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Abstract

Title of Thesis: Quantitative Analysis of Compartments in the Leg and Implications for Trauma Surgery

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Compartment syndrome is characterized as an excess in swelling leading to an increase in pressure in a limited space and a lower extremity fasciotomy is performed to mitigate the effects. A two-incision fasciotomy is performed on the medial and lateral sides of the leg, accessing the posterior superficial, deep superficial, anterior and lateral compartments respectively. Ongoing studies have shown the lateral compartment is commonly decompressed incorrectly. This error has led to the hypothesis that there is variability in septum position and that using the fibula as a landmark can lead to erroneous incision placement in patients. CTA scans were analyzed to assess septum position. Findings indicate that the septum position shifts anteriorly progressing distally down the leg, indicating variability at different points in the leg. If surgeons do not take septum variability into consideration when decompressing the lateral compartment, this can lead to incorrect decompression of the lateral compartments.

Quantitative Analysis of Compartments in the Leg and Implications for Trauma Surgery

by

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Dissertation submitted to the Faculty of the Graduate School of the
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Introduction

The concept of compartment syndrome was first introduced by Volkman in 1881 (Michelson, 2002). Volkman brought to attention the idea that within a few hours after injury, paralytic contractures could occur leading to ischemia or insufficient arterial flow (Michelson, 2002). This also led to the realization that applying tight bandages after surgery could lead to insufficient arterial flow into limb compartments. This theory held for several decades, with Thomas, Murphy, and Jones (Michelson, 2002) each expanding on the concept. Jones came to the final conclusion that compartment syndrome can be caused by pressure from "within or without contracture", a conceptual realization underpinning modern understanding of this condition (Michelson, 2002). Eichler and Lipscomb were the first to come up with the surgical technique for performing a fasciotomy procedure (Michelson, 2002), which mitigated the deleterious effects of compartment syndrome.

Compartment syndrome most commonly occurs in the forearm and leg but can also occur in other parts of the body such as hands, feet, abdomen, and gluteus compartments (Elliot and Johnstone, 2003). Anywhere in the body where muscles are organized into distinct compartments surrounded by fascia are suspectable to compartment syndrome. The leg is treated more often than other areas in the body for compartment syndrome, with the procedure of a lower extremity fasciotomy the most common method to mitigate the effects of compartment syndrome.

Compartments in the legs are groups of muscle tissue, nerves, and blood vessels surrounded and held tightly together by fascia (Hall-Craggs, 1995). Because the fascia surrounding leg compartments are essentially inelastic and cannot expand, compartment syndrome is characterized as excess swelling within the compartment leading to (or due to) an increase in pressure in a limited space (Henderson, 2015). This excess swelling and increase in pressure can cause damage to the nerves, muscles, and blood vessels in the compartment. Of greatest concern is if the compartment pressure exceeds that of vascular inflow pressure, then insufficient oxygen will reach the tissues in the compartment leading to ischemic injury. If not treated promptly, it can cause tissue necrosis, functional impairment, and potentially lead to amputation of limb or death. There are numerous cases (burns, crush injury, massive resuscitation, etc.) in which a person can develop compartment syndrome and it is instrumental that a physician is able to identify signs and symptoms early as the window of effective intervention may be only 3-5 hours post injury (Bowyer, 2015).

Compartment syndrome can be tested using intracompartmental pressure monitoring, which directly measures pressure inside the compartment to determine if compartment pressure is at a level that may result in ischemic injury (Henderson, 2015), however primary diagnosis is typically achievable by physical examination of the patient. Intracompartmental pressure is usually measured when the physical diagnosis may be unreliable or in an unconscious patient where the patient is unable to provide symptom reporting. Numerous devices have been created to measure tissue pressures (e.g. Stryker needle), each having their own pitfalls or limitations. These devices can result in false positives, producing a variation of pressures in an individual who doesn’t have compartment syndrome (Boody and Wongworawat, 2005). Thus, compartment syndrome is typically diagnosed via clinical suspicion and obtaining a physical exam (Henderson, 2015).

The five P's are a mnemonic for remembering the physical examination: Pain (out of proportion or with passive stretch); Pallor (loss of skin color tone); Paresthesia (a tingling or numbness feeling); Paralysis (inability to operate the muscles within the compartment); and Pulselessness (absences of distal pulses from arteries traveling through the compartment). These signs and symptoms are used in a clinical exam to test for the potential of compartment syndrome. Pain out of proportion is the first sign of compartment syndrome, with excessive pain on passive stretch of muscles within the compartment reported the most sensitive diagnostically (Konda et al, 2017). However, diagnostic sensitivity and specificity of these tests are similar to those of compartment pressure measures and can also lead to false positives (Henderson, 2015). This rise in false positives leads to an unnecessary diagnosis of compartment syndrome, which must be treated via fasciotomy (Henderson, 2015). However, a false positive rate may be acceptable to avoid an excessive false negative, rate which may result in a failure to diagnose an actual problem and possible loss of limb or life with an untreated compartment syndrome.

There are four compartments that compromise the leg; anterior, lateral, superficial posterior and deep posterior, each having distinguishing characteristics. These compartments are bound by the crural fascia and separated by intramuscular septa which extend inward from the crural fascia and anchoring into the tibia and fibula bones to divide the leg muscles into the compartments (Figure 1). The crural fascia and intermuscular septa are strong connective tissue sheets comprised of dense fibrous connective tissue devoid of fat and are essentially inelastic in nature. The anterior compartment holds the primary extensor muscles of the foot, the lateral compartment holds the eversion muscles, and the superficial posterior and deep compartment holding flexors and inversion muscles. Correct function of all four compartments is thus critical for locomotion stability of an individual.

