A Preliminary Study of Blunt Force Trauma Using a New Computer-Controlled Impact Device: An Exploration of Force and Fracture Type using Domestic Pig Juvenile Ribs (*Sus scrofa domesticus*)

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Submitted in partial fulfillment of the course FORS 4095E

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ABSTRACT

When studying bone trauma, many questions have to be answered such as identifying the type of trauma, the timing and the force used to cause the injury. The latter is difficult to answer, as no previous studies have been able to provide concrete data to determine the force. This study focuses on blunt force trauma to the ribs using a hammerhead, and studying the potential relationship between the type of fractures and the induced force. To do so, a newly constructed, computer-controlled impact device was utilized to strike juvenile domestic pig ribs and record the force at the moment of impact with an incorporated load cell. A total of 20 ribs were struck perpendicular to the long axis of the rib on the external surface, inducing 21 fractures. Transverse fractures were the most prevalent type observed. Upon examination of the applied force, no significant differences in the force applied were found between all of the different categories of fractures, with the exception of transverse and oblique groups with the non-fractured group.

KEYWORDS: Forensic science, Forensic Anthropology, Blunt force trauma, Force, Fracture

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CHAPTER 1:
INTRODUCTION AND BACKGROUND

1.1 Introduction & Statement of Problem

Bone trauma is of great relevance in forensic anthropology. It is used to help the anthropologist and the pathologist determine the manner and mechanism of death, as well as the identification of the deceased (1, 2). Additionally, forensic anthropologists also need to determine if the bone trauma occurred antemortem, perimortem or postmortem (3). Davidson, *et al*. (1) list three questions be answered when assessing bone trauma: “When did the trauma occur? How was it induced? How much force was applied to cause the observed injury?” Unfortunately, no studies have been able to provide concrete data to help answer this last question. Mole, *et al*. attempted to determine if the force of blunt force trauma to porcine skulls could be determined by analyzing the impact injuries induced, but no significant trend was observed (4).

Establishing benchmark data of force applied in relationship to the extent of impact trauma and bone trauma observed, would assist in reconstructing the assault, provide potential information on the assailant, and provide reliable data for use in court. To that end, this study is an attempt at using a newly devised machine to inflict blunt force trauma and record force, acceleration, and displacement data to racks of porcine ribs while under controlled conditions. This study marks the first time such an apparatus has been used to investigate the possibility of being able to apply such data to mammalian ribs.

1.2 Blunt Force Trauma

Trauma is defined as an injury of the living tissue resulting from a force that is extrinsic to the body and causes injury to both soft and hard tissues (1). Trauma can be divided into different categories, including blunt force trauma, sharp force trauma and ballistic trauma (1, 5). Those three types of trauma are the most commonly encountered in homicide cases and therefore, of great forensic relevance (4).

Blunt force trauma has been defined as “relatively low-velocity impacts over a relatively large surface area” (6). Some of the superficial injuries due to blunt force trauma include bruising, abrasions and lacerations. Bruising occurs when blood vessels are damaged by a force, which results in a leakage of blood beneath the skin. Abrasions are superficial wounds and do not cause subcutaneous bleeding, as the trauma is only to the epidermis and not the dermis. Lacerations, on the other hand, are injuries that penetrate through the epidermis, resulting in a tear into the dermis and below (7).

Deep indicators of blunt force trauma consist of damage to skeletal tissues. Macroscopic and microscopic injuries to the cortical and/or the trabecular bone are such indicators (1). Injuries to bone due to blunt force trauma may be due to direct or indirect trauma, each of which involves different types of fractures (5-6).

1.3 Mechanisms of Blunt Force Trauma Fractures

1.3.1 Composition of bone

The two basic components of bone are compact or cortical bone, and spongy bone. The cortical bone constitutes the dense outer layer of the bone, while the spongy bone, also called trabecular bone, consists of intersecting arches of bone spicules typically found within the ends of long bones and supporting protuberances and other point of muscle attachment (9). Molecularly, bone is composed for the most part of collagen fibers, which gives its elastic property. The fibers act as nucleation sites for the formation of hydroxyapatite crystals, which gives bone its strength and rigidity (2).

1.3.2 Rib anatomy

In this study, racks of juvenile ribs were used as an analogue for a human thoracic cage. These ribs were be subjected to trauma on the exterior surface on an area of the rib known as the body. The body of the rib is the main broad curved structure that results in the characteristic arc shape of the rib. In articulation, the rib cage provides a large area of the body that is typically injured in cases of assault. Therefore, it is an important area to assess in assault cases, and more specifically physical abuse cases (9-10).

1.3.3 Strain and stress

Two important concepts regarding the mechanism of bone fracture are strain and stress. When a force is applied to the bone, strain describes the dimensional change that the bone undergoes (11). Stress is used to calculate the force applied over the area (8). Since the components of the bone give it a level of inherent elasticity, the bone can, at first, absorb a limited amount of force without consequence. When the stress continues to be applied, the forces are absorbed through elastic deformation. This allows the bonds between the atoms to temporarily bend, and the bone will go back to its initial form once the stress is removed (2). However, if the stress reaches a certain point, called the *yield point*, the bone absorbs the forces through plastic deformation, permanently bending the bonds between the atoms. The bone is not able to take back its original shape and if the stress does not stop, the bone will reach the *failure point*, at which point fractures occur (8). The relationship between stress and strain is illustrated in the Young's modulus (Figure 1.1).

