (0 = no pain, 10 = unable to move). The frequency of pain scale ratings is shown in Figure 2. On average, the survey responders estimated that patients ranked pain associated with the chest tube as a 4.75 ± 1.58 (mean ± s.e.m). When the pain scale ratings were broken down by healthcare provider, physicians, nurses, and PAs estimated the average pain to be a 4.65 ± 1.66, 5.00 ± 1.49, and 4.40 ± 1.34 (mean ± s.e.m), respectively. All providers thought the average pain a patient endures falls between "moderate" and "distracting," and there was no significant difference between pain scale ratings among the HCPs.

While the HCPs estimated the pain to fall between a 4 and 5 on the pain scale rating, a prior study by Refai et al., reveals that patients ranked the static and dynamic pain associated with the chest tube as a 2.6 ± 2.0 and a 4.1 ± 2.1, respectively.[5] These patient-provided pain ratings are similar to those provided by healthcare professionals, thereby supporting the accuracy in clinical observations of pain from the healthcare provider's standpoint.

In a "check all that apply" question, healthcare providers were asked to select the locations from which they thought the pain originated from. The answer choices included the intercostal space, pleural cavity, incision, skin, and subcutaneous suture. The results are outlined in Table 1. It appears that the majority of responding doctors, nurses, and PAs believe that pain originates from the intercostal

Table 1. Percent of all responding HCPs selecting that specific location as one origin of pain.

	Dr.	Nurse	PA	Other
Intercostal Space	82.6%	63.2%	80.0%	
Pleural Cavity	58.7%	63.2%	60.0%	
Incision	30.4%	26.3%	20.0%	100%
Subcutaneous Suture	21.7%	5.3%	20.0%	
Skin	26.1%	21.1%		

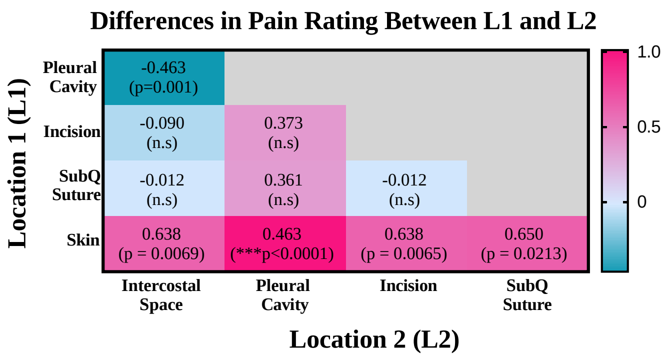

Fig. 3. Heatmap illustrating the differences in the average pain scale rating between locations (n=71). The numerical values provided are given as the average pain scale rating in L1 minus the average pain scale rating in L2. Results analyzed using a one-way ANOVA with multiple comparisons.

space and pleural cavity. Fewer than half of the providers thought pain emanates from the incision, suture or skin. These findings run entirely counter to the initial hypothesis that suggested the largest source of pain was due to the forces impinging on the subcutaneous suture.

The average pain scale ratings were calculated for each location. The results are illustrated in the heatmap shown in Figure 3.

Results reveal that the average pain scale rating, given by HCPs who selected the dermis as one location of pain, was significantly higher than any other pain origin. This finding shows that while many providers do not believe the dermis to be a common source of discomfort, when the provider does believe that pain originates from the skin, the pain is significantly worse and more intense.

Additionally, there appeared to be a significant difference in pain scale rating between the pleural cavity and the intercostal space, as depicted in Figure 3. The intercostal nerves, which are the anterior rami of the first 11 thoracic nerves, transmit signals between the intercostal muscles and the costal and cervical portions of the parietal pleura.[22,23] The visceral pleura, which directly encompasses the lungs, lacks sensory innervation and cannot feel pressure, pain, or temperature fluctuations.[24,25] Thus, the lack of nociceptors in part of the pleurae may explain the discrepancy in survey results with regard to location of pain associated with the chest tube.