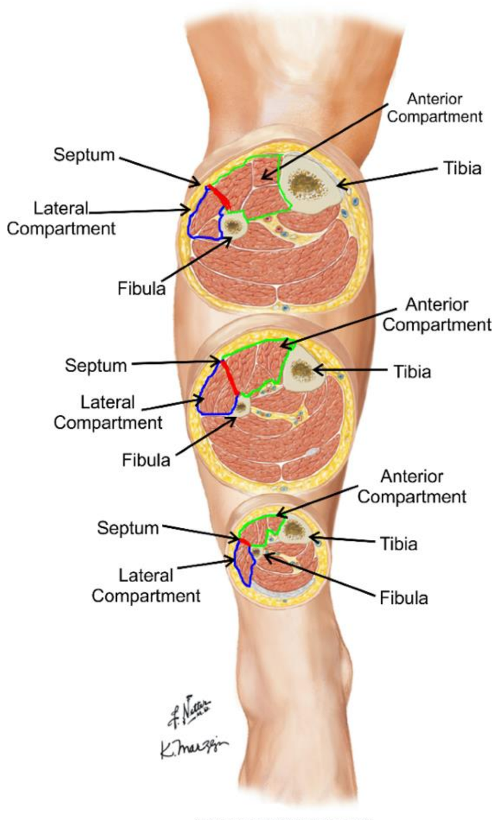

Figure 1: Diagram of the organization of the leg. Each cross section is indicative of the upper, middle, and lower half of the leg, and shows how the leg is compartmentalized. The anterior compartment is outlined in green, the lateral compartment in blue, and the intermuscular septum dividing the two compartments in red.

To relieve the increased compartment pressures associated with compartment syndrome, a two- incision fasciotomy is commonly performed (Singh et. al, 2015). Incisions are performed on the lateral and medial sides of the leg, with the lateral incision accessing the anterior and lateral compartments while the medial incision accesses the deep and superficial posterior compartments. Although the two-incision compartment release on the lateral and medial side is the most common approach, orthopedic surgeons may use different incision sizes. The orthopedic approach is typically similar to the trauma approach; however, the length of the incision is smaller, lengthening only if necessary (Thaeter, 2016). Creating a smaller incision increases healing time and is cosmetically more appealing to patients (Thaeter, 2016), however the approach can be slower to perform compared to a larger incision. Thus, trauma surgeons are more likely to extend the incision the entire length of the leg initially, leaving about two finger breadths between the head of the fibula and the lateral and medial malleolus. Although this can extend healing time and create more scarring, this method ensures that the surgeon is able to quickly visually identify each compartment in the leg and result in complete decompression quickly by aiding visibility in a situation where there may be anatomical disruption from associated traumatic injury.

In order to ensure complete fasciotomy decompression surgeons are taught the technique of placing the medial incision two finger breadths posterior to the tibia and the lateral incision two finger breadths anterior to the fibula (Singh et al, 2015). Surgeons who take the Advanced Surgical Skills for Exposure in Trauma (ASSET) course are taught to place the medial incision one thumb or two finger breadth posterior to the tibia and the lateral incision one finger breadths in front of the fibula (American, 2010). Thus, there is disagreement in the literature with the incision landmarks and positioning.

Data from our ongoing studies has shown the medial incision is performed accurately resulting in high likelihood of successful decompression of the superficial posterior compartment. However, the deep posterior compartment is commonly insufficiently decompressed due to errors in access by improper performance of the detachment of the soleus muscle from the tibia. On the lateral side, our study also shows that the anterior compartment is commonly missed due to incision placement too posterior relative to the position of the intermuscular septum between the anterior and lateral compartments. This results in the surgeon proceeding posteriorly and finding the septum between the lateral and superficial posterior compartments, misidentifying it as the septum between anterior and lateral compartments. This, we conjecture, leads to our observation of the common lateral mistake in the decompression of failing to decompress the anterior compartment.

This error in placement and septum identification suggested that there may be variability in the septum position such that the fibular landmark used to place the skin incision could lead to erroneous identification of the septum in some patients. The goal of this study is to investigate patients admitted to the hospital for trauma related injuries to determine if there is indeed variability in the position of the intermuscular septum between the anterior and lateral compartments relative to the fixed bony landmarks of the tibia and fibula. Circumferential measurements of the fascia and skin were also measured to estimate patient body habitus as a co-variant parameter. By determining the amount of variability, we aim to assess and recommend an alternative incision placement that differs from two finger breadths anterior to the fibula on the lateral side of the leg as a possible means to increase identification accuracy of the intermuscular septum and success of lateral compartment decompression.

Methodology

Data from our laboratory has shown that when using the fibula as a landmark for the lateral leg fasciotomy, surgeons are more likely to decompress the compartments incorrectly, completely missing the anterior compartment (Mackenzie et al, 2017; 'unpublished observation' Puche et al, 2020). We have hypothesized that using the tibia as a landmark will improve correct decompression of the anterior and lateral compartments. Quantitative analysis of the compartment position was conducted to assess possible reliability of the tibial landmark and degree of septal positional variation between patients. A retrospective analysis using Computed Tomography Angiography (CTA) scans from the University of Maryland Medical Center, Shock Trauma Radiology Database was performed using the eUnity software. This method was selected due to CTA scans showing abnormalities in blood vessels which can lead to compartment syndrome, as well as these scans showing the full length of the leg (tibial plateau to malleolus). MRI or CT datasets of the length of the leg are often incomplete as they are selective for a discrete injury location (e.g. MRI of an ankle injury usually does not extend to the knee).

Participants were selected from the hospitals' database from the years 2012-2019. Patients selected for the study were admitted to the hospital for a trauma injury to the lower extremity and a CTA performed to assess the injury. Patients ranged from 18-100 years old, both male and female. Patients were excluded if they were pregnant, their CTA scan was incomplete throughout the lower extremity or if the CTA did not provide necessary resolution for septal identification. A total of 1,000 scans were evaluated for these criterion, and 82 meeting the exclusion and inclusion criteria and analyzed further.