Various mechanisms may lead to the failure point, and thus, bone fracture. The first mechanism can be due to a force suddenly applied to the bone. The second mechanism can be due to repeated stress. And the last of these may be due to bone diseases, such as osteoporosis, which reduces the density of the skeletal tissue (1).

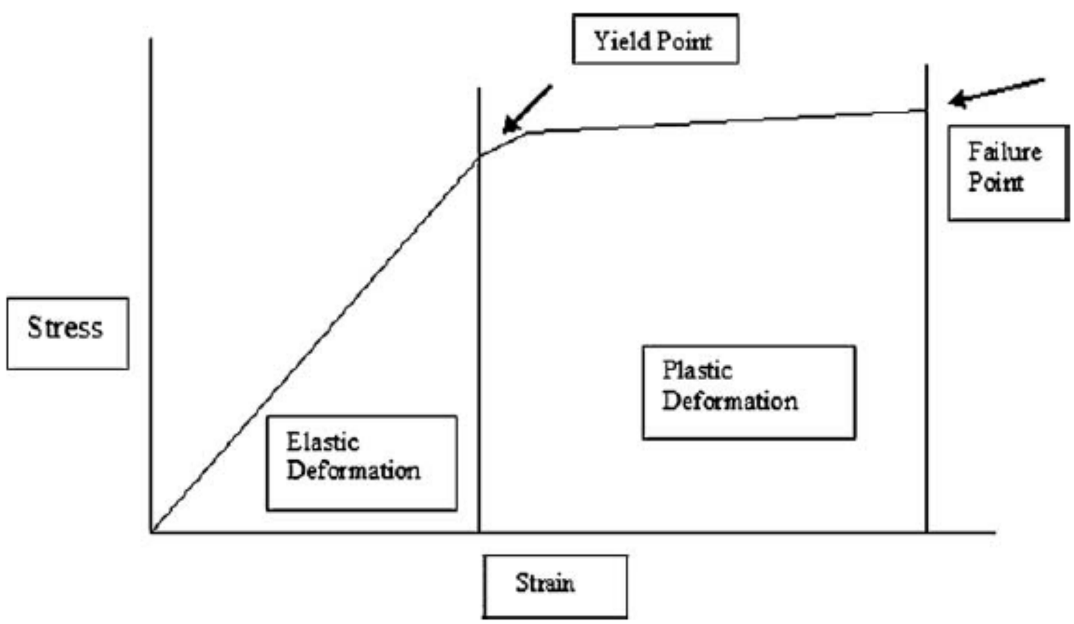

Figure 1.1 Relationship between stress and strain: Young's modulus (from Love & Symes, 2004) (2)

1.3.4 Forces

Five major forces can lead to bone fracture: tension, compression, rotation, shear and bending (1, 8). *Tension* occurs when two forces act in opposition, away from each other. On the contrary, *compression* happens when two forces act in towards each other (11). *Shear forces* occur when the forces are not in the same direction but are parallel to each other, and *rotation* forces are produced when the load applied provokes a twist to the axis. Lastly, *bending* forces are a combination of tension, compression and shear forces. When a bone experiences bending, one side of the bone is under tension, while the other is under compression, and shear forces are applied in between. In cases of bending, bone failure will first be noticed on the side of the bone on which tension is applied (8). Figure 1.2 illustrates all five forces.

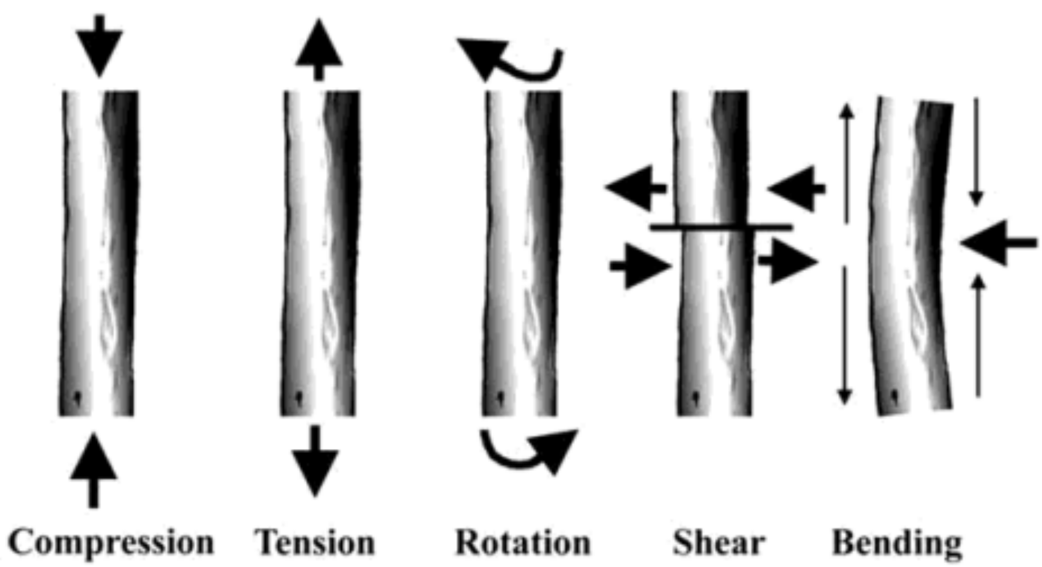

Figure 1.2 The five major forces of fracture (from Galloway, *et al.,* 2014) (8)