Additional Survey Findings

Respondents were allowed to provide feedback in the comments section of the survey. In total, 19 out of the 71 responders left additional comments. Those who wrote additional feedback mentioned that chest tube pain is highly related to chest tube type (n=2). Specifically, providers believe that pleural chest tubes are more painful than mediastinal tubes. They also mentioned that pain associated with the tube is highly dependent on diameter of the tube (n=4). Smaller tubes cause less pain, but they become kinked or clot off much more frequently. These findings support prior results from Rahman et al., and Shalli et al., who also acknowledge the inherent tradeoff between chest tube size and chest tube kinking.[7,9]

Regarding the actual pain associated with chest tubes, two providers thought the pain was sharp, and three HCPs thought that this pain worsened with chest movement and sometimes hindered the patient's ability to take deep breaths. This feedback coincides with a previous report that pain associated with the chest tube after forced expiratory effort is slightly higher than static pain.[5] Thus, movement and forces on the tube are the likely causes of pain.

Finite Element Analysis

A heatmap of maximum stress, strain, and deformations within each layer are shown in Figure 4. Illustrations depicting the distribution of Von Mises stress, strain, and deformations in each component of the thoracic cavity model are shown in Figure 5 on the following page.

Stresses Concentrate on the ribs

As illustrated in Figure 5, it appears that when the chest tube is pushed or pulled, the majority of the stress is concentrated on the skin and within the ribs themselves. Specifically,

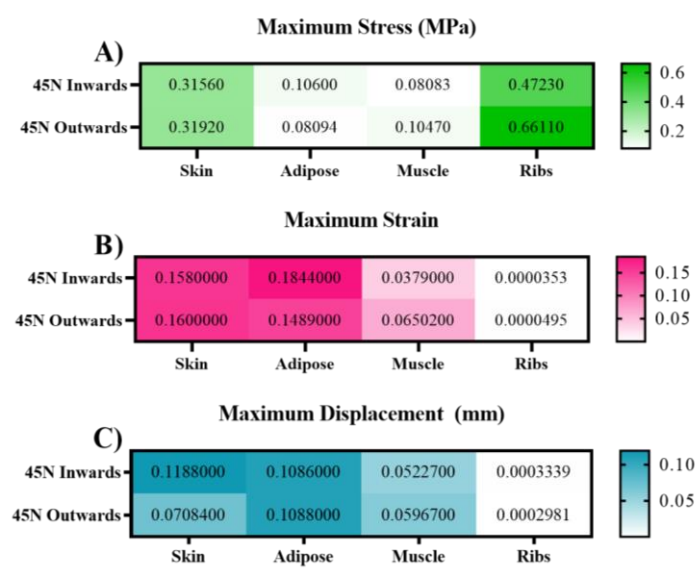

Fig. 4. Heatmap illustrating the maximum (A) stress, (B) strain, and (C) deformation within each layer of the thoracic cavity model.

stresses appear to concentrate at the insertion site and at the 4th suture-skin junction, which is labeled in Figure 1D for reference. With regard to the ribs, the stresses seemed to be the greatest in the fifth rib, closest to the insertion site. As depicted in Figure 4A, the maximal overall stress was found in the ribs, which bears a 0.47 MPa and 0.66 MPa stress for a 45N force inwards and outwards, respectively. These results, coupled with survey responses that rank pain within the intercostal space as a 4.85 ± 0.06
on the standard pain scale, hint that stress concentrations may be a major determinant of perceived discomfort radiating from the intercostal space.