All measurements were performed using a CTA and reformatted to sagittal or cross-sectional views for respective measurements. A measurement of the length of the leg was obtained from the sagittal reformat, this measurement was from the tibia plateau to the distal end of tibia shaft at the ankle joint (all measurements recorded in millimeters). The entire length of the leg was divided evenly into three sections total (one fourth, one half, three fourths) and measurements were taken at each point. Next, a measurement from the center of the tibia to the center of the fibula was obtained and a perpendicular measurement from the center of the fibula to the skin was obtained. This perpendicular measurement ran over the junction point of the intermuscular septum, between the anterior and lateral compartments. The angle between the tibia/fibula line and the septum position line was recorded. A second anterior compartment arc circumferential measurement was obtained starting from the lateral edge of the tibia to where the crural fascia connected to the intermuscular septum between the anterior and lateral compartments, giving a perimeter value for the anterior compartment superficial surface. These measurements made up the data for the anterior compartment. The total circumference of the crural fascia of the leg and circumference of the skin were also made at each level to generate a ratio between crural fascia and skin as an estimate of leg subcutaneous tissue (i.e. body habitus of the leg).

Analysis of the compartment septum position and variability in the leg was performed with cross correlation to variable of injury location, leg length, and body habitus were performed. Previous studies looking at variability in the leg only assessed compartment pressures (Large et. al., 2015), and not the positioning of the compartments or the distance between each compartment and septum relative to the tibia and fibula.

This study was able to use precise instruments to obtain numerical values for septal positions relative to bony landmarks commonly used for surgical incision placement.

Results

Assessment of Variability in Intermuscular Septum Position

The correct placement of incisions is critical to any surgery. In the case of the lower extremity fasciotomy we hypothesized that the placement of incisions relative to the position of the intermuscular septum between the anterior and lateral compartments was leading to error. This could be due to improper initial incision placement or to variability in the position of the septum such that it is not always at the location that the surgeon expects. To assess the variability of septum position from patient to patient the position of the intermuscular septa was measured relative to the fixed boney architecture of the tibia and fibular.

We also considered that the relative position of the septum, i.e. the relative arrangement of the compartments, were likely to change along the length of the leg. Therefore, measurements were taken at three evenly spaced levels proximal to distal along the leg; at 25% of the distance from the tibial

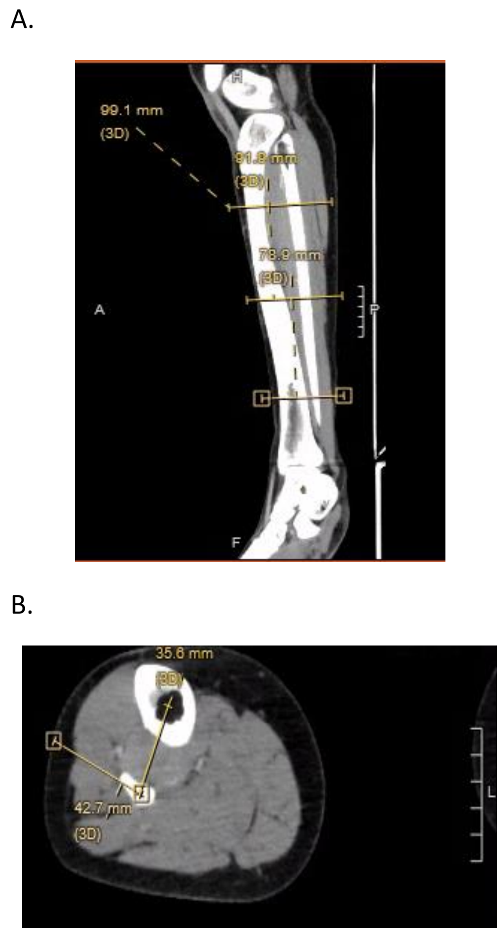

Figure 2: Diagrammatic representation of the measurement strategy. (A) Coronal CTA showing the 25%, 50%, and 75% proximal to distal measurement points on the leg. (B) Tangential CTA of the patient in A, showing the angular measurement of the intermuscular septum between the anterior and lateral compartments relative to a line between the fixed bony architecture of the tibia and fibula. Scale bars in A and B represent 5 mm each.

plateau to the ankle joint, at 50%, and at 75% of distance. For the septum position, we measured the angle made by a line between the center point of the tibia and fibular bones and a second line extending out across the junction of the intermuscular septum with the crural fascia (Figure 2). A larger angle is thus a more posterior location for the intermuscular septum, while a shallower angle is a more anterior position.

The average septum positional angle was 38.0 ± 7.2 degrees at the 25% distal level, which is typically the most muscular part of the leg. This angle reduced progressively distally along the leg to 35.3 ± 6.4 degrees at 50% distance and 23.7 ± 4.4 degrees at the 75% distal location closer to the ankle (Figure 3). This suggest that a fixed incision spacing along the length of the leg, for example two fingers in front of the fibula, would be slightly tangential to the line formed by the intermuscular septum position. An incision moving slightly anteriorly at the distal end would compensate for the shifting relative septum position.

Our second consideration was the degree of variability in the septum position between individuals. We observed that the angular position of the intermuscular septum between the anterior and lateral compartments exhibited a wide range of values between individuals (Figure 3). The mean at the 25% distal level was 38.0 ± 7.2 degrees, however the range was 23.8-60.5 degrees. At the 50% point on the leg, the mean was

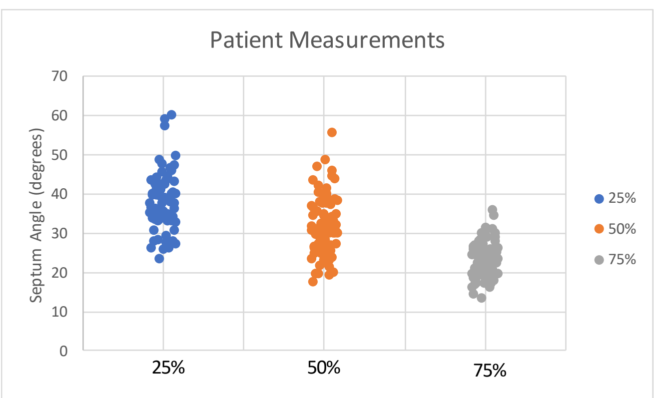

Figure 3: Scatter plot of individual patient measurements at proximal to distal positions on the ordinate of at 25%, 50%, and 75% of the leg length. N= 82 patients.