1.3.5 Direct and indirect trauma

Trauma resulting in bone fracture can be classified as *direct trauma* or *indirect trauma* (8). Trauma is identified as *direct* if the fractures observed are at the point of impact (5, 8). This usually happens when the target is immobile or moving very slowly (8). The typical fractures found in direct trauma injuries include transverse, comminuted, penetrating and crush fractures (5) (Figure 1.3). *Indirect trauma* is characterized by injuries that are not at the point of impact. Indirect trauma injuries are often observed when the target was accelerating or decelerating at the moment of impact (8). The usual fractures resulting from indirect trauma are oblique, spiral, greenstick, buckle, avulsion, impaction and compression fractures (5, 8) (Figure 1.4).

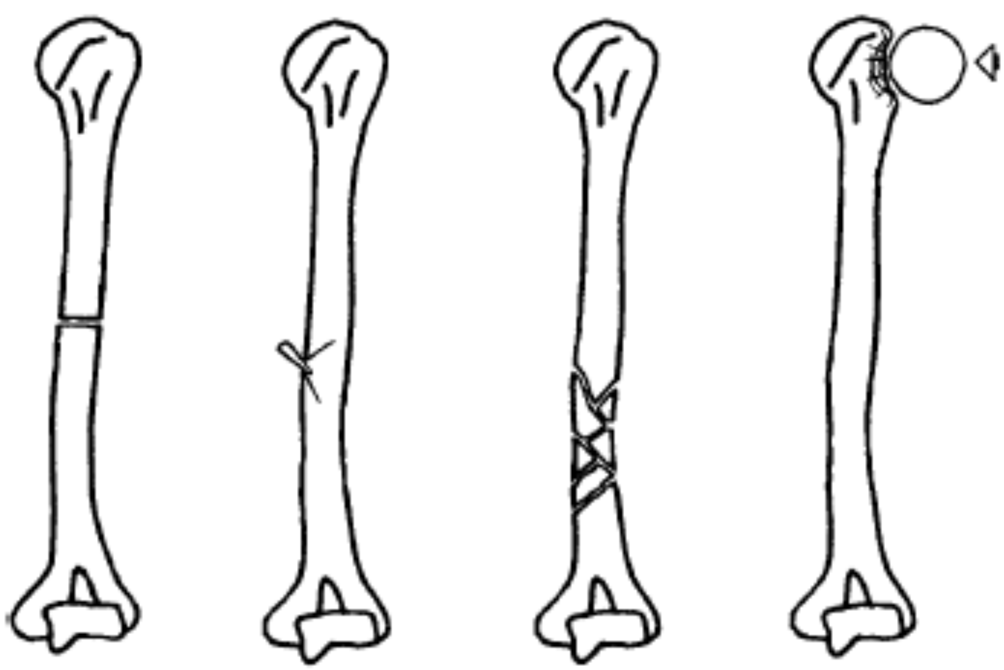

Figure 1.3 Direct trauma fractures: transverse, penetrating, comminuted and crush fractures (from Lovell, 1997) (5)