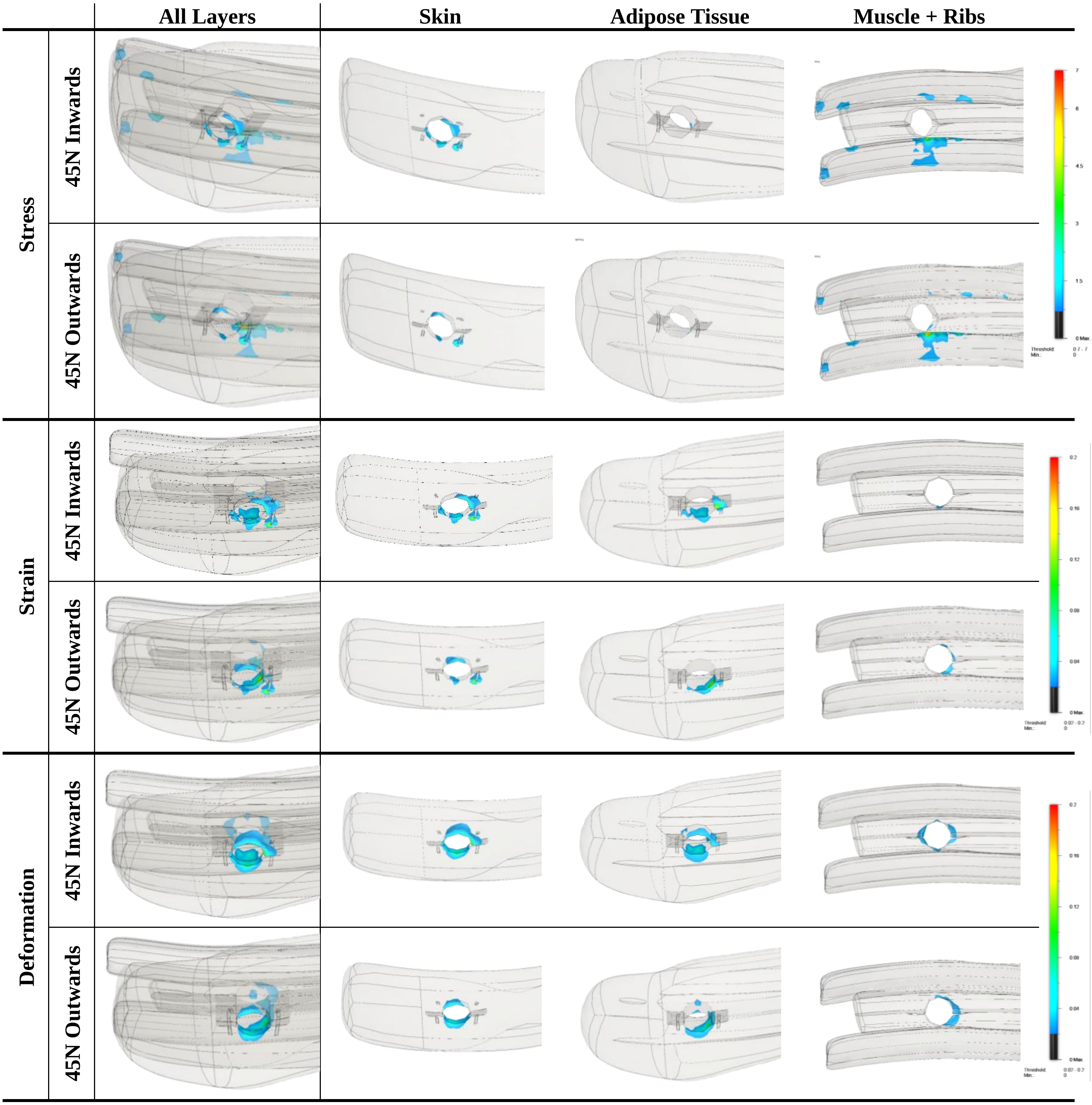

Fig. 5. Distribution of stress, strain, and deformation in each layer of the thoracic cavity model.

One such explanation linking stress to bone pain may lie in the activity of periosteal afferent nerve fibers.[26] Although little is understood about the physiology of these neurons, preliminary research suggests that "the overwhelming majority of the periosteal afferents are mechanically sensitive." This therefore implies that changes in pressure and static stress are predominantly responsible for increases in activity of nociceptors in bone.

Findings from Ge et al., offer evidence that muscle mechano-nociceptors are more responsive to stress than to other mechanical stimuli.[27] Specifically, they have shown that the neuronal response for muscle mechano-nociceptors, derived from a Rat Gracilis Muscle model, is "significantly…and substantially more highly correlated with compressive stress than force, strain, or displacement." This evidence, along with the idea that the majority of periosteal fibers are mechanically sensitive, suggest that stress specifically activates nociceptors in intercostal region Therefore, it seems likely that the current FEA results are somewhat predictive of the primary muscle pain that HCPs have observed in patients.

Skin and Adipose Tissue Bear Most of the Strain and Deformation

From images in Figure 5 that depict the FEA distribution of strain throughout the model, it appears that the majority of the strain and deformation occurs largely in the skin and adipose tissue. As previously revealed in Figure 3, HCPs rated the dermis as significantly more painful than all other locations. Together, these two results suggest that skin deformations and strain may be the primary cause of dermal pain.

Nociceptors in skin and their respective mechanotransducers offer one physiological mechanism that can relate FEA results to perceptions of pain. Within the context of the chest tube thoracostomy procedure, it can be assumed that primary innervation of cutaneous nociceptors involve primarily type I Aδ afferents and C-fibers.[28] Type I Aδ fibers are known to mediate acute, well-localized pain. While there have been several candidates for the primary mechanotransducer responsible for converting mechanical stimuli into electrical responses, TRPV2 seems to be the likely culprit.[28] It is an osmotic-stretch activated ion channel that is robustly expressed in medium- and large-diameter Aδ fibers. Osmotic stretch could arguably be due to either stress or strain upon tissue; however, stress or force alone -- without deformation -- would not activate a TRP channel. Therefore, the results of our simulations, which indicate strain as the primary mechanical response within skin, support the explanation that stretch activated TRP channels may elicit dermal discomfort.

C-fibers are responsible for the "slow," aching pain that a patient may feel after a chest tube has been in place for a sustained period of time.[28] Research suggests that certain C-fibers, known as "silent nociceptors," only become sensitive to noxious mechanical stimuli if they are "primed" with inflammatory mediators present in the surrounding skin.[15] Thus, if the thoracostomy site is not properly covered and wound exudate leaks from the incision site, the nearby cutaneous nociceptors may become "primed" to sense mechanical stimuli, such as pulling or tugging. This may cause mechanical allodynia where even the slightest touch can trigger the immense pain. Although the survey results found that HCPs were largely unconcerned with absorption around the incision site, wound exudate and silent nociceptors must still be included in the discussion around a device-based approach to reduce pain associated with the chest tube.

Mechanical Response in the Skin are not Location-Dependent

As illustrated in Figure 6, the stress and strain values around

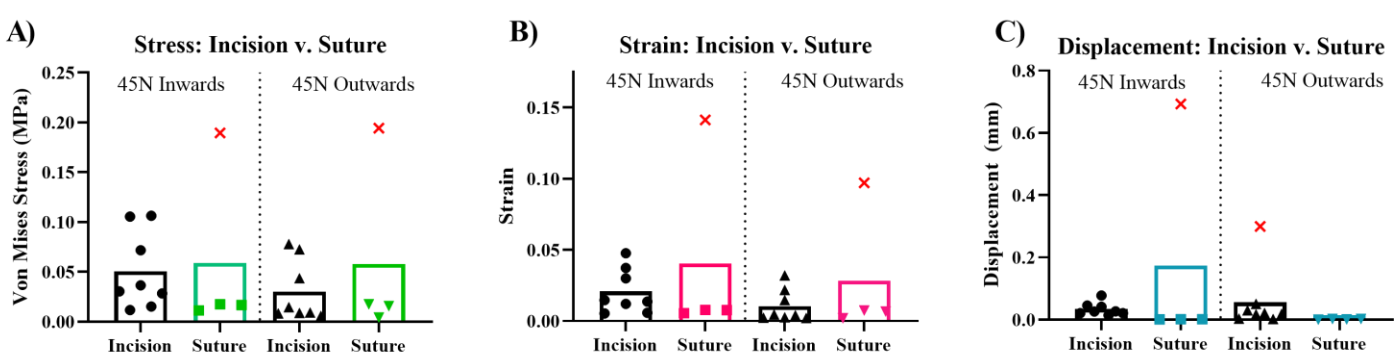

Fig. 6. Bar graphs depicting the (A) stress, (B) strain, and (C) displacement within the skin layer at 8 points surrounding the incision and 4 point representing each suture-skin junction. Outliers are marked with a red "X" (Grubbs alpha = 0.05).

the sutures versus the incision site are not significantly different. This therefore suggests that pain within the skin itself is not spatially-dependent. A Grubbs outlier test revealed one outlier among the raw stress and strain values taken from the suture. This indicates that under external load, the stress and strain may concentrate near one suture-skin junction, rather than be distributed equally across all dermal-stitch intersections.