35.3 ± 6.4 degrees with a range from 17.9-56.0, and at the 75% distal point the mean of 23.7 ± 4.4 degrees exhibited a range of 13.8-36.2 degrees. These observations indicate that assumptions that the intermuscular septum is always going to be directly deep to an incision two fingers anterior to the fibular is incorrect. Depending on the patient the septum may be considerably more anterior or posterior to that initial incision placement point and depending on the position along the leg the septum location will progressively shift more anteriorly closer to the ankle.

Injury Type

We also hypothesized that injury to the leg directly could result in edema or disruption that shifts the septal position when compared to injuries to another part of the lower extremity (e.g. thigh or foot injury). To assess this, patients were grouped by injury type- into direct or indirect trauma to the leg categories. Injuries that were classified as direct were those that were the result of blunt or penetrating trauma to the leg including

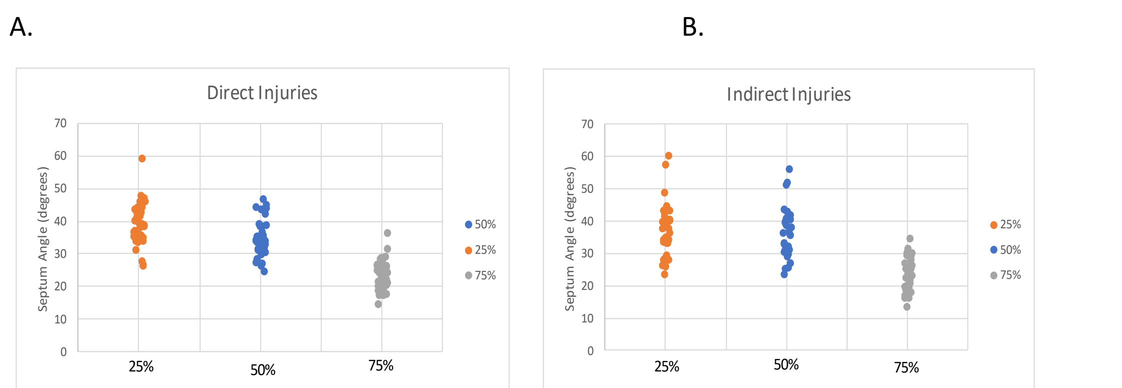

Figure 4: Measurements are from proximal to distal positions on the ordinate at 25%, 50%, and 75% of the leg length. (A) Scatter plot of individuals who had direct injuries to the leg. N= 50 patients. (B) Scatter plot of individuals who had indirect leg injuries, i.e. injuries occuring in the thigh or foot (N= 32 patients)

gunshot wounds, fractures, etc. Indirect injuries were similar types of injury but occurred in the thigh or foot and did not directly involve the leg. As above, measurements were taken at three evenly spaced points from proximal to distal along the leg (25%, 50%, and

75% of the distance from the tibial plateau to the ankle joint). We observed that for direct injuries, the average angle made between the bony architecture and the intermuscular septum at the 25% distal level was 38.4 ± 6.34 degrees (range 26.4-59.3; Figure 4A) while for indirect injuries the angle was 37.4 ± 8.5 degrees (range 23.8-60.5: Figure 4B). At the 50% distal level direct injury angles were 34.6 ± 5.4 degrees (range 24.7-46.6; Figure 4A) and indirect injuries 36.7 ± 7.79 degrees (range of 23.6-56.2 degrees; Figure 4B). At the 75% distal level, the angle for direct injuries was 23.7±3.86 degrees (range 14.7-36.2; Figure 4A) and for indirect injuries 23.6 ± 5.24 (range 13.8-34.7; Figure 4B).

These findings suggest that there is no significant variability between injury directly to the leg or injury to another part of the lower extremity at each distal level with p values of 0.58, 0.16, and 0.92 respectively. This observation indicates that, even in the most muscular part of the leg, at 25% and 50% distal levels, the septum position with direct injury is not affected by any anterior or lateral compartment edema around the muscular part of the leg that could be occurring. Thus, the position of the injury should not be a factor in consideration for the surgeon to changing the approach to how and where the lateral incision is placed for the leg fasciotomy procedure with respect to finding the intermuscular septum.

Anterior Compartment Circumferential Segments Length

As a second approach to assessing the position of the intermuscular septum between the anterior and lateral compartments, we measured the arc segment circumferential length of the crural from the tibia to the junction of the intermuscular septum and crural fascia. This relationship was used as alternative means to validate the septum angle relative to the bony architecture of the tibia and fibular used above. The arc segment circumferential length of the crural fascia (Figure 5) over the anterior compartment is independent of the position of the fibular as the anterior compartment arc circumferential measure is based solely on the tibia edge.

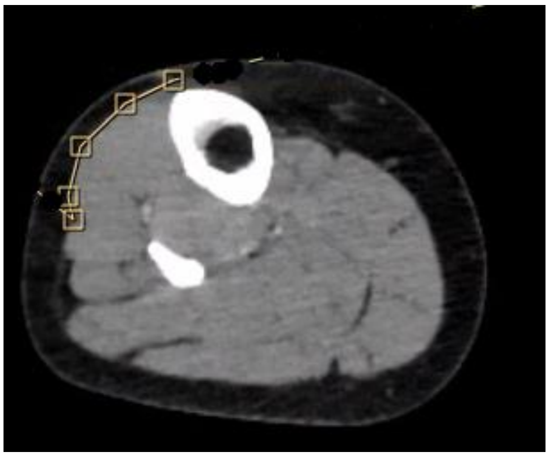

Figure 5: Cross sectional image of the patient showing the measurement of the crural fascia and skin. The ratio between these circumference measures forms and estimate body habitus in the leg.