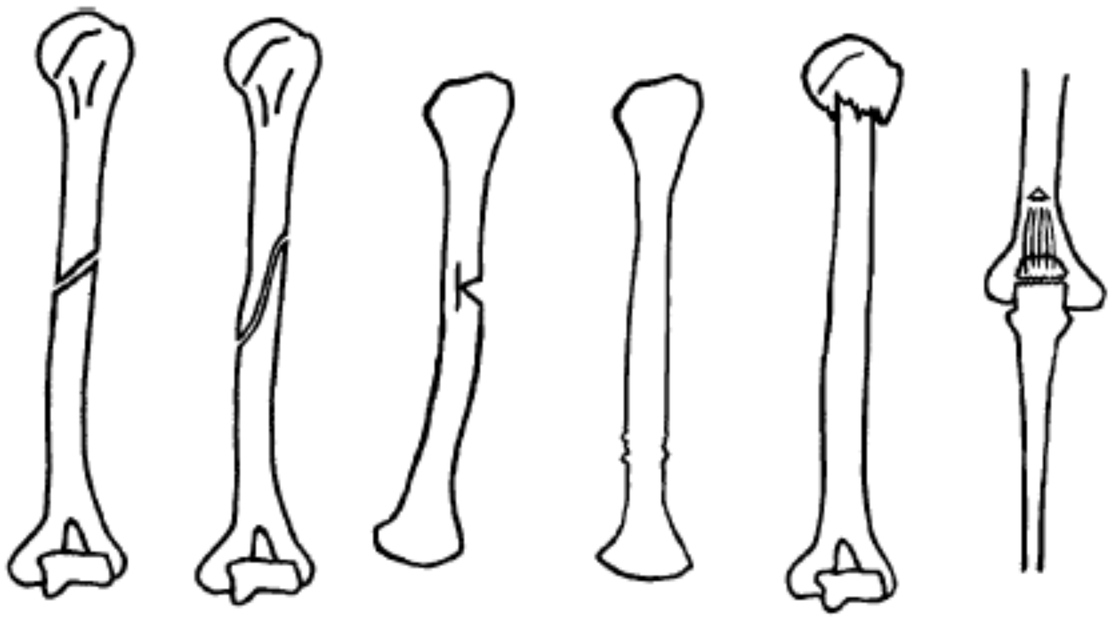

Figure 1.4 Indirect trauma fractures: oblique, spiral, greenstick, buckle, impaction and avulsion fractures (from Lovell, 1997) (5)

1.4 Types of Ribs Fractures Resulting From Blunt Force Trauma

Two different types of fractures are observed in cases of blunt force trauma: *incomplete* and *complete* fractures (8). Bone fractures are considered incomplete when the fracture line only goes partially across the bone. They are typically found in children (2, 8). *Complete* fractures, however, have a fracture line that passes completely through the bone (8).

Incomplete fractures on ribs include *bow fractures*, *buckle fractures* and *greenstick fractures*. *Bow* fractures are an extreme bending of the bone in its entirety and are usually a result of compression and tension forces. Their histologic characteristics are multiple oblique microfractures (8). *Buckle* fractures, also called torus fractures, are defined by Love and Symes (2) as fractures “wherein the bone failed at the point of compressive stress prior to failure at the point of tensile stress.” Compression forces typically cause buckle fractures. *Greenstick* fractures are characterized on one side of the bone with a fracture, and the other side only presenting a bend (8); essentially incomplete transverse fractures.

On ribs, complete fractures are mainly, but *transverse* and *oblique* fractures may occur (8). *Comminuted* fractures involve more than two fragments detached from the bone. Those fractures typically occur when the force applied to the bone is so strong that in order to spread the energy from the trauma, several fracture lines are created (8, 11). A *transverse* fracture goes through the entirety of the bone width at a right angle and an oblique fracture cuts the bone diagonally. When transverse and comminuted fractures are both present, this is a *crush fracture* (8). Another type of complete fractures that can occur in blunt force trauma, even though less common on ribs, are *spiral fractures* (8). They occur when one end of the bone is immobile and the other end is being rotated.

An important element that can be determined from rib fractures is the direction of the impact. This is done based on the location of the fracture. If a fracture is near the angle of the rib, the force originated from the anterior side of the body. A fracture will be found near the neck and head of the rib, if the force is applied on the posterior side of the body. And a force applied on the sides would result in fractures on both the body of the rib and the neck and head of the rib (5).

1.5 *Sus scrofa domesticus* (domestic pig) as a Human Substitute

Animal tissues are often used as a substitute for human. Domestic pig (*Sus scrofa*) has been found to be one of the best analogues to use in place of humans (12). Domestic pig features prominently in a variety of forensic studies (13-14). Therefore, juvenile pork ribs are used instead of human ribs. Juvenile bones differentiate themselves from adult bone by their greater elasticity. Thus, the conclusions of this study can only apply to immature mammalian bones.

1.6 Research Goals

To date, no published research has studied blunt force trauma on ribs in order to quantify the force that was applied to provoke the resulting injury. To the author's knowledge, this study is the first to establish benchmark data that may be used to estimate the amount of force used to induce particular forms of blunt force trauma evidence to bone.

CHAPTER 2:

MATERIALS AND METHODS

2.1 Rib Samples

Two racks of side juvenile pork (*Sus scrofa domesticus*) ribs were bought at Tarini Bros Meat Market in Sudbury, Ontario (Figure 2.1). One rack was of right ribs and the other one of left ribs. Each rack contained 13 ribs. Both racks were kept in a fridge for a day before being used for the experiment. Each rack was cut in half in order to obtain smaller samples (Figure 2.2). Thus, we obtained four samples labeled: “top right rack” (TR), “top left rack” (TL), “bottom right rack” (BR) and “bottom left rack” (BL). For each of these samples, the ribs were numbered from one to seven, and were labeled respectively R1 to R7. After the two right racks were hit to induce trauma, all the samples were placed in the freezer of the Department of Forensic Science at Laurentian University. When needed, they were removed and left in a refrigerator for a day to thaw. Once thawed, the two left racks were subjected to blunt force trauma. For the remaining of the experiment, all the samples were kept in the refrigerator, until defleshed and cleaned.

2.2 Impactor Trauma Device

The “impactor” was built by the students in the Bharti School of Engineering, under the supervision of Dr. Brent Lievers, with the collaboration of the Department of Forensic Science at Laurentian University (Figure 2.3). The machine is composed of an arm with an attachment at its extremity to attach different weapons. Blunt and sharp weapons can be used in order to induce blunt or sharp force trauma. In the case of our research, the head of a hammer, of diameter 2.5 cm, was the weapon of choice (Figure 2.4). The arm also contains a load cell which records the force apply at the moment of impact. The load cell was calibrated by the company Durham Instrument on November 3rd, 2015 and will need to be calibrated again on November 3rd, 2016.