Conclusion

This research has shed light on the severity, cause, and location of pain in patients with chest tubes. The finite element analysis revealed that stress responses to external loads exist concentrate in the ribs, while strain and deformations occur within the skin and adipose tissue. Periosteal afferent nerve fibers and osmotic-stretch activated TRP channels offer one such explanation supporting the conclusion that stress is the predominant trigger of intercostal pain, while strain or deformation is the predominant cause of dermal discomfort. Thus, it seems as though the model is somewhat predictive of clinical observations of pain. Ideally, the presented research will lay the groundwork for future studies where *in silico* finite element analysis can model and predict locations and severity of pain. Furthermore, the simulations may also be used to help design devices to address and reduce pain in the thoracic cavity and beyond.

Limitations

As with any computer-aided design, limitations exist in the model and in the *in silico* simulation results themselves. First and foremost, a computer model is only as accurate as its parameters. In the current design, a plethora of assumptions were made with respect to the shape, size, and properties of each component of the thoracic cavity. For example, the thickness of adipose tissue was set to be 4 millimeters, yet this value is largely dependent on body size and weight. Therefore, the model likely loses its predictive power for pain in underweight and overweight individuals. Some of the biomechanical parameters listed in Supplementary Table 1 were derived from simulations, rather than discrete Instron testing. Thus, there exists a propagation of uncertainty inherent to the model and the FEA results that it produces. Lastly, the simulation itself is approximate, and given the impossible nature of isolating a section of the thoracic cavity, the error between the FEA results and the real biomechanical properties of the chest wall will never be fully understood.

Future Directions

Immediate next steps for the current work include gathering more information from healthcare providers and extending market research to include patients as stakeholders. More simulations with varying loads, different directions, and different diameter chest tubes would also provide a more complete picture of how magnitude and direction alter stress concentrations and deformations within each layer of the model. Lastly, simulations can be used to inform prototypes that can reduce stresses and strains in the skin, adipose tissue, muscle, and ribs.

End Matter

Author Contributions

The authors declare no conflict of interest.
This article contains supporting information appended to the document.

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References

1. Utter, G. H. The Rate of Pleural Fluid Drainage as a Criterion for the Timing of Chest Tube Removal: Theoretical and Practical Considerations. *Ann. Thorac. Surg.* **96**, 2262–2267 (2013).
2. Dev, S. P., Nascimiento, B., Simone, C. & Chien, V. Chest-Tube Insertion. *N. Engl. J. Med.* **357**, e15 (2007).
3. Tube Thoracostomy: Overview, Indications, Contraindications. (2020).
4. Muzzy, A. C. & Butler, A. K. Managing chest tubes: Air leaks and unplanned tube removal. *American Nurse* https://myamericannurse.com/wp-content/uploads/2015/05/ant5-Chest-Tube-420.pdf (2015).
5. Refai, M. *et al.* The impact of chest tube removal on pain and pulmonary function after pulmonary resection†. *Eur. J. Cardiothorac. Surg.* **41**, 820–823 (2012).
6. Antanavicius, G., Lamb, J., Papasavas, P. & Caushaj, P. Initial chest tube management after pulmonary resection. *Am. Surg.* **71**, 416–419 (2005).
7. Rahman, N. M. *et al.* Effect of Opioids vs NSAIDs and Larger vs Smaller Chest Tube Size on Pain Control and Pleurodesis Efficacy Among Patients With Malignant Pleural Effusion: The TIME1 Randomized Clinical

Trial. *JAMA* **314**, 2641 (2015).

8. Ruparel, R. K. *et al.* Securing a Chest Tube Properly: A Simple Framework for Teaching Emergency Medicine Residents and Assessing Their Technical Abilities. *J. Emerg. Med.* **53**, 110–115 (2017).
9. Shalli, S. *et al.* Chest Tube Selection in Cardiac and Thoracic Surgery: A Survey of Chest Tube-Related Complications and Their Management. *J. Card. Surg.* **24**, 503–509 (2009).
10. Garland, C., Wilson, J. A., Parsons, M. H. & Dubrowski, A. The Application of Low-fidelity Chest Tube Insertion Using Remote Telesimulation in Training Healthcare Professionals. *Cureus* **11**, (2019).
11. Yoshimura, A. *et al.* An Effective Training Program for Chest Tube Drainage for Medical Interns in a Clinical Simulation Laboratory. *J. Nippon Med. Sch.* **79**, 403–408 (2012).
12. Tatli, O. *et al.* A novel method for improving chest tube insertion skills among medical interns. *Saudi Med. J.* **38**, 1007–1012 (2017).
13. Yamada, T. *et al.* Three-Dimensional Printing of Life-Like Models for Simulation and Training of Minimally Invasive Cardiac Surgery. *Innov. Phila. Pa* **12**, 459–465 (2017).
14. Bergquist, J. R., Morris, J. M., Matsumoto, J. M., Schiller, H. J. & Kim, B. D. 3D printed modeling contributes to reconstruction of complex chest wall instability. *Trauma Case Rep.* **22**, 100218 (2019).
15. Purves, D. *et al.* Nociceptors. *Neurosci. 2nd Ed.* (2001).
16. Mesbah, A., Yeung, J. & Gao, F. Pain after thoracotomy. *BJA Educ.* **16**, 1–7 (2016).
17. Brannon, H. L. The Individual Layers of Skin and Their Functions. *Verywell Health* https://www.verywellhealth.com/skin-anatomy-1068880 (2020).
18. Störchle, P. *et al.* Measurement of mean subcutaneous fat thickness: eight standardised ultrasound sites compared to 216 randomly selected sites. *Sci. Rep.* **8**, (2018).
19. Yoshida, R. *et al.* Measurement of intercostal muscle thickness with ultrasound imaging during maximal breathing. *J. Phys. Ther. Sci.* **31**, 340–343 (2019).
20. Ribcage | 3D CAD Model Library | GrabCAD. https://grabcad.com/library/ribcage-1/details?folder_id=6102485.
21. DEKA800008LF - Pleur-evac A-8000 Series Chest Drains with Wet Suction/Wet Seal | Medline Mobile. https://m.medline.com/sku/item/MDPDEKA800008LF.
22. Intercostal Space - an overview | ScienceDirect Topics. https://www-sciencedirect-com.proxy01.its.virginia.edu/topics/medicine-and-dentistry/intercostal-space.
23. Mahabadi, N., Goizueta, A. A. & Bordoni, B. Anatomy, Thorax, Lung Pleura And Mediastinum. in *StatPearls* (StatPearls Publishing, 2021).
24. Pintelon, I. *et al.* Sensory Receptors in the Visceral Pleura. *Am. J. Respir. Cell Mol. Biol.* **36**, 541–551 (2007).
25. The Pleurae - Visceral - Parietal - TeachMeAnatomy. https://teachmeanatomy.info/thorax/organs/pleurae/.
26. Nencini, S. & Ivanusic, J. J. The Physiology of Bone Pain. How Much Do We Really Know? *Front. Physiol.* **7**, (2016).
27. Ge, W. & Khalsa, P. S. Encoding of Compressive Stress During Indentation by Group III and IV Muscle Mechano-Nociceptors in Rat Gracilis Muscle. *J. Neurophysiol.* **89**, 785–792 (2003).
28. Basbaum, A. I., Bautista, D. M., Scherrer, G. & Julius, D. Cellular and Molecular Mechanisms of Pain. *Cell* **139**, 267–284 (2009).
29. Brannon, H. L. *et al.* Which Part of the Skin Protects You From Injury? *Verywell Health* https://www.verywellhealth.com/skin-anatomy-1068880.
30. Pawlaczyk, M., Lelonkiewicz, M. & Wieczorowski, M. Age-dependent biomechanical properties of the skin. *Adv. Dermatol. Allergol. Dermatol. Alergol.* **30**, 302–306 (2013).
31. Comley, K. & Fleck, N. A. A micromechanical model for the Young's modulus of adipose tissue. *Int. J. Solids Struct.* **47**, 2982–2990 (2010).
32. Chawla, D. A., Mukherjee, D. S. & Non-Member, B. K. Mechanical Properties of Soft Tissues in the Human Chest, Abdomen and Upper extremities. 12.
33. Young's modulus of trabecular and cortical bone material: ultrasonic and microtensile measurements - PubMed. https://pubmed.ncbi.nlm.nih.gov/8429054/.
34. Li, C., Guan, G., Reif, R., Huang, Z. & Wang, R. K. Determining elastic properties of skin by measuring surface waves from an impulse mechanical stimulus using phase-sensitive optical coherence tomography. *J. R. Soc. Interface* **9**, 831–841 (2012).
35. General theory of skin reinforcement.

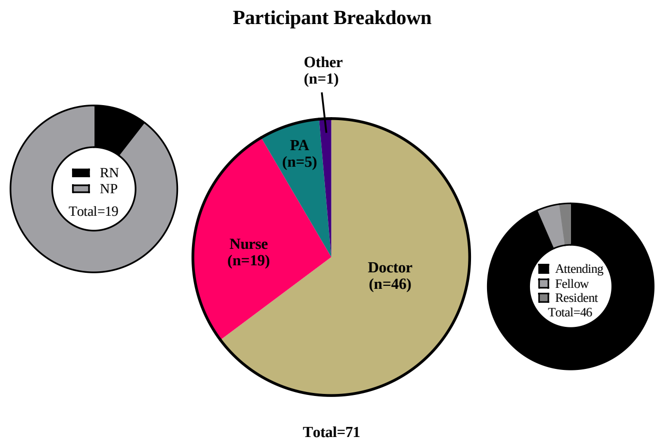
https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0182865.

36. The elastic modulus and Poisson's ratio of cortical bone, cancellous bone, cartilage, meniscus and four ligaments. (2015) doi:10.1371/journal.pone.0127293.t002.
37. Molecules | Free Full-Text | An Economic, Modular, and Portable Skin Viscoelasticity Measurement Device for In Situ Longitudinal Studies | HTML. https://www.mdpi.com/1420-3049/24/5/907/htm.
38. Geerligs, M., Peters, G. W. M., Ackermans, P. A. J., Oomens, C. W. J. & Baaijens, F. P. T. Linear viscoelastic behavior of subcutaneous adipose tissue. *Biorheology* **45**, 677–688 (2008).
39. Lima, K. M. M. e, Costa Júnior, J. F. S., Pereira, W. C. de A. & de Oliveira, L. F. Assessment of the mechanical properties of the muscle-tendon unit by supersonic shear wave imaging elastography: a review. *Ultrasonography* **37**, 3–15 (2018).
40. Goldstein, S. A. The mechanical properties of trabecular bone: Dependence on anatomic location and function. *J. Biomech.* **20**, 1055–1061 (1987).
41. Densities of Different Body Matter. http://www.scrollseek.com/training/densitiesofdifferentbodymatter.html.
42. Analysis on Vibration Characteristics of Air Film Damping with Open Boundaries. https://www.hindawi.com/journals/mpe/2019/1414872/.
43. Mohamed, A., Alkhaledi, K. & Cochran, D. Estimation of mechanical properties of soft tissue subjected to dynamic impact. *J. Eng. Res.* **2**, 26 (2014).
44. (PDF) Determining mechanical parameters of the bone using a vibro-acoustic method. https://www.researchgate.net/publication/333057056_Determining_mechanical_parameters_of_the_bone_using_a_vibro-acoustic_method.
45. Dynamic Tensile Properties of Human Skin. 9 (2012).
46. True stress–strain relationships of the fat, fibroglandular and tumor... | Download Scientific Diagram. https://www.researchgate.net/figure/True-stress-strain-relationships-of-the-fat-fibroglandular-and-tumor-tissues-used-in-the_fig4_49630040.
47. Poulard, D. & Subit, D. UNVEILING THE STRUCTURAL RESPONSE OF THE RIBCAGE: CONTRIBUTION OF THE INTERCOSTAL MUSCLES TO THE THORACIC MECHANICAL RESPONSE. 14.
48. Dunham, C. E., Takaki, S. E., Johnson, J. A. & Dunning, C. E. Mechanical properties of cancellous bone of the distal humerus. *Clin. Biomech.* **20**, 834–838 (2005).
49. The mechanical properties of human adipose tissues and their relationships to the structure and composition of the extracellular matrix | American Journal of Physiology-Endocrinology and Metabolism. https://journals.physiology.org/doi/full/10.1152/ajpendo.00111.2013.
50. Kuthe, C. D., Uddanwadiker, R. V. & Ramteke, A. Experimental evaluation of fiber orientation based material properties of skeletal muscle in tension. *Mol. Cell. Biomech. MCB* **11**, 113–128 (2014).
51. Bone Mechanical Properties in Healthy and Diseased States. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6053074/.

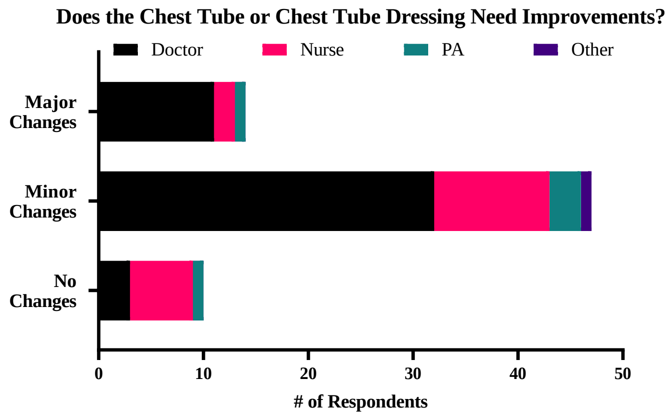
Supplementary Materials:

Supplementary Table 1: Biomechanical properties necessary to skin, adipose tissue, muscle, and trabecular bone in CAD.

	Skin	Adipose Tissue	Muscle	Trabecular Bone
Thickness (mm)	4 [29]	4 [18]	4 [19]	N/A
Young's Modulus (GPa)	0.012[30]	1E-6[31]	0.0025[32]	14.8[33]
Poisson Ratio	0.48[34]	0.4[35]	0.4[32]	0.62[36]
Shear (MPa)	0.005[37]	0.0075[38]	0.00103 [39]	20.7[40]
Density (g/mL)	1.116[34]	0.9094[41]	1.06[41]	1.75[41]
Damping Coefficient	0.2[42]	2.25[43]	2.25[43]	0.4195[44]
Yield Strength (MPa)	21[45]	0.001[46]	0.05[47]	44.1[48]
Tensile Strength (MPa)	27.2[45]	0.0125[49]	0.337[50]	2.6 [51]



Supplementary Fig. 1. Breakdown of responding healthcare providers based on profession and title.



Supplementary Fig. 2. Healthcare provider's opinions on whether the chest tube or chest tube dressing needs improvement (n=71).

Supplementary Table. 2. Healthcare provider's likeliness to adopt a new and improved chest tube or chest tube dressing.

	Dr.	Nurse	PA	Other	**Total**
Extremely Unlikely	1				**1**
Somewhat Unlikely				1	**1**
Neither	2	1	1		**4**
Somewhat likely	21	5	2		**28**
Extremely likely	18	7	1		**26**
Total	**42**	**13**	**4**	**1**	**60**

Supplementary Table. 3. Breakdown of prioritization of changes to be made to the chest tube (n=58). Three out of the 61 providers who thought that the chest tube needed improvements did not complete the question. They are excluded from subsequent data analysis.

		Dr.	Nurse	PA	Other	Total
Minimize Pain	Count	15	8	1	1	**25**
	% within HCP	37%	66%	25%	100%	**43%**
Reduce Kinks/Clots	Count	19	2	1		**22**
	% within HCP	46%	17%	25%		**38%**
Increase Absorbency	Count	7	2	2		**11**
	% within HCP	17%	17%	50%		**19%**
Total	**Count**	**41**	**12**	**4**	**1**	**58**
	% within HCP	**100%**	**100%**	**100%**	**100%**	**100%**