Overall, as expected, the arc circumference of the anterior compartment crural fascia decreases while progressively distally along the leg as the overall circumference of the leg decreases closer to the ankle. As with angular position measures above, there was considerable variability in the anterior compartment crural fascia arc segment length between individuals, with a mean of 3.80 ± 4.48 cm (range 2.32-4.71 cm) at 25% distal level, 2.81 ± 3.66 cm (range 1.95-3.78) at 50% distal level and 2.05 ± 2.07 cm (range 1.51-2.53cm) at 75% distal level. The larger arc segment at 25% aligns with the anatomy of the leg, as this level has the greatest amount of muscle and connective tissue present. From this analysis, we conclude the same relative variability patient to patient that is present with the angular measure is also present when using an independent anterior compartment arc circumferential measurement relative to the tibia.

When we cross correlated the arc segment circumference of the anterior compartment crural fascia with the angular measure relative to the bony architecture, there was a positive correlation. At the 25% level, the septum angle and fascia are the greatest and shows the strongest positive correlation, r^2= 0.46, p=< 0.00001 (Figure 6A). Moving distally, at the 50% level, there is also a

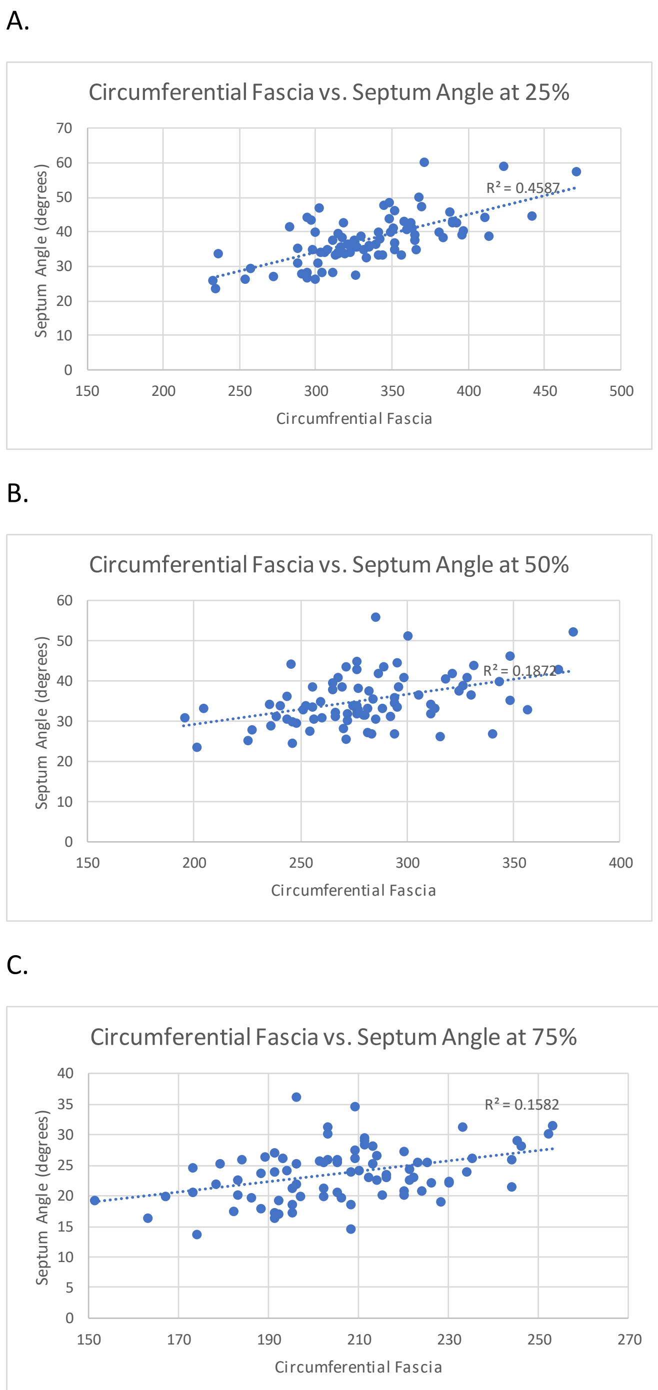

Figure 6: Scatter plot showing the relationship between circumferential arc length of the crural fascia over the anterior compartment and the intermuscular septum angle at 25% distal level (A), 50% distal level (B), and 75% distal level (C) (N=82).

weaker positive correlation and significance with an r^2=0.19 and p=< 0.00001 respectively (Figure 6B). At the 75% level, there was also a significant correlation (p= < 0.00001), although this level had the weakest overall correlation between fascia circumference and septum angle with r^2= 0.15 (Figure 6C).

The absence of a perfect correlation between the two measurements could be due to ‘bulging’ muscles in some individuals that increase the arc circumferential measure or that there is slight variation in the fibula position that contributes to variance in the angular measure. Since the fibula landmark is not part of the arc segment measure, that variability is not present in the arc circumferential measures. Overall, we observed significant patient to patient variability in the intermuscular septum position between the anterior and lateral compartments using two independent measures.

Leg Length

We hypothesized that septal position may be related to the height of the individual. Since limb and torso lengths can vary, resulting in variation between the height of the individual and the length of their limbs we compared septal position to the length of the leg. The length of the leg was measured from the tibial plateau to the lateral malleolus. We cross-correlated the leg length with septal angle at the three proximal to distal levels as above, the 25%, 50%, and 75% position. At all three levels there was no clinically relevant correlation of septal angle compared to leg length (Figure 7). Thus, the use of height is not a predictor of septal position.

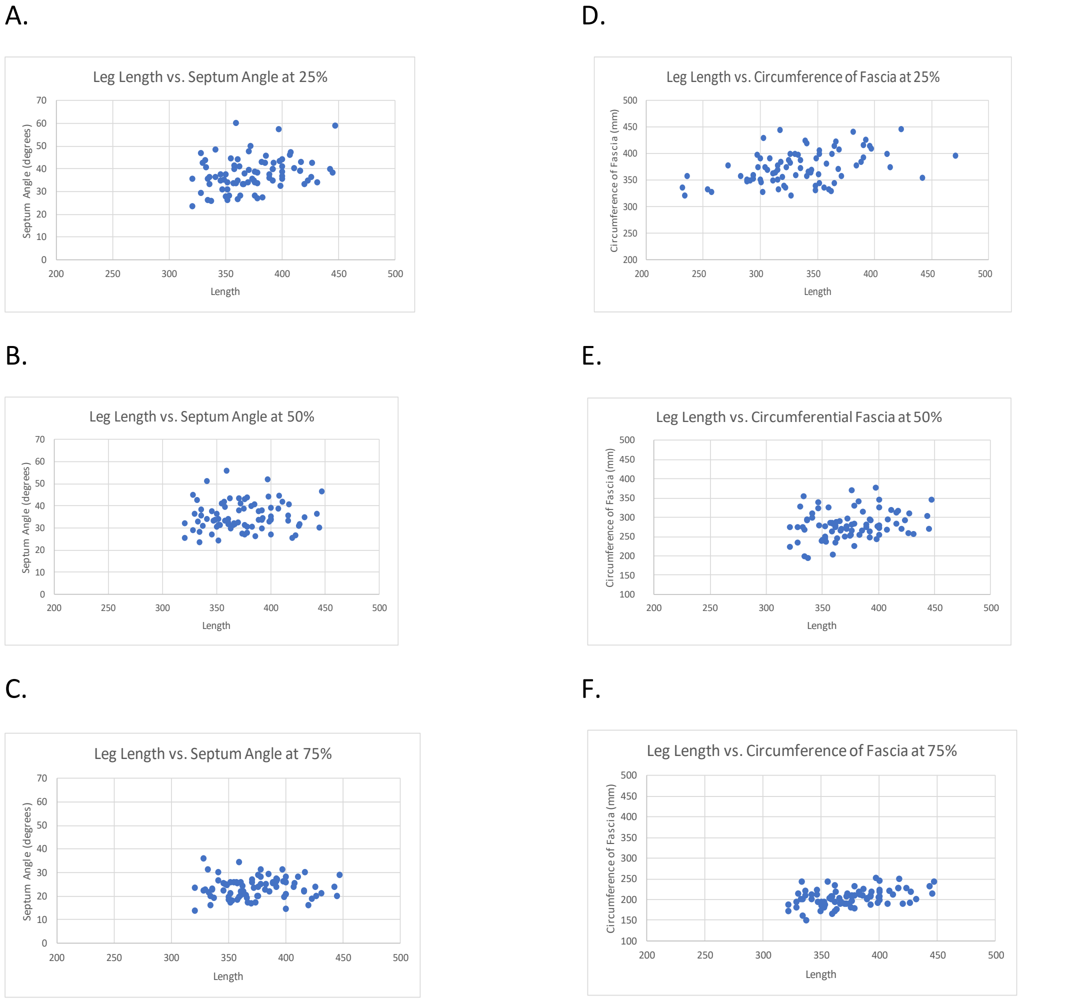

Figure 7: Scatter plot showing the relationship between leg length and septal angular position (panels A-C; N=82) or arc circumferential measurement of the anterior compartment (panels D-F N=82). There was no correlation between leg length and angle at 25% of the distance from the tibia to the ankle (A), 50% (B), or at 75% (C). There was also no correlation between habitus of the leg and circumferential distance at 25% of the distance from the tibia to the ankle (D), 50% (E), or at 75% (F).

Body Habitus

The second possible predictor of septal position we considered was the body habitus of the individual. Typical measures of weight or body mass index (BMI) have well known limitations when body fat is unevenly distributed or in muscular individuals. Therefore, to assess the body habitus specifically of the leg tissues, we used the ratio of the circumference of the crural fascia to the circumference of the skin as an indicator for patient's body habitus. Individuals who had a ratio closer to 1 have a skinny leg, with limited subcutaneous tissue, while those who had lower fascia: skin ratios have leg with larger amounts of subcutaneous tissue.

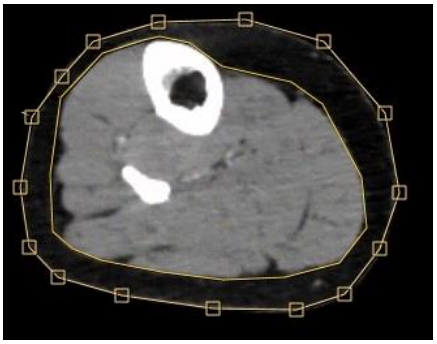

Figure 8: Cross sectional image of the patient showing the crural fascia and skin. The ratio between these circumference measures was used to obtain the fascia to skin ratio.

This ratio was compared against the angular position of the septum and the arc circumference measure of the anterior compartment of the crural fascia to determine if there was a relationship that could predict septal position using body habitus (Figure 8). There was no clinically relevant relationship between the body habitus metric and either the angular position (Figure 9A-C) or anterior compartment arc circumference (Figure 9D-F). Thus, we conclude that body habitus cannot be used to predict the exact location of the intermuscular septum between individuals.

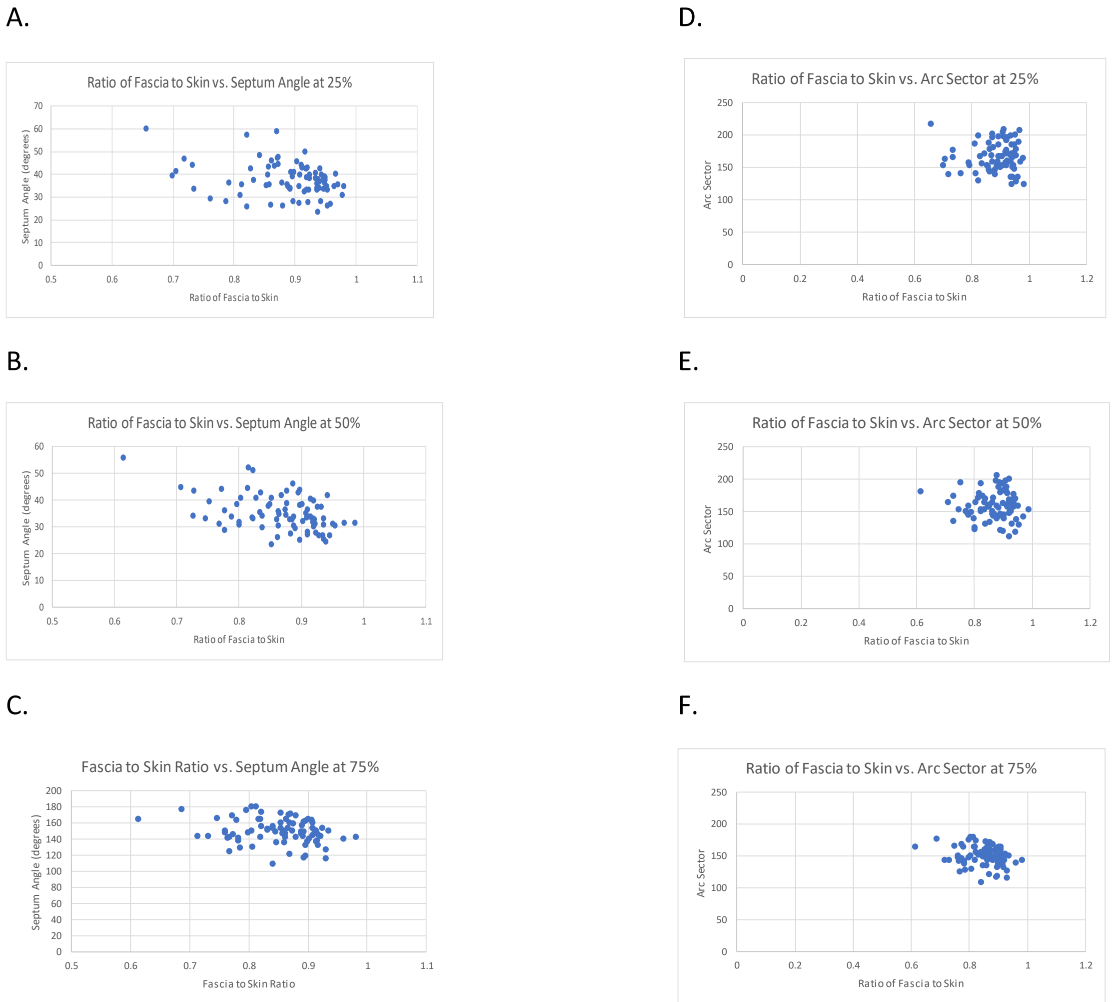

Figure 9: Scatter plot showing the relationship between body habitus and the leg and arc circumferential measurement of the anterior compartment (N=82). There is no correlation between habitus and angle at 25% of the distance from the tibia to the ankle (A), 50% (B), or at 75% (C). There was also no correlation between habitus of the leg and circumferential distance at 25% of the distance from the tibia to the ankle (D), 50% (E), or at 75% (F).

Discussion

The fasciotomy procedure is commonly used to mitigate the effects of compartment syndrome. This procedure is performed on the medial and lateral sides of the leg using a two-incision four compartment approach (Bowyer, 2015) and taught in the Advanced Surgical Skills Exposure for Trauma course (ASSET). Our ongoing studies have shown that on the medial side of the leg the superficial posterior compartment is most commonly decompressed correctly, but the deep posterior compartment is not due to a failure to adequately detach the soleus muscle from the tibia (Mackenzie et al, 2017; 'unpublished observation' Puche et al, 2020). On the lateral incision the lateral compartment is commonly decompressed, but the anterior compartment is frequently missed when decompressing (Mackenzie et al, 2017; 'unpublished observation' Puche et al, 2020). The reason for the high failure to decompress the anterior compartment which does not require the more complex muscular detachment step of the posterior deep compartment, is unclear.

We hypothesized that a contributing factor to the error rate in the anterior compartment may be variability in the intermuscular septum position between the lateral and anterior compartment. This could lead the surgeon to misidentify the septum between the lateral and posterior superficial compartments as the septum between anterior and lateral compartments. This would result in a failure to decompress the anterior compartment and "double" decompressing the superficial posterior compartment from both sides of the leg.

This study was conducted to determine if there is significant variability in septum position using radiology scans of patients who were admitted to the hospital for lower extremity trauma injuries. These patients are in a category where a trauma fasciotomy may be required and, thus, are a population of clinical interest. Computed tomography angiogram (CTA) scans from the University of Maryland Shock Trauma Radiology Database were analyzed for the position of the septa relative to the bones of the leg. Overall, we found that; (a) as the septum progresses distally down the leg the relative septum position shifts anteriorly resulting in shifting septum position at distinct points on the leg; and (b) that there was considerable variability in where the intermuscular septum is located between individuals even when accounting for the anterior to posterior progression of septal position.

This study was restricted to analysis of data sets pertaining to patients who came in for trauma related injuries. Compartment syndrome can be due to several traumatic or non-traumatic injuries; however, non-traumatic injuries (e.g. athletic overuse compartment syndrome) are typically seen in the context of orthopedics and this study was focused upon fasciotomy approaches utilized during trauma surgery. Common traumatic injuries can fall into the category of gunshot wounds, motor vehicle collisions, or stab wounds. Those who experience traumatic injuries to the leg have a high chance of developing compartment syndrome and needing a fasciotomy procedure (Bowyer, 2015). In a military context, this risk is elevated in a combat setting. With the advancements in military armor overall injury rates have reduced, but the proportion of injury types has shifted to the extremities (Goldberg, 2010). Thus, adequate and accurate fasciotomies are needed in this context. While there are differences in injury type between traumatic and non-traumatic mechanisms, the underlying anatomy of our trauma patients is unlikely to differ significantly from a population of non-traumatic conditions. However, we recognize that there is a need to assess septum position and landmark recommendations in the context of non-traumatic orthopedic conditions.

The observation we have made, that the septum shifts relatively more anteriorly as it progresses distally down the leg, creates variability in septum position at different points in the leg. We think this is an important concept for surgeons to understand and consider. This could lead to the crural fascia opening being incomplete if the surgeon doesn't compensate and follow anterior and posterior to the line of the septum to fully decompress the anterior and lateral respectively.

The two-incision fasciotomy procedure is the recommended trauma technique to decompress the lateral compartment in the Advanced Surgical Skills for Exposure in Trauma (American, 2010). To obtain correct incision placement, important landmarks are identified; the lateral malleolus, head of the fibula, tibial shaft, and the patella. The classical lateral incision placement is two fingerbreadths anterior to the fibula, starting two fingerbreadths distal to the head of the fibula extending to two fingerbreadths proximal to the lateral malleolus. The fibular nerve (common peroneal nerve) runs parallel to the anterior compartment, and if transected, can lead to further morbidity, thus care must be taken to avoid injuring the nerve during the procedure. Once the subcutaneous tissue is open and the crural fascia exposed, the intermuscular septum is identified. A perpendicular (transverse) incision is made through the crural fascia such that it spans the intermuscular septum allowing openings into the anterior and lateral compartments. Longitudinal incisions in the crural fascia are made the full length of the skin incision opening the lateral and anterior compartments. While this is taught in the ASSET course, not all references in the literature are congruent with the ASSET landmark identification. Correct incision placement is a predictor of overall outcome of fasciotomies in cadavers, however there is still considerable error in the decompression of the anterior compartment (Mackenzie et al, 2018). These findings bring into question if the initial incision placement recommended in the ASSET guide is best for recognition and successful decompression of the anterior compartment.

The classical landmark for the incision placement is one or two finger breadths anterior to the fibular in the ASSET training manual (American, 2010). However, this could be difficult to identify in an obese patient, when there is enhanced tissue rigidity due to compartment syndrome, or if there is significant subcutaneous tissue edema.

An incision placed more posteriorly by using the fibula as a landmark, may result in a tendency for the surgeon to work posteriorly due to the enhanced visibility that provides in a supine patient. Working anteriorly “up and under” the skin toward the tibia is less obvious and this aspect may lead to a tendency to be overlooked by the surgeon. This could result in the observed misidentification of the septum between the superficial posterior and lateral compartments as the septum between the anterior and lateral compartments. Why is this septum being ‘found’ and misidentified so frequently? The data in this study shows that the intermuscular septum position is variable, ranging from a 14-61 degree angular position relative to the line between the fibula and tibia at the mid proximal of the leg or an arc circumference from the tibia ranging from 2.32-4.71 cm. In a patient with a shallow septum angular position and small arc circumferential position, the intermuscular septum is more anterior than expected and closer to the tibia. This may lead to the surgeon misidentifying the septum between the lateral and superficial posterior compartments as the intermuscular septum separating the lateral and anterior compartments. Our findings indicating that as septum position varies from patient to patients, making the initial incision slightly more anterior using the tibia as a defined landmark may result in enhanced view and easier access for surgeons to find the correct intermuscular septum. We conjecture this would lead to correct decompression of both the anterior and lateral compartments more frequently.

A trauma fasciotomy procedure is said to be complete only if all compartments are decompressed correctly. If a compartment is missed and not recognized clinically it can lead to a decrease in perfusion pressure of the tissues and ultimately ischemia and possible loss of limb (Bowyer, 2015). Tissue necrosis results in breakdown products of the necrotic tissue entering the bloodstream and leading to kidney damage, a condition known as rhabdomyolysis. It has been observed that patients have a high chance of poorly managed compartment syndrome prior to the onset of rhabdomyolysis (Donaldson et al, 2014) indicating this condition is a key clinical concern of an incomplete fasciotomy. Diagnosis of compartment syndrome that has been delayed more than eight hours leads to irreversible damage of both muscles and nerves, potentially causing morbidity with loss of limb or even loss of life from rhabdomyolysis induced kidney failure (Donaldson et al, 2014).

Are there any patient demographic factors that could predict intermuscular septal position and improve accuracy? We considered that the height and body habitus of an individual may be a predicting factor in where the septum is located. However, when we cross-correlated the septum angular position with height, as defined by the length of the tibia, there was no useful correlation between leg length and position. Similarly, when we considered body habitus defined by the ratio between skin and crural fascia circumference (i.e. subcutaneous tissue volume) there was also no significant predictive power of septum position using body habitus measurements. Thus, the stature of an individual should not be taken into consideration as an indicator of septum position in an individual.

These findings suggest that the initial incision placement should be moved slightly more anteriorly through changing the landmark guidance to two finger breadths or one thumb breadth posterior the tibia. This recommendation is also advised because an individual who has compartment syndrome is likely to have a swollen or deformed leg. The fibula is difficult to palpate in a non-swollen leg and would increase in difficulty to palpate for in a swollen leg. On the contrary, the tibia is easily palpable in both swollen and non-swollen legs. This incision placement ensures that the surgeon is more accurately positioned relative to the variations observed in the intermuscular septum position. It is also important for surgeons to be aware of that variability and make sure that they have checked sufficiently far anteriorly so as not to miss the septum in patients where it may be a shallow angle.

Our proposition is that using the lateral edge of the tibia is a more reliable landmark, since the tibia is palpable in individuals with edema, tissue rigidity, and more palpable than the fibula in obesity. Thus, we propose the initial incision be two fingerbreadths or one thumb breadth posterior to the tibia depending on the patient stature and extend to the currently recommended two fingerbreadths distally to the fibula head and two fingerbreadths proximally to the lateral malleolus. These finding support the hypothesis that there is variability in septum position from patient to patient and suggest that the initial incision placement should be moved slightly anterior, giving the surgeon room to work anterior to posterior. These findings also confirm that leg habitus and BMI or weight should not be used to predict septum position. Due to the limited time an individual can stay with compartment syndrome, it is important that a surgeon is able to diagnose and treat compartment syndrome early. If not treated in a timely manner or if all compartments aren't fully decompressed, this can lead to limb loss, necrosis and potentially death. These discoveries suggest that the way other fasciotomy procedures are performed should be looked at carefully. One small change to the procedure, as above, could lead to higher success rate and limit the need for performing a fasciotomy again.

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