Figure 2.1 Full left and right side juvenile pork ribs (Photo by C. Holinier)

Figure 2.2 Rack of ribs separated in half. The top part has 7 ribs and the bottom part has 6 ribs. (Photo by C. Holinier)

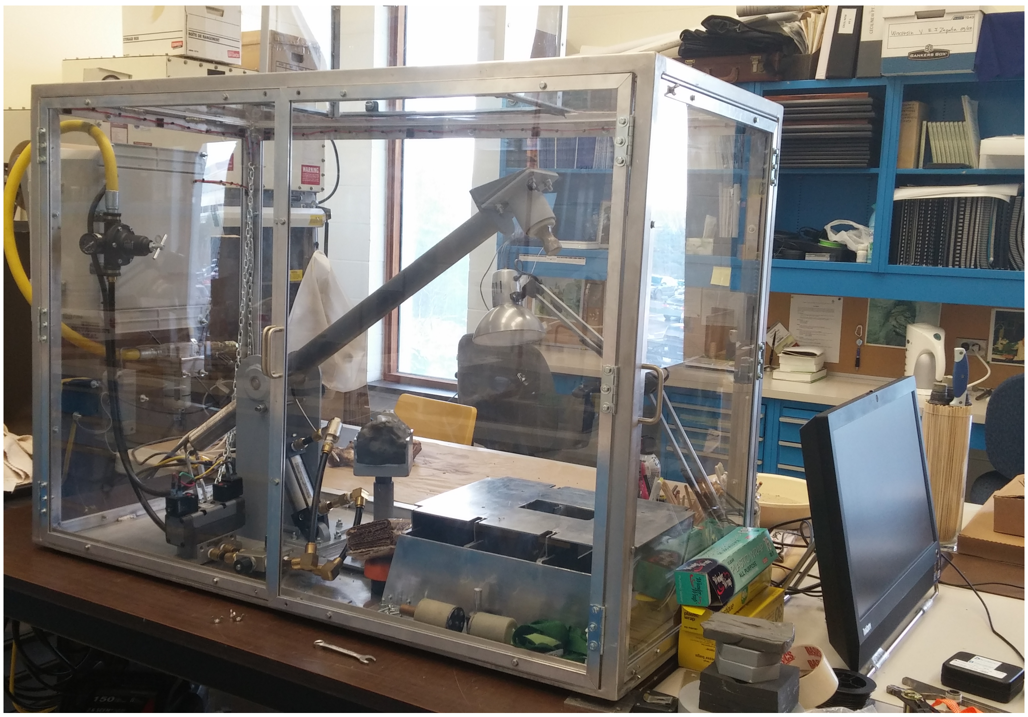

Figure 2.3. The impactor machine and the computer connected to it. (Photo by C. Holinier)

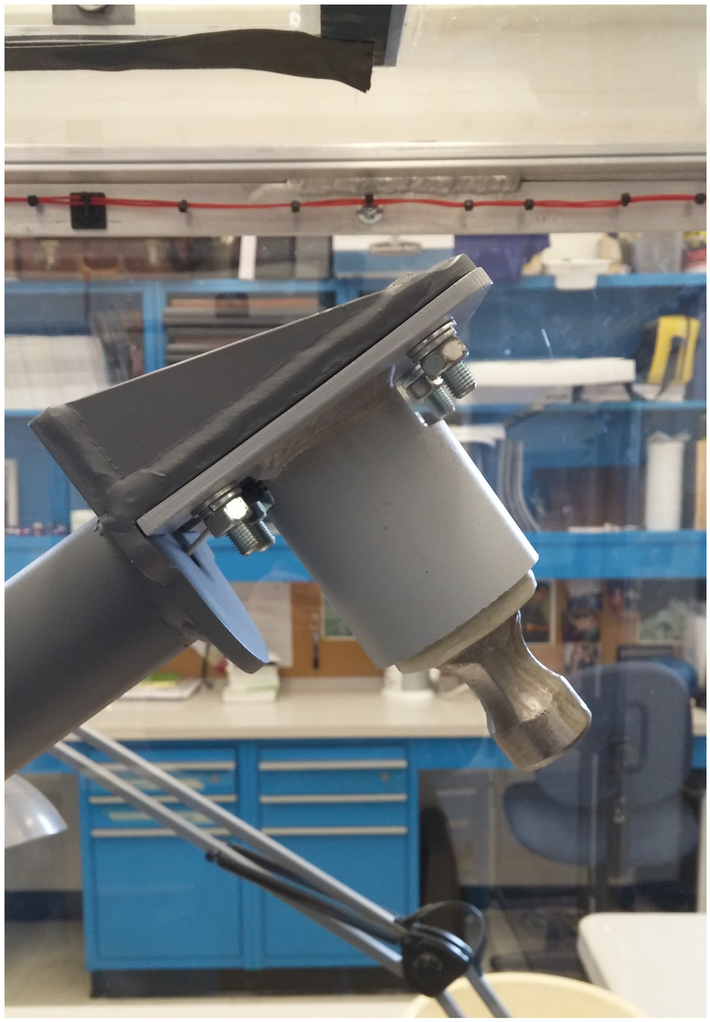

Figure 2.4 Head of the hammer used to induce blunt force trauma. (Photo by C. Holinier)

The samples were positioned on the metal plate of the impactor. For this research, the metal plate was set at a ninety-degree angle with respect to the head of the hammer. The plate has an opening at the site of impact in order for the energy to disperse. A block of clay is positioned under the arm to attenuate impact rebound of the arm.

The hammer is attached to an armature and driven by a pneumatic valve system attached to a compressor (brand: Porter Cable and serial number: N310415). The air compressor tank that was used has a maximum pressure of 150 psi. The amount of air released during each trial determines the velocity, and can be controlled by a gated valve. Each rotation of the valve knob corresponds to a set velocity (Table 2.1). The velocity range allowed by the machine is 2.5 m/s to 6.0 m/s.

Table 2.1 Velocity according to the knob rotations (Blake LeClair, personal communication, September 24, 2015).

Knob Rotations (counterclockwise)	Velocity (m/s)
0.0	2.5
0.5	2.5
1.0	3.4
1.5	4.1
2.0	4.6
2.5	5.0
3.0	5.6
3.5	5.8
4.0	5.9
4.5	6.0

The impactor system is connected to a computer with software for this specific machine. The software is named “Bone Impactor.” It uses built-in safety sensors to cut power if the doors of the machine are not properly closed. This software also records the velocity (in meters per second) during each trial, the force (in Newtons) at the moment of impact, the acceleration throughout the trial, as well as the displacement of the arm.

2.3 Trauma Infliction

Each of the half racks were positioned on the metal support of the impactor, with a piece of brown construction paper and cardboard underneath in order to avoid having the ribs go completely through the hole of the plate at the moment of impact (Figure 2.5). Table 2.2 indicates the velocities used for each rib, as well as the location of the impact (i.e. costal or intercostal). No rib was hit twice.

2.4 Preparation for Macroscopic and Microscopic Analysis

After all the specimens were struck by the impactor, each rib was cut off the rack and defleshed using dissection scissors. Each rib was then wrapped in brown construction paper, labeled accordingly and stored in the refrigerator of the Department of Forensic Science until the next step.

The defleshed ribs were boiled individually in beakers for approximately four hours, using hot plates and in a fumehood. The temperature of the hot plates was set at 150°C, which kept the temperature of the solution between 60°C and 80°C. Each beaker was labeled to track the rib being prepared. The solution in the beaker consisted of tap water and tergazyme 1% solution, using a 20L of water to 200mL of tergazyme 1% solution ratio.

Once the remaining flesh turned into a white/beige color, the rib was taken out of the solution, rinsed with lukewarm tap water and the flesh was gently removed using tweezers and a brush. The clean ribs were then placed on brown construction paper, labeled and left to dry.

Figure 2.5 Half rack of ribs positioned on the metal plate of the impactor, prior to impact. (Photo by C. Holinier)

Table 2.2 Velocity and area of impact for each rib.

Rib	Velocity (m/s)	Costal (C) or Intercostal (I)
TR R1	4.96	Costal
TR R2	-	-
TR R3	5.66	Costal
TR R4	-	-
TR R5	4.44	Costal
TR R6	5.62	Intercostal with rib TR R7
TR R7	5.62	Intercostal with rib TR R6
BR R1	4.53	Costal
BR R2	-	-
BR R3	4.56	Costal
BR R4	4.57	-
BR R5	4.57	Costal
BR R6	4.51	Costal
TL R1	3.48	Costal
TL R2	3.49	Costal
TL R3	2.57	Costal
TL R4	2.72	Costal
TL R5	2.78	Costal
TL R6	2.81	Costal
BL R1	3.87	Costal
BL R2	4.04	Costal
BL R3	5.65	Costal
BL R4	6.02	Costal
BL R5	5.95	Costal
BL R6	-	-
BL R7	-	-

2.5 Stereomicroscope Analysis

The last step of the experiment consisted of looking at the fractures on each rib using a stereomicroscope in order to help visualize the margins of the fractures. For each rib, the presence or absence of a fracture was noted. The fractures were categorized as to type.

The collected data were subject to an Analysis Of Variance (ANOVA) in order to evaluate relationships between the force applied to induce the fracture to a rib and the types of fractures that were observed. Two Chi-square tests were performed in order to assess any differences between the ribs that were fractured and those that were not, using different ranges of force. Finally, T-Tests were done to compare the different categories of fractures two by two.

CHAPTER 3:

RESULTS

A total of twenty ribs were struck with a single blow to induce blunt force trauma. However, twenty-one fractures were obtained as rib TL R2 was observed to have two different fractures. Table 3.1 lists the different type of fractures obtained, the number of fractures for each type, the range of the forces observed, and the mean, standard deviation and standard error of those forces.

Table 3.1 Fractures observed after inducing different ranges of forces

Type of Fractures	# of Fractures	Range of Forces (N)	Mean of Forces (N)	Standard Deviation (N)	Standard Error (N)
Transverse	8	612 – 2250	1278	580	205
Oblique	4	1078 – 1856	1479	436	218
Greenstick	3	651 – 1627	1025	526	304
Spiral	1	1376	1376	-	-
Scrape	1	1909	1909	-	-
Incomplete compression	1	1382	1382	-	-
No Fracture	3	215 – 686	459	236	136
All Fractures	21	215 – 2251	1194	572	128

A rib with a transverse fracture is pictured in Figure 3.1. The break goes completely through the bone perpendicularly to the body of the rib. Figure 3.2 shows an oblique fracture. The break goes completely through the bone at an angle. A rib exhibiting a greenstick fracture is represented in Figure 3.3. A spiral fracture can be seen in Figure 3.4. And finally, Figure 3.5 shows a rib with both a transverse fracture and an incomplete compression.

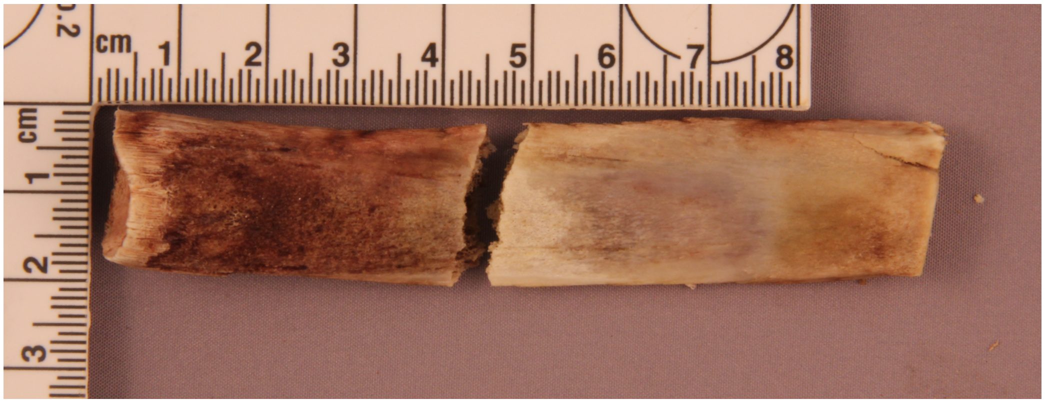

Figure 3.1 Rib TR R3 exhibiting a transverse fracture (Photo by C.Holinier)

Figure 3.2 Rib TR R6 exhibiting an oblique fracture (Photo by C. Holinier)

Figure 3.3 Rib TR R1 exhibiting a greenstick fracture (Photo by C. Holinier)

Figure 3.4 Rib BL R3 exhibiting a spiral fracture (Photo by C. Holinier)

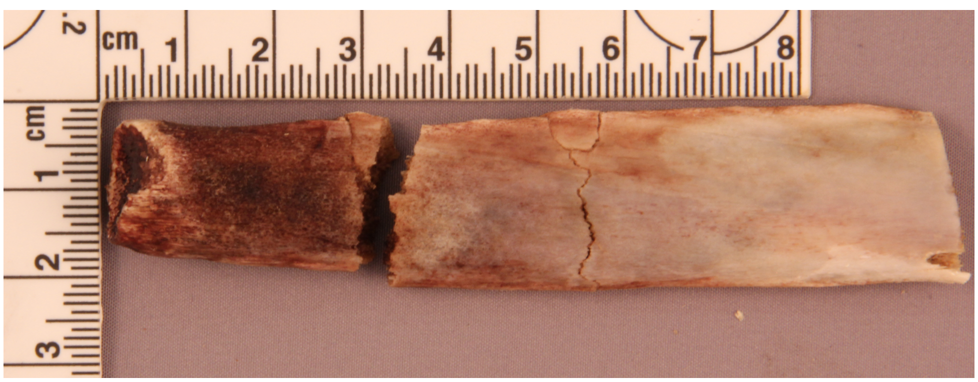

Figure 3.5 Rib TL R2 exhibiting a transverse fracture and an incomplete compression fracture (Photo by C. Holinier)

An Analysis Of Variance (ANOVA) was performed in order to establish if there was a significant difference between fracture categories. The test was a one-way ANOVA with an alpha value of 5%. The p-level obtained was 0.186. Thus, it was concluded that there was no significant difference between the groups.

Two Chi-Square Tests were then done to determine if there was a difference between the ribs that were fractured and those that were not. The first test was performed using 500N intervals starting at 0 and ending at 2500N. The test established that there was a significant difference in the amount of force induced between the ribs that were fractured and the ones that did not break. At an alpha level of 5%, the value obtained was 0.0067. The second chi-square test was done using only two ranges of force (0 N-700 N and 700 N-2500N). A significant difference in the amount of force induced between the fractured ribs and non-fractured ribs (was concluded at alpha level of 5%, the value obtained was 0.0008).

T-Tests of the force means were performed to compare categories two by two. This demonstrated no significant differences between transverse, oblique and greenstick fractures (Table 3.2). However, there were significant differences between transverse fractures and the group of no fracture, and between the oblique fractures and the group of no fracture. It was not possible to compare the spiral, the scrape and the incomplete compression fractures as each of them only occurred once.

Table 3.2 t-Tests results to compare the means of the different categories of fractures

Categories	P-level
Between Transverse and Oblique	0.520
Between Transverse and Greenstick	0.528
Between Transverse and No Fracture	0.009
Between Oblique and Greenstick	0.291
Between Oblique and No Fracture	0.011
Between Greenstick and No Fracture	0.188

CHAPTER 4:

DISCUSSION

4.1 Analysis of the Results

Bones inherently are resist strain and stress until the failure point is reached and a fracture results (2). In this study, juvenile ribs were used, and thus, exhibit a greater amount of elasticity and resistance to fracture as they can undergo a greater degree elastic deformation (8). The results have demonstrated that, overall, there was a significant difference in the amount of force applied to the ribs that resulted in fractures and the ones that did not. This confirms the fact that a certain threshold, or intensity, of force needs to be reached to actually induce a fracture. The second chi-square test performed showed that there was a significant difference between the number of ribs that were struck with a force lower than 700 N and did not fracture compared to the number of ribs that were struck with a force higher than 700 N and did fracture. Thus, it seems that the presence of a fracture would indicate that the force applied at the moment of impact was most likely superior to 700N. However, it is not currently possible to establish 700N as a threshold as no previous studies have produced reliable data as a basis of comparison. Moreover, the range of force obtained for each category of fracture in this study cannot be compared with other studies as most of those examined the forces involved in blunt force trauma to the head and not ribs (4, 15-16).

T-tests were used as a mean of comparing the force means of two categories with one another. Significant differences were observed between the group of non-fractured ribs with the transverse fracture group, and with the oblique fracture group. No significant difference was found when comparing the greenstick group with the non-fractured ribs group, the transverse fracture group, or the oblique fracture group. And finally, the spiral, scrape and incomplete compression fracture groups were not compared as they each only occurred once. These findings suggest that it is not possible to give a range of force based on the type of fracture observed.

As shown in Table 3.1, the largest number of fractures obtained was in the transverse fracture category. Transverse fractures occur when a force is applied perpendicular to the length of the bone. The machine impacted the ribs perpendicularly and in the middle of the width of the shaft. This explains the dominance of transverse fractures in our results. Furthermore, two of the oblique fractures can be explained by the fact that a single blow, positioned intercostally (between the two ribs), induced the two fractures. The ribs were only hit by the margins of the hammerhead. Those results are in accord with Gonzalez, *et al*. study as cited in Galloway, *et al*. (17), that rib fractures are usually characterized by transverse and oblique fractures.

4.2 Limitations and Considerations for Future Research

The most important limitation in this study was the sample size. Indeed, the statistical assessment suffered from it. Our sample only involved 20 ribs and 21 fractures, which makes it a small sample. In the future, the sample size should be increased.

It is recognized that the set up of the impactor apparatus could have affected the results. The area of the rack of ribs that was being hit was positioned above an opening in the metal support plate. The purpose of this opening is to help dissipate the energy coming from the blow. However, during the experiment, it appeared that the rack would be pushed down in the opening, and one of the blows actually led to a fractured rib that was not hit. This fractured rib was not included in the results. In the future, filling this opening with some ballistic gel would likely give more support to the ribs, while permitting the energy to dissipate. Moreover, the gel would give a similar structural support as in the human body.

Future research could replicate this study with the modifications mentioned above and use different blunt objects, as well as use sharp force trauma instead of blunt force trauma. It would also be interesting to study different angles of impact, which is a possibility thanks to the movable metal support plate that can be set to different angles. And finally, a study could focus on the differences in fractures between costal and intercostal strikes, mostly to assess if transverse fractures and oblique fractures are more recurrent in one of those two categories.

CHAPTER 5:

CONCLUSION

Transverse fractures were found to be the most prevalent in this study. Overall, significant differences were found in the amount of force applied when comparing juvenile ribs struck but did not fracture with the transverse fracture group or with the oblique fracture group. No other significant differences were found between the different types of fractures obtained. A potential threshold of 700N was identified and could indicate the minimum amount of force applied at impact to observe a fracture. However, further research is needed to confirm this finding. This preliminary study is a first step in using a larger sample size and by making small modifications to the impactor, as discussed above.

APPENDIX

Raw data

Table A: Force applied at impact for each rib and the type of fracture observed

Rib	Force (N)	Transverse fracture	Oblique fracture	Greenstick fracture	Spiral fracture	Scrape	Incomplete compression	No fracture
BR R1	1125.56		X					
BR R2		X						
BR R3	705.323	X						
BR R4								
BR R5	651.203			X				
BR R6	685.869							X
TR R1	612	X						
TR R2								
TR R3	1309.28	X						
TR R4								
TR R5	2250.84	X						
TR R6	1856.2		X					
TR R7	1856.2		X					
BL R1	1078.46		X					
BL R2	1904.03	X						
BL R3	1375.69				X			
BL R4	1908.85					X		
BL R5	1626.55			X				
BL R6								
BL R7								
TL R1	796.305			X				
TL R2	1382.13	X					X	
TL R3	475.676							X
TL R4	1264.08	X						
TL R5	792.502	X						
TL R6	214.581							X

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