Progression of Soft Tissue Contusions in Behind Armor Blunt Trauma

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Abstract. Behind Armor Blunt Trauma (BABT) occurs when body armor is struck by an incoming ballistic munition, causing a high-rate loading event between the body armor's back face and the wearer's torso. Previous studies have demonstrated the risk of BABT injuries to thoracic organs in terms of impact energy. Further study of soft tissue injuries produced during BABT impacts is needed to complete the understanding of BABT. This study performed 35 BABT impacts on the interior right thigh of live porcine specimens as a surrogate model for humans to further understand the injury response of soft tissue. A blunt indenter with a similar shape and recruited mass to previously performed studies was used to impact the live porcine specimens across a range of energies. Each impact location was carefully chosen to avoid overlapping skeletal or abdominal regions, only impacting the skin and underlying tissues. The porcine specimens were then survived from 1 to 30 days after the impact to monitor the progression of injury across differing impact energy levels and post-impact survival periods. Injuries ranged from minor contusions that fully healed by 12 days after a low energy impact of 50 Joules [J], to severe injuries that produced significant swelling, skin necrosis, volumetric muscle loss, and large hematomas at the impact location. At the highest energies of 270 to 330 J, these injuries did not heal by the end of the 30-day survival period, with visible scarring on the skin, volumetric muscle loss, and unorganized muscle growth. Observations throughout the survival periods and subsequent mechanical testing of the muscle tissue indicate that most low to medium-energy impacts to muscle can heal within one month after impact; however, high-energy impacts showed potentially permanent changes to the muscles and skin.

1. INTRODUCTION

Body armor is designed to stop an incoming ballistic munition by absorbing and dispersing the impact energy. This is achieved through deformation of the body armor. While body armor is designed to prevent penetrative injuries, the resulting body armor deformation creates a high rate loading event to the underlying anatomy. This can cause physiological and structural injuries to the bones, soft tissue, and organs resulting in an injury modality referred to as behind armor blunt trauma (BABT) [1-3]. These injuries, though not as severe as penetrative injuries, can result in substantial pain, inflammation, and functional impairment in the region of impact. In some severe cases, there are potential long-term health consequences, such as localized tissue necrosis, hematoma formation, myositis ossificans, and volumetric muscle loss [4-13].

Understanding the pathophysiological progression of deep tissue contusions from behind armor blunt trauma is critical for improving protective gear design, clinical interventions, and rehabilitation strategies. Studies on blunt injuries from sports, such as American Football, may provide a path forward, as they have documented player recovery timelines, the type and severity of injury observed, and the initial treatment of these injuries [7,8,11,13-17]. While these studies help provide the injury patterns and recovery process of contused muscles, many are retrospective studies with unknown impact parameters or conditions. Studies utilizing live animal and human volunteer models that control the impact location, impact severity, and the mechanism of impact can provide further insight into these types of injuries [11,15,16].

Live porcine specimens have been shown to be a viable human surrogate for studying injuries due to their anatomical and physiological similarities to humans [18-22]. However, while porcine specimens serve as a useful model for initial injury research, an important consideration is that, unlike humans, they continuously grow throughout their lives [23]. This growth may influence the mechanical properties and healing response of tissues, including the rate and extent of tissue regeneration following an injury that

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would not be seen in a human throughout a longitudinal study. Despite this, the pig remains a valuable model for studying the initial stages of tissue damage and recovery, providing important information that can guide the development of better protective armor and treatment strategies for human injuries.

Simulating a BABT injury in a live porcine model serves as a valuable tool for understanding the severity and recovery process of such injuries in humans. When a porcine specimen is impacted, it results in a controlled injury that mimics the physical damage that might occur in a combat setting. The extent of functional impairment following the contusion provides critical data regarding the impact on mobility and overall physical performance for humans. This information is essential when assessing a soldier's readiness to return to duty, as it helps determine how the injury affects their ability to perform tasks requiring physical strength, coordination, and endurance. Evaluating recovery through this model ensures that soldiers are not prematurely cleared for duty, promoting both their safety and operational effectiveness.

The importance of proper return to duty is imperative as the return to duty rate of military personnel evacuated due to musculoskeletal injuries was approximately the same as those evacuated due to combat related injuries (3.3% vs 2.8% return to duty, respectively) [24]. Additionally, muscle contusions have been shown to be the fourth most common injury treated among infantry brigade teams [25]. With musculoskeletal injuries being highly prevalent in the military, there is a need for new methods to understand, prevent, and reduce their impact. Recent research has identified the regions of the body that are most susceptible to injury during deployment but still lack detailed analysis that clarifies the mechanisms behind them [26,27]. The next step is to study how deep tissue contusions present themselves in musculature to elucidate new diagnostic procedures. The objective of this study was to quantify how BABT soft tissue contusions evolve as a function of impact severity and time post-impact.

2. METHODS

2.1 Live porcine preparation

Experimental testing on thirty-five (35) live Yorkshire porcine specimens was performed at the University of Virginia (UVA) with live animal testing protocols approved by the UVA Animal Care and Use Committee (protocol number 4379-12-21) and U.S. Army Animal Care and Use Review Office (protocol number MT21006.031.e002). Porcine were allowed to acclimate to the testing facility for at least three days before experimental testing was performed. Live porcine were induced with propofol through an intravenous catheter prior to intubation. Once intubated, the porcine was kept under anesthesia with Isoflurane and medical air. A local analgesic, Bupivacaine, was administered at the target impact location prior to impact. Additionally, a long-acting 96-hour analgesic, Buprenorphine, was administered subcutaneously in the thin flank skin. Further administration of analgesics was not used unless discomfort was noticed by the veterinarian care staff. Analgesics that might aid in the recovery process or reduce the inflammatory response to the injury were not employed in this study to study how a soft tissue contusion would change over time in the event of an untreated injury.

2.2 BABT impact testing

A high-rate pneumatic impactor was designed to propel a 3D-printed indenter at live porcine to study the change of musculoskeletal properties due to BABT injuries. The profile of the indenter was modeled after the backface deformation profile of hard body armor [2] and had a diameter of 10.2 centimeters [cm]. By using an indenter with this profile, injuries were characterized based on a generic threat as opposed to a specific munition or body armor. The indenter was equipped with an onboard accelerometer (Endevco 7270A) to measure the acceleration-time history of the impact with a combined mass of 247 ± 2.8 grams [g].

Thirty-five (35) total porcine specimens (mass = 43.02 ± 3.80 kilograms [kg]) were impacted for this study with survival periods ranging from 1 to 34 days post impact and target impact energies ranging from 47.98 to 338.20 Joules [J], see Table 1. There were five target survival periods and seven target impact energies, allowing one impact per combination of duration and impact energy. The reference test matrix used can be seen in Table 2. The actual test matrix (Table 1) has impact energies that are not listed in the reference test matrix (Table 2)

With the porcine specimen laying supine, a target impact location was chosen on the interior of the hind right leg. Positioning of the impact location was made by palpation of the hind leg to find where the center of the indenter would make maximal contact with the underlying soft tissues. Once a target location was found, a comparable location was found on the left thigh to serve as a control. The porcine

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specimen was then moved beneath the barrel of the impactor, ensuring that the impact would avoid any of the abdominal or skeletal regions. Further, the specimen's right hind thigh was placed in contact with the end of the barrel to ensure an orthogonal impact condition. The porcine was then recovered from anesthesia, returned to its cage, and monitored for any signs of discomfort over the post-impact survival period. On the final day of the survival period, photos were taken of the hind legs to visually compare the surface-level damage.

Table 1. Test matrix. Specimen mass is the mass of the porcine on the day of impact. Survival time is the time in days the specimen was survived after the impact.

Specimen Number	Target Impact Energy (J)	Actual Impact Energy (J)	Specimen Mass (kg)	Survival Time (days)
CP001	100	76.38	44.4	30
CP002	40	47.98	44	30
CP003	100	122.40	42	20
CP004	50	50.13	43.2	20
CP005	150	144.88	44.4	30
CP006	300	276.31	40.6	6
CP007	225	231.58	39.6	6
CP008	150	165.67	47.0	11
CP009	150	142.67	47.0	5
CP010	190	185.84	40.6	30
CP011	50	47.65	43.6	1
CP012	80	90.56	41.2	1
CP013	150	159.88	39.8	20
CP014	50	48.60	45	5
CP015	80	77.53	45.4	5
CP016	190	180.06	42.2	20
CP017	230	236.22	40.3	30
CP018	150	145.40	50	1
CP019	120	111.14	40	1
CP020	80	83.85	42.2	12
CP021	190	179.30	53	11
CP022	230	230.87	50	13
CP023	275	310.11	43.6	30
CP024	230	237.82	43.2	20
CP025	275	250.98	40	20
CP026	120	140.29	38.4	5
CP027	190	181.65	40.4	1
CP028	120	109.91	40.7	12
CP029	230	222.99	38.0	1
CP030	270	267.02	38.2	1
CP031	190	173.46	40.8	6
CP032	310	296.70	43.8	20
CP033	270	251.45	39.8	13
CP034	340	332.34	52	34
CP035	310	338.20	41.2	8

Table 2. The reference test matrix to appropriately test a range of impact energies at discrete times post-impact.

		Days Post-Impact				
		1 Day	5 Day	12 Day	20 Day	30 Day
Impact Energy (J)	50 J					
	80 J					
	120 J					
	150 J					
	190 J					
	230 J					
	270 J					

2.3 Mechanical testing

On the final day of the survival period, both hind legs were removed for mechanical testing. A custom test device (Figure 1) was used to perform confined quasi-static compression tests (compression rate of 1.3 mm/s) on excised tissue samples (diameter = 10.2 cm, depth = 4.5 cm) to assess through-the-thickness changes in the muscle tissue. The test device was equipped with a flat, cylindrical plate (diameter = 2.54 cm) attached to a linear actuator to quasi-statically compress the tissue while recording the compressive force via a load cell (Honeywell model 31 series, 50 lb.) at a sampling rate of 500 Hz. Excised tissue samples were taken from the impact location on the right thigh and an equivalent location on the left thigh to serve as direct control for the impacted tissue.

The skin and subcutaneous tissues were removed from the samples to measure the force response of the two underlying muscles, the Gracilis and Semimembranosus. Once placed in the testing cup, the travelling head was brought into contact with the surface of the Gracilis at the sample's center point. The sample was then compressed to 25% strain to assess the loading response of the tissue. Tests were conducted at the center of each impact site, as well as at a similar location on the unimpacted contralateral sample to assess the differences between the impacted tissue and healthy tissue from the same specimen. To ensure there were no edge effects from the confined quasi-static compression tests, additional tests were performed 2.54 cm radially outward from the center point and at higher strain levels. At the completion of mechanical testing, the impacted tissue samples were bisected to visually inspect the contusion capsule within the muscles.

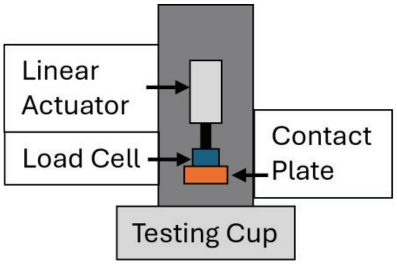

Figure 1. Diagram of the test device used for quasi-static mechanical testing.

3. RESULTS

The peak force of each quasi-static compression test was taken as an approximation for through-the-thickness stiffness of the tissue. Figure 2 shows an interpolated map of the peak compressive force responses at 25% strain from the impacted tissue as a function of the impact energy and survival time post-impact. The plot shows the peak forces in a color bar relative to the maximum force observed from this test series. Blue indicates low peak forces and low muscle stiffness while red indicates high peak forces and high muscle stiffness. The bottom right portion of the plot is uncolored because there were no tests performed within that specific impact energy and survival period. Additionally, control data is not plotted as it has an impact energy of 0 J. Control data had an average peak force 2.7 ± 1.6 Newtons

[N] (n = 26). Fewer data points were used as these 26 were tested within seven hours post euthanasia. Control data showed greater variance in samples tested later than 7 hours post euthanasia and were excluded due to the potential effect of rigor mortis in control tissue.

Table 3 visualizes the presence of observable contusion at each survival period end point through shaded cells in the test matrix. Cells shaded red indicate that contusion was observed in the skin and muscles. Yellow shaded cells indicate that no contusion was observed in the skin, but there was contusion in the muscles. Some high energy impacts with long survival periods were observed to have scarring on the skin at the impact location but no contusion. These tests are shaded as yellow in the test matrix as a scar is treated as a different injury than a contusion within this study. Cells shaded green did not have any observable contusion in the skin or muscles.

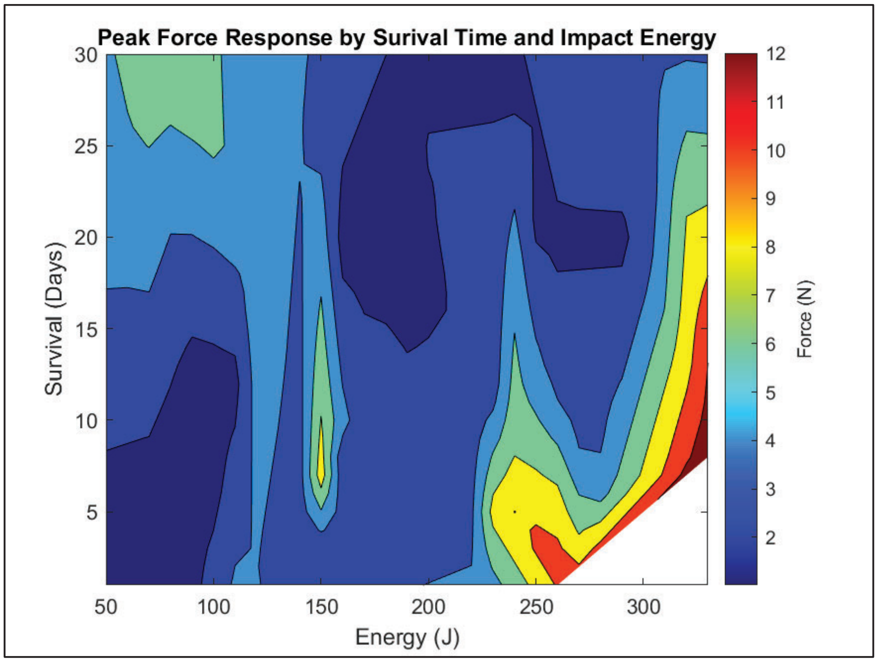

Figure 2. Interpolated peak force response of impacted muscle at its center point is by varying impact energy and survival time post-impact.

Table 3. Injury observations of surface level and deep tissue contusions. Red cells indicate contusion observed in the skin and muscle. Yellow cells indicate contusion only observed in the muscles. Green cells indicate no contusion observed.

				Days Post-Impact				
Color Key		Impact Energy (J)		1 Day	5 Day	12 Day	20 Day	30 Day
			50 J	🟥	🟨	🟩	🟩	🟩
RED: Contusion in skin and muscle			**80 J**	🟥	🟨	🟨	🟩	🟩
			120 J	🟥	🟥	🟨	🟩	🟩
YELLOW: Contusion in muscle			**150 J**	🟥	🟥	🟥	🟨	🟩
			190 J	🟥	🟥	🟥	🟨	🟨
GREEN: No contusion			**230 J**	🟥	🟥	🟥	🟥	🟨
			270 J	🟥	🟥	🟥	🟥	🟨

Exemplary images of the contusions within the deeper muscle, the Semimembranosus, can be seen in Figure 3. The three photos were taken from three different tests of equivalent impact energy to show the progression of a contusion from 1 day post impact to 30 days post impact. Figure 3A shows a contusion in the Semimembranosus at 1 day post impact. The dark red area of the muscle is the contused portion of the muscle. The discoloration indicates the formation of a contusion capsule as the spread of damage is mitigated. In this specimen, there was observable contusion in the skin and muscles. Figure 3B shows a contusion in the Semimembranosus at 11 days post impact. The contusion capsule has decreased in size, and the discoloration around the contusion capsule is different to that of the contusion itself. The change of color surrounding the contusion capsule shows the progression of healing and removal of the contusion. There was no observable contusion in the skin of this specimen. Figure 3C shows a fully healed Semimembranosus with no signs of contusion at the impact site 30 days post impact. No observable contusions were noted in the skin or muscles at the impact location of this porcine specimen.

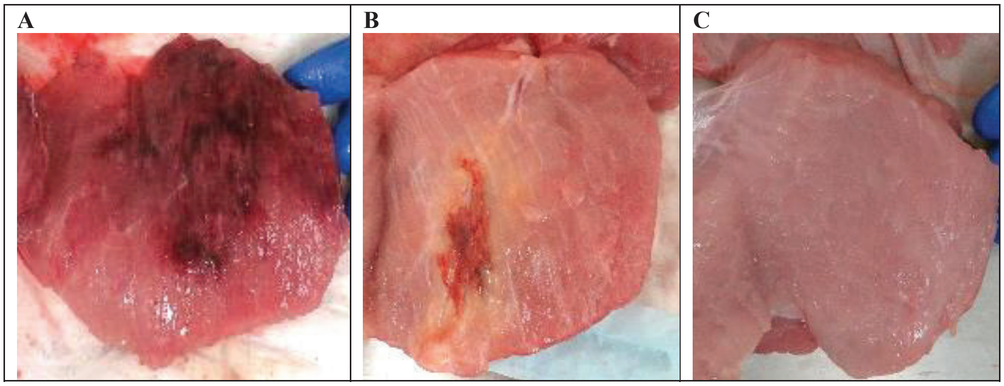

Figure 3. A) Fresh contusion in the Semimembranosus at 1 day post impact. B) Contusion capsule that is healing in the Semimembranosus at 11 days post impact. C) No contusion in the Semimembranosus at 30 days post impact.

4. DISCUSSION

The results from the quasi-static mechanical testing provide insights into the behavior of impacted versus control muscle tissue. The interpolation of peak forces from impacted tissue and the associated analysis reveals the muscle's mechanical response varied with impact energy and survival time post-impact. The variation in peak forces, as seen by the color-coded plot in Figure 2, suggests that the muscle's response to impact is sensitive to both the magnitude of the energy imparted and the time elapsed following injury. Lower peak forces are indicated by dark blue, while the highest peak forces are represented by dark red. This gradient suggests that muscle tissue undergoes varying levels of stiffness following impact, which could be indicative of differing degrees of damage or repair over time.

This change in stiffness is relevant to the study of contusions, as the mechanical properties of muscle during healing reflect underlying changes such as edema formation, necrosis, fibrosis, and scar tissue development. The confined quasi-static compression method used here allows for a qualitative assessment of these changes based on stiffness profiles. However, it does not directly quantify the specific contributions of fluid content, fibrotic tissue, or inflammation without additional imaging or histological correlation. When combined with dissection findings, this method offers strong qualitative insight into the material state of the muscle at different recovery stages.

The exclusion of certain control samples tested more than 7 hours post-euthanasia revealed an increase in the mean peak force (5.1 ± 5.7 N, n = 35) as compared to the samples tested within 7 hours (2.7 ± 1.6 N, n = 26). A two-sample t-test further highlighted the statistical significance of the difference between the two control groups ($p = 0.005$), reinforcing the idea that control muscle tissue behaves differently when considering only fresh samples. This observation suggests that post-mortem changes in muscle tissue can influence the results of mechanical tests, even when some samples were frozen. Thus, excluding these samples offers a more accurate representation of muscle tissue behavior.

For low-energy impacts (<150 J), full recovery occurred by 30 days. Peak forces increased over time, and a temporary spike was observed around day 8, attributed to the formation of a solidified contusion capsule. This capsule represented a stage in the healing process where tissue damage stabilizes before being remodeled. Following this peak, forces declined, suggesting muscle regrowth and structural restoration. These impact levels caused only mild to moderate damage and did not result in significant long-term deficits. The muscle tissue was able to repair effectively by the end of the 30-day period.

For impacts around 200 J, the results demonstrated that the peak forces remained low throughout the entire 30-day survival period. Serious contusions in the skin and muscle were noted from all

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specimens tested at this energy level, with the injury followed by the normal recovery process. This indicates that the solidified contusion capsule and edema were not present during the end point intervals when the quasi-static mechanical tests were performed. The absence of these injuries was confirmed during muscle bisection following the mechanical testing, as shown by the lack of solidified capsule in any test in Figure 3B. Across all survival periods, the tissue appeared to follow the recovery trend shown in Figure 3, but the lack of granularity of end points between 12- and 30-days hides some of the contusion mechanics. By the end of the 30-day survival period, only a small contusion remained within the muscle with nearly complete recovery from initial injury.

In contrast, impacts greater than 230 J caused more extensive and persistent muscle injury. Stiffness remained elevated through 30 days, and healing was incomplete. Scarring at the impact site and deeper muscle contusions indicated more severe tissue disruption. These injuries likely damaged muscle fibers beyond the threshold for rapid repair, resulting in structural changes that could impair function. The observed skin scarring further suggests a traumatic impact, and the extent of damage does not bode well for recovery of the underlying muscle tissue.

While quasi-static compression of excised muscle is not a standard clinical tool, previous studies have used unconfined compression tests on muscle to assess its properties by using small, excised samples [28-30]. The approach used in this study, while qualitative, complements these methods by providing mechanical variation of the tissue's state, allowing correlation between tactile stiffness and structural injury, particularly when imaging is not feasible or when evaluating internal mechanical properties directly. Used as palpation analogs, quasi-static tests can help assess whether muscle is healing or if deeper damage, like edema or necrosis, is present. By combining tactile stiffness data with visual cues, researchers can estimate injury severity and recovery trajectory. However, this method cannot directly measure internal pathology. As shown in Table 3, while injuries are often obvious on day 1, they become more difficult to evaluate by day 5 and beyond without invasive or imaging-based confirmation.

Muscle samples from short survival periods after high-energy impacts exhibited large contusions, swelling, and necrosis. Dissections at 1 and 5 days post-injury revealed disorganized, blackened necrotic tissue, and edema pockets. These injuries were not found at lower energy levels or beyond day 5, indicating early onset and resolution of acute tissue death. The edema was often encased in a hardened capsule distinct from surrounding tissue and sometimes contained pus, suggesting localized infection. Without histological analysis, the composition of this capsule remains speculative, but its tactile and visual differences imply a pathological response.

Specimens with longer survival times showed unorganized regrowth around the contusion zone. Muscle fiber misalignment was especially apparent near the injury site and contrasted with the more uniform structure of distal muscle fibers. This disorganization, often indicated by tan discoloration (Figure 3B), likely corresponds to active tissue remodeling and capsule removal. Bisecting these muscles showed poor integration between new and existing fibers, suggesting a lack of structural continuity. Such misalignment could limit muscle contractility or strength and may contribute to longer recovery timelines. Imaging tools like ultrasound could help verify these findings in vivo.

The highest energy impact of 338.20 J resulted in the specimen heavily favoring the contralateral leg, resisting use of the impacted leg for support, and requiring additional Buprenorphine days after the impact. This condition persisted for nearly the entire survival period of 8 days with symptoms appearing after the first day. The inability for this porcine specimen to articulate the impacted hind leg and the accompanying symptoms met the humane endpoint criteria within the protocol. This was not the desired outcome from this specimen as it was intended to survive for 12 days post-impact. This result indicates that this energy level should be treated as an upper bound for allowable energy transfer.

By day 30, visible contusions on the skin had resolved for the highest energy impacts, but significant internal scarring remained. This scarring suggests deeper tissue damage not visible externally. Although muscle did not show overt fibrosis, persistent contusions imply that healing was incomplete. Even without visible scarring, disrupted fibers and prior necrosis could result in lasting structural or functional impairment. These effects may manifest as reduced strength, flexibility, or coordination in affected regions.

The absence of visible muscle damage does not guarantee full recovery. High-energy impacts may trigger maladaptive healing responses, such as fibrosis, which can alter normal muscle architecture. Given the observed skin scarring, it is plausible that similar structural changes also occurred within the muscle, even if they were less obvious. For individuals exposed to repeated high-energy impacts, these internal alterations could lead to chronic muscle damage, limited mobility, or higher injury susceptibility. Although live porcine models offer significant insight into muscular injury and recovery, they have limitations when extrapolating to human function.

Since live porcine specimens lack the ability to replicate such complex, task-specific behaviors, they limit our understanding of how muscular injuries truly impact functional performance in human daily life or work environments. Although there were occasional signs of favoring the contralateral side, the animals generally exhibited minimal outward signs of distress, even in the presence of significant leg swelling. This lack of observable discomfort and task performance capabilities in the porcine model underscores the challenge of correlating mechanical damage to pain perception in animals with that which a human might experience. This highlights the need for further research to better understand how these injuries affect the animal's functional capacity and how that might be extrapolated to human models.

5. CONCLUSION

This study created a methodology for studying the progression of soft tissue contusion healing in live porcine specimens as a surrogate model for humans. Visual inspection of the impact location indicated that skin contusions across all energy levels tested would heal by 30 days post impact. In all tests, contusions in the muscle were observed even after there was no contusion in the skin. However, some of the high energy impacts resulted in scarring in the skin after the contusion healed within the skin. The highest energy impacts still had muscle contusion after the 30-day survival period, indicating a longer recovery period for complete healing. Scar tissue formation in the skin is an injury that was not an intended consequence of this study but illuminates the potential complications of severe BABT impacts. Since no porcine survived longer than one month post impact, it is unclear whether there would also be permanent changes in the underlying musculature. It should be noted that these injuries should have healed at some point after one month, but this study did not elect to study these injuries beyond one month.

In the event of a BABT injury, contusions in the skin that healed within one week of impact should expect the muscle contusions to be healed within two to three weeks of impact. Skin contusions that last at least two weeks after the impact substantially reduce the likelihood of the muscle contusion healing within one month. Since skin contusions healed before the muscle contusions in this study, visual inspection cannot be used independently of another diagnostic measure to assess injury. Quasi-static mechanical testing of excised muscle tissue offers a promising approach to quantify BABT induced muscle contusions and their healing processes. The combination of palpation and visual inspection of the impact site is a good preliminary indicator of the severity of injury within the soft tissues.

However, the lack of complex, task-specific behavior in the porcine model restricts the direct comparison to human recovery, emphasizing the need for further studies that bridge this gap to better predict functional outcomes following muscle injuries in humans. Further studies, particularly those involving imaging and long-term monitoring, will help refine the quantification of recovery from muscle injury. Overall, this research provides essential information on the mechanical properties and recovery dynamics of muscle tissue following impact, offering a foundation for future studies aimed at improving injury management and rehabilitation strategies, particularly for high-energy impacts.

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