Development of a physical human thorax surrogate dedicated to blunt ballistic impacts

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Abstract. In the field of biomechanics, conducting experimental setups on cadavers can be challenging due to ethical constraints. To overcome this issue, physical or numerical surrogates can be used. In the case of blunt ballistics, numerical surrogates have gained significant interest as they aid in designing ballistic protections. However, the characterisation and modelling of body armour remains difficult which is why physical surrogates are sometimes preferred. In this study, the authors propose the development of a physical human thorax surrogate, named SurHUByx, dedicated to injury risk prediction in blunt ballistic impacts, such as those from Less Lethal Projectiles or bullets hitting armour. The surrogate is based on the geometry of the existing numerical model HUByx, which was validated against numerous impacts. In order to build the physical surrogate, a simplified finite element model called SurHUByx FEM was used. Replication of experimental reference cases conducted on Post Mortem Human Subjects validated this simplified FE model. Once validated, SurHUByx FEM was used as a basis to build SurHUByx, its physical twin. Once built, the physical surrogate was compared with the well-known test of Bir et al., the surrogate global behaviour of the surrogate was validated. The physical surrogate was then equipped with sensors inside internal organs and on ribs to capture local data during impact cases with Less Lethal projectiles and firearms and armour. Injury risk prediction curves were constructed based on the data obtained from the sensors and these curves can now help in injury prediction.

1. INTRODUCTION

Optimisation has become a crucial aspect of developing new technologies, especially in the field of safety and protection. The optimisation of protective devices like body armour can enhance the performance of police officers and soldiers while reducing their weight. In addition, the development of new less-lethal kinetic energy weapons requires a thorough understanding of the human thorax behaviour under blunt impact to ensure both non-lethality and sufficient stopping power. However, conducting experiments on humans or cadavers is difficult due to strict ethical guidelines. As a result, researchers have developed surrogates to mimic the human thorax behaviour behind armour or a Less Lethal Kinetic Energy (LLKE) weapon. There are two types of surrogates: numerical and physical ones. Recently, biofidelic Finite Element models such as HUByx (Hermaphrodite Universal Body YX) [1, 2] [1, 2, 3], SHTIM (Surrogate Human Thorax for Impact Model) [4], and WALT (Waterloo Thorax Model) [5] have gained popularity when studying blunt ballistic impacts. However, the difficulty in developing these models lies in the characterisation and numerical modelling of body armour. Therefore, physical surrogates are sometimes favoured to evaluate the effectiveness of armour. However, so far, only clay has been approved by the NIJ standard [6]. Other materials like 10% or 20% ballistic gelatin, Permagel, ballistic soap, Roma Plastilina No. 1 clay, or styrene-ethylene-butylene-styrene (SEBS) based-gel have also been used, but these surrogates are in the form of a cubic block [7]. Anthropomorphic human surrogates such as Ausman (Bass C. , et al., 2006), SSO (Skin-Skeleton-Organs) [9], MHS (Modular Human Surrogate) [10], HSTM (Human Surrogate Torso Model) [11], and BTTR (Blunt Trauma Torso Rig) (Bolduc & Anctil, Improved Test Methods for Better Protection, a BABT Protocol Proposal fo STANAG 2920, 2010) have been developed, but only a few physical surrogates are consistent with ballistic biomechanical corridors. Moreover, physical surrogates which do not include internal organs can only provide global data.

To create a more detailed human torso model, Roberts et al. proposed a reverse engineering method using a biofidelic numerical model called HTFEM (Human Torso Finite Element Model) to develop a biofidelic physical surrogate of the human thorax HSTM (Human Surrogate Torso Model)

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[13]. This method was interesting and enabled them to build numerical and physical twins but neither the initial FE model biofidelity nor the physical surrogate was checked. To overcome this limitation, the authors proposed a reverse engineering method using a biofidelic numerical surrogate as a reference (HUByx) to build a biofidelic physical surrogate of the human thorax called SurHUByx (Surrogate HUByx).

This study proposed the creation of a physical surrogate using a reverse engineering method. Once created and validated, this physical surrogate was used to replicate field impact cases to plot injury risk prediction curves.

First the SurHUByx FEM model was developed by simplifying the HUByx model and combining the cortical and trabecular parts of bones and cartilage into a single entity [14]. The spine was modelled as a single part, and only the essential organs such as lungs, heart, liver, and spleen were included. The consistency of its behaviour in terms of force and deflection over time within the established corridors was evaluated using Bir et al. experiments as a reference (Bir, Viano, & King, 2004). The anthropometry of SurHUByx FEM was consistent with a 50th percentile, indicating its potential as a basis for building a physical surrogate. Secondly, the study described the construction of the physical surrogate SurHUByx. Comparisons of its behaviour to Bir et al. experiments and corridors were conducted to assess its biofidelity and validate it for protection assessments. Finally, sensors were added to record more local data inside internal organs and on ribs. Cadaver and field impact cases were replicated with the physical surrogate and injury risk prediction curves were built for lungs, heart, and ribs based on the replications.

2. MATERIAL AND METHODS

The HUByx FEM was used as a reference to create a simplified biofidelic numerical surrogate (SurHUByx FEM) which will be used to create its physical twin named SurHUByx. Subsequently, SurHUByx FEM was used to create SurHUByx. SurHUByx was then compared to Bir et al. corridors. Once validated, it was used to construct injury risk functions using locally recorded data. The entire process is outlined in Figure 1 and described in detail in the relevant sections.

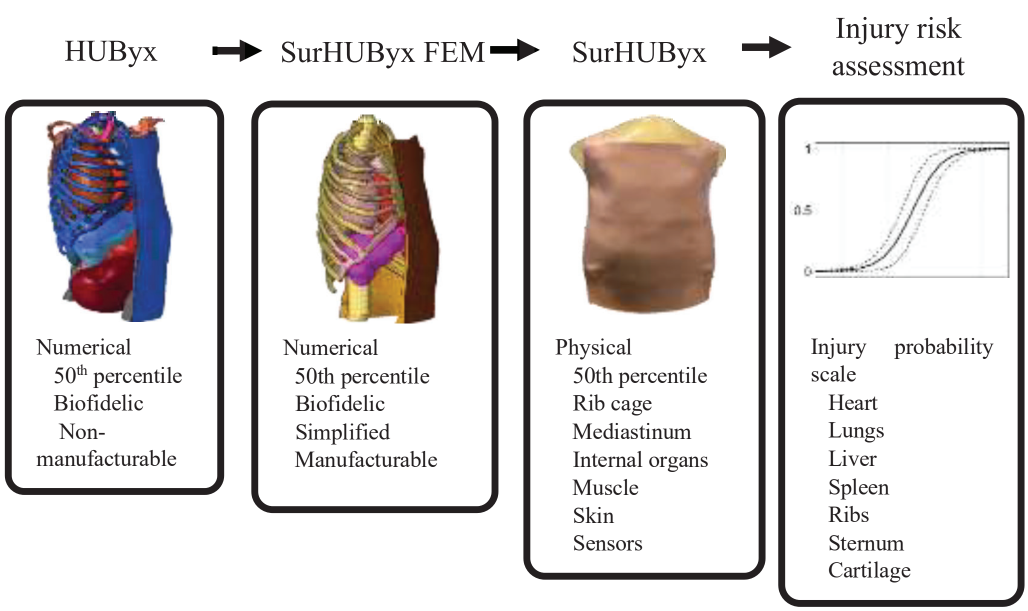

Figure 111. Reverse engineering procedure: from finite element model to its physical twin

2.1 SurHUByx FEM creation and validation process

2.1.1 Creation and simplifications

The HUByx model was used as a basis to develop SurHUByx, but due to its complexity, a simplified FE model was necessary. This simplified model was based on the removal of undesired components and geometrical simplifications. Concerning internal organs, only heart, lungs, liver and spleen were kept.

All the vertebrae were assembled as a continuous part representing the spine. In addition to these parts, SurHUByx was made of skin, muscle mediastinum and rib cage. Fat was made from muscle which resulted in a softer muscle.

Concerning the rib cage in the HUByx model the bones and cartilages were modelled using cortical and trabecular parts, which were unified in SurHUByx through an equivalence in terms of bending stiffness. This merged the cortical and trabecular parts of bones and cartilage and computed their equivalent properties.

To ensure that the physical surrogate could be built using readily available materials on the market, the material laws used in the simplified FE model needed to accurately represent the behaviour of those materials that can be feasibly manufactured. To that aim, a reverse engineering method was used. First, readily available material was mechanically tested. Then, its response was analysed and its properties computed. If this tested material had similar properties to the initial material implemented in the FE model, the properties of this manufacturable material were used to replace the initial ones in the simplified FEM. If the properties of the tested manufacturable material did not match with the initial properties, harder or softer materials were tested.

By using this method to find a surrogate for bones, the authors found that the ideal material can match either the desired Young modulus or the strain to failure. In order to avoid early bone fractures, the authors decided to use a polyurethane resin for the surrogate bones material, since it had the relevant strain to failure. In order to have consistent structure using this material, an equivalence in bending stiffness (EI), with E the Young modulus and I the moment of inertia, was conducted. The unknown was the diameter of the equivalent structure. This equivalence was performed for each rib, varying the increase of cross section along the ribcage. This material behaviour was modelled using an elasto-plastic tabulated law.

This increase in cross section resulted in a reduction of intercostal space, but previous impact case replications showed that this space was necessary to accurately represent the human thorax behaviour in case of intercostal bullet [16]. Therefore, the height of the surrogate was increased to maintain the same intercostal space. The change in ribs cross section also impacted the cartilage cross sections and material properties. Ultimately, an elastomeric resin was found to be a suitable substitute for cartilage, which was implemented in the code using an elastic law.

The Hybrid III crash test dummy vinyl skin was identified as a suitable material to simulate human skin [17]. For the internal organs, muscle, and mediastinum, a gel made of Styrene-Ethylene-Butylene-Styrene (SEBS) material was used in different concentrations. This gel has various advantages, including mechanical consistency and transparency [18, 19]. SEBS based-gel used for the internal organs were previously characterised for their hyper viscoelastic behaviour by Bracq et al. [20]. To simplify the implementation of SEBS based-gel used for muscle and mediastinum, they were modelled using an elastic law.

After its creation, the anthropometry of the SurHUByx FEM was compared to that of a 50th percentile human. The comparison revealed that the SurHUByx FEM anthropometry is similar to that of a 50th percentile male human, making it possible to validate the global behaviour of SurHUByx FEM using Bir et al. impacts.

2.1.2 Validation process

The authors aimed to compare the behaviour of their model with established biomechanical corridors by replicating the impacts performed by Bir et al. (Bir, Viano, & King, 2004). In Bir et al. study, thirteen Post Mortem Human Subjects (PMHS) were impacted with various projectiles at different speeds over the mid sternum. The impacts were categorised into three conditions: Case A (140g projectile at 20 m/s), Case B (140g projectile at 40m/s), and Case C (30g projectile at 60m/s). These tests helped establish biomechanical corridors. The authors numerically replicated these impact cases by applying an initial velocity to the impactor that struck the SurHUByx FEM in a similar manner to the experimental tests. By recreating these impact cases, the authors compared the force time, displacement time curves and VCmax (maximal viscous criterion) values between their numerical model and the biomechanical corridors.

2.2 SurHUByx construction and validation process

2.2.1 Fabrication process

The surfaces of the SurHUByx FEM mesh were used to construct the SurHUByx geometry, which was then imported into a computer-aided design (CAD) software. All components and junctions between the

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parts were modelled using the CAD model. The junctions between the ribs/cartilage and cartilage/sternum were held together by a mortise and tenon system and glue. The spine was perforated to allow the insertion of the ribs, which were secured with small axes to allow for natural breathing movement. The mediastinum was designed with shaped holes to accommodate the organs and divided into two parts to facilitate insertion. The intercostal muscles were embedded in the surrogate muscle and mediastinum, while the skin was tightly fitted around the muscle. CATIA V5 software was used to create the CAD model for the surrogate.

After the CAD model was finalised, the CAD modelling of moulds began. Various moulding processes were used. Silicon moulds were used to create the bone parts, while moulds for the cartilage were directly printed in 3D using Polylactic Acid (PLA). High Temperature Polyamide reinforced with carbon fiber (PAHT CF15) was used to 3D print moulds for the muscle, mediastinum and internal organs as this material could withstand high temperatures during the mould casting process. Moulds for bones, costal cartilages, spleen and one part of the mediastinum are presented in Figure 112.

(a) (b) (c) (d)

Figure 112. Silicon moulds for bones (a), PLA moulds for costal cartilages (b), PAHT CF15 moulds for spleen and mediastinum (c and d)

All the parts were then moulded and assembled together. Figure 113 depicts the different stages of the SurHUByx FEM (a), CAD model (b), assembled surrogate (c), surrogate without skin (d), and surrogate without muscle (e). Once the surrogate was assembled, it was submitted to Bir et al. impacts to determine the thoracic wall displacement and compare it to biomechanical corridors, similar to the SurHUByx FEM.

(a) (b) (c) (d) (e)

Figure 113. SurHUByx FEM (a), SurHUByx CAD model (b), SurHUByx (c), SurHUByx without skin (d) and SurHUByx without muscle (e)

2.2.2 Impact cases replication for global behaviour validation

In order to assess the physical surrogate similarity to human biomechanics, the Bir et al. tests were replicated by the authors (Bir, Viano, & King, 2004). They ensured similar conditions, such as launching projectiles with pneumatic launchers at a specific speed, and positioned the SurHUByx on an inclined surface to ensure direct anterior impact level with the 8th thoracic vertebrae. The skin was removed to accurately adjust the impact location (Figure 114a), and a distance of 50 cm was maintained between the launcher and surrogate (Figure 114b). For cases A and B, a 140 g projectile (including sabot projectile and rings) that was 100 mm long and 36.5 mm in diameter was used. The projectile for case C was 30 g (including tracking rod), 28.5 mm long (without the tracking rod) and 36.5 mm in diameter. The projectiles were made of Rubber Baton L5A7 (Pains Wessex Schermuly (UK)) (Figure 114c). Guide rings were utilised to control the speed of projectiles, and a lateral camera at 22000 fps recorded images to track the projectile displacement and record data. Once the contact between the projectile and the dummy ended, the tracking was stopped. The comparison between the cadavers, SurHUByx, and SurHUByx FEM responses included analysing force-time, deflection-time curves, and VCmax values over the three impact conditions.

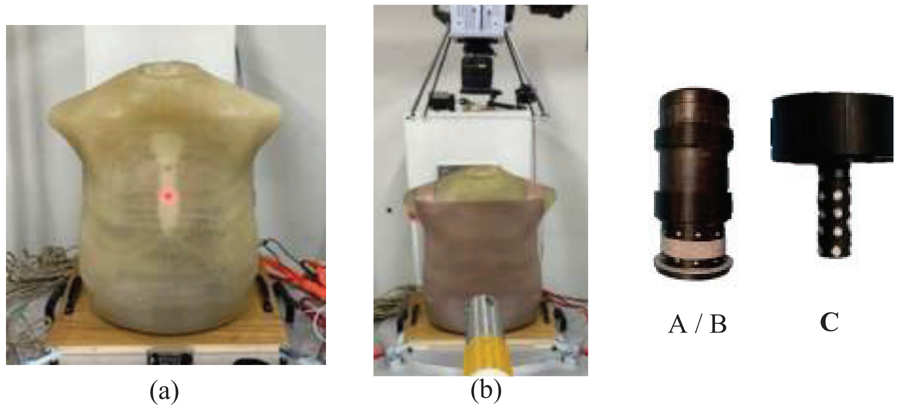

Figure 114. Point of impact (a), experimental setup (b), projectiles (c)

2.2.3 Inclusion of sensors and acquisition channels

After validating the overall performance of the surrogate, the authors aimed to obtain more detailed data by strategically placing sensors inside organs and on ribs.

For internal organs, Interlink Electronics® FSR sensors were used and positioned to record frontal events data. These sensors were placed in the center of the lungs, heart, liver, and spleen and were powered by a 5V current generator. The data were captured at 1 MHz by a YOKOGAWA DL750 (1).

For ribs, strain gauges were placed on critical areas of the rib bones to allow for up to 3% strain, consistent with the material properties used to build the bone surrogate. Ribs 1 to 8 were instrumented with 1 to 3 strain gauges, for a total of 30 gauges placed on the surrogate ribs. The strain gauges were mounted with quarter Wheatstone bridges and data were recorded by another YOKOGAWA DL750 (2) at 1 MHz. Due to the limited number of ports available on the YOKOGAWA, only 15 gauges could be connected at a time. As a result, only the 15 closest strain gauges to the impact location were connected. Figure 115 illustrates the placement of the sensors and a schematic representation of the acquisition system.

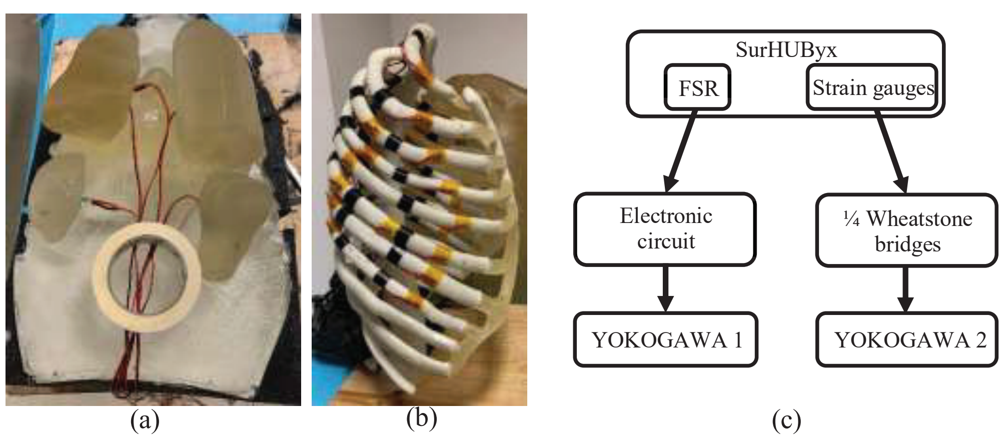

Figure 115. FSR Sensors embedded in organs (a), strain gauges (b) and acquisition system (c)

2.2.4 Impact cases replication for injury prediction

To correlate the captured data with injury assessment, the authors conducted experiments using LLKE weapons with five impact cases. Three of these cases were taken from Bir et al. study on cadavers (Bir, Viano, & King, 2004), while the remaining two were extracted from case reports by Kobayashi and Mellen [16], and Wahl et al. [21]. Eight cases involving firearms and armour were also extracted from case reports established by Riffault [22, 23]. The ammunition used in these cases ranged from 9mm to

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18.5mm, at velocity range from 245 m/s to 410m/s and various soft armours using Kevlar® were used as protection.

To replicate the impact cases from Bir et al., similar conditions were used as described in the study, such as shooting range and impact location. For the other two impacts with Less Lethal Weapons, the projectiles were launched using their respective weapons, Flash-Ball® and Brugger & Thomet®.

For the replication of firearm cases, a universal ballistic breech and barrels of different lengths and diameters were used to fire various projectiles at the desired speeds. Before each impact, a calibration shot was performed to ensure that the projectile was launched at the desired speed, and the bore sight was checked. The projectile speeds were measured 2 m before the impact using a HPI Doppler radar. The replication cases were validated when both the impact location and the desired speed matched with the case report. The projectiles and armours used were equivalent to the ones described in Riffault reports.

Table 32 provides an overview of the replicated cases and their corresponding AIS scores. The report of the experimental study did not specify the organ on which the AIS score was established. Impacts were replicated from the softer to the harder ones, and a total check of the surrogate was conducted between each impact to ensure its physical integrity. If any damage was detected on the SurHUByx, the necessary repairs were carried out to enable the experimental tests to continue.

Table 32 Case report details

Case	Projectile	Impact velocity [m/s]	Body armour	AIS
Bir A	37 mm – 140 g	20	-	0
Bir B	37 mm – 140 g	40	-	2
Bir C	37 mm – 30 g	60	-	0
Kobayashi	eXact iMpact	95	-	3
Wahl	Flash Ball	110	-	3
260-2	9 mm	380	16 layers	3
261	9 mm	380	16 layers	2
263	Brenneke	360	20 layers	4
264-2	Brenneke	385	2 * 16 layers	3
279	9 mm	380	10 layers	1
283	Brenneke	410	20 layers	4
287	9 mm	370	20 layers	1
289	9 mm	370	20 layers	3

3. RESULTS

3.1 Global behaviour

The thoracic displacement of SurHUByx FEM and SurHUByx were compared to biomechanical corridors for the three impact conditions, and the results are illustrated in Figure 116 and Figure 117. The parameter VCmax was also calculated, and the results were compared to cadaveric experiments as illustrated in Figure 118. SurHUByx FEM produced displacement time curves and force time curves that were consistent with Bir et al. corridors for all three impact cases. VCmax values for SurHUByx FEM were also consistent with experimental range values obtained by Bir et al. Similarities of results obtained between SurHUByx and HUByx validated the whole simplification procedure.

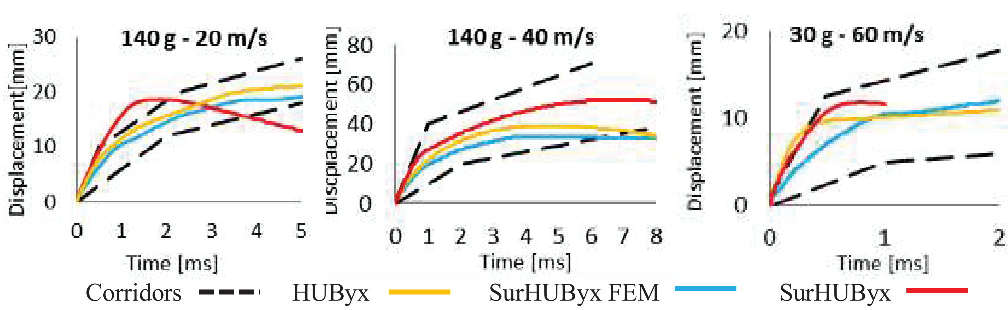

Figure 116. Displacement/time curves for the three impact cases (A, B and C)

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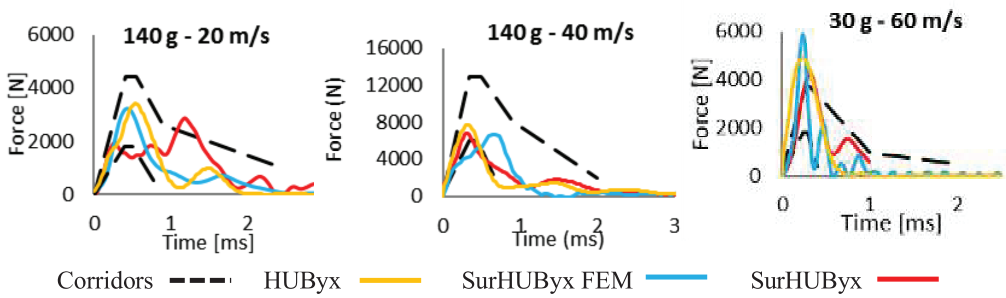
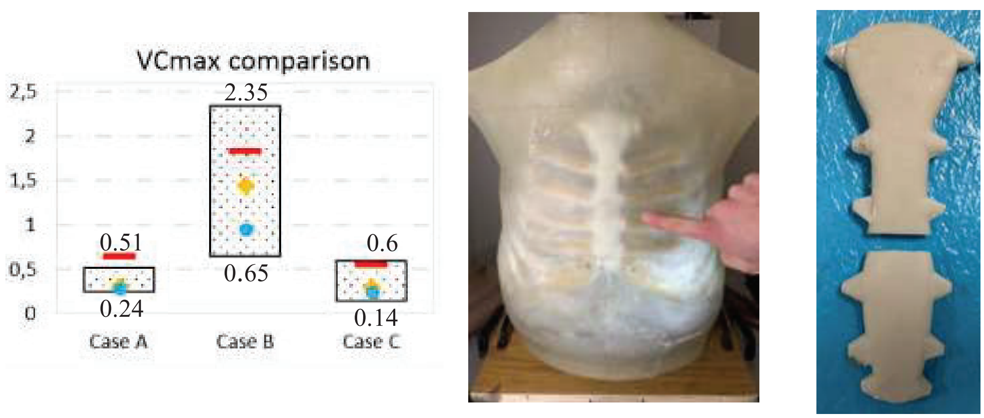


Figure 117. Force/time curves for the three impact cases (A, B and C)

The tracking method used in the experimental study produced results that were consistent with corridors for all three impact cases, with SurHUByx generally in the upper part of the displacement/time corridors for cases A and C, and in the middle of the corridor for case B. SurHUByx was in the lower part of the force/time corridors for cases A and B and in the upper part for case C. VCmax values for SurHUByx were also consistent with experimental range values reported by Bir et al. (Figure 118 left). Sternal fracture was observed on SurHUByx for case B only (Figure 118 middle and left), which is consistent with observations on cadavers. These results validated the SurHUByx behaviour in terms of global



response.

Figure 118. VCmax comparisons between cadaveric experiments, HUByx, SurHUByx FEM and SurHUByx (left) and fracture pattern over the sternum for case B: with muscle (middle), sternum only (right)

3.2 Injury prediction

Once the overall behaviour of SurHUByx was validated, the local behaviour was assessed by collecting data from 13 impact cases. It is worth noting that SurHUByx ribs did not break in any of the experiments, but if the human subject suffered from sternal or cartilage rupture, SurHUByx also exhibited sternal fracture or cartilage rupture. The strain gauge data showed that when no injury was present, small amplitude curves were observed, as depicted in Figure 9 (a). In contrast, when a fracture occurred, the

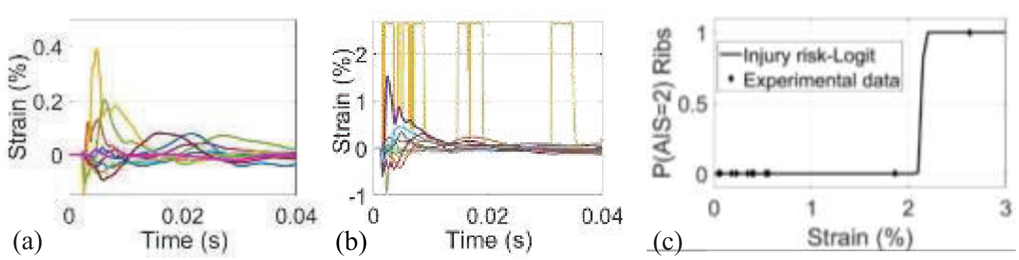


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Figure 119. Typical curves obtained from strain gauges: no injury (a), injury (b), Injury risk function AIS=2 ribs (c)

curves showed higher amplitudes, and at least one strain gauge saturated at 2.63%, as illustrated in Figure 9 (b). The maximum value of all the connected strain gauges was used to build a logistic regression. This logistic regression was built using the LOGIT model and represents the probability of an AIS score of 2 on ribs Figure 9 (c). The prediction bounds were not defined with the actual data.

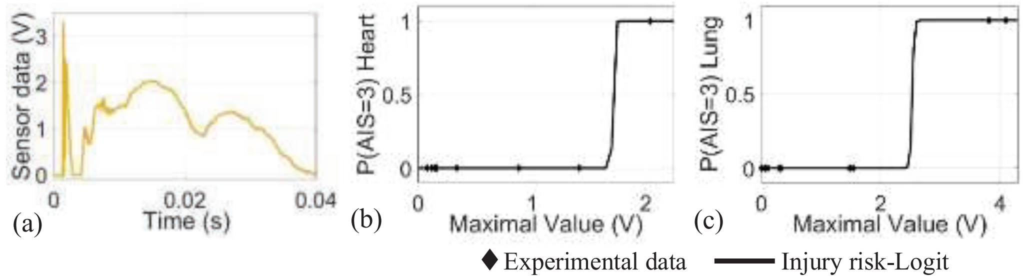

Figure 120. Typical curves obtained from FSR sensors (a), Injury risk function AIS=3 for heart (b) and lung (c)

The FSR sensors showed similar curves for all the internal organs, as seen in Figure 120 (a). These curves had two phases, with the first phase a quick and intense peak, and the second phase longer but with less amplitude. Both phases provided consistent information. For both lungs and heart, the maximum value of the sensors in the second phase was used to build the logistic regression. Injury prediction curves for an AIS score of 3 on the heart and lungs were developed and shown in Figure 120 (b and c). The prediction bounds were not defined with the actual data. Data were also recorded for the spleen and liver, but since no injury was reported, no injury curve could be plotted. There was no indication of sensor saturation in any of these organs.

4. DISCUSSION

Numerical models are often used in mechanics to replicate physical phenomena through simulations [24, 25]. The traditional approach involves creating a model to predict the behaviour and then validating it with physical experiments. This study proposes a reverse engineering method: the creation of a biofidelic numerical model, which is used to select manufacturable materials with the desired behaviour, to build a physical surrogate. A similar approach was used by Roberts et al. to develop HSTM and HTFEM [13], but these models have not been validated against animal or cadaveric data. That is why this study uses the HUByx model as a reference, which represents a 50th percentile human thorax, and which was validated regarding various impact cases [1, 3]. In order to address the wide range of variations in human morphology and response to loading, the study used biomechanical corridors as a validation method, which is a common practice in the biomechanical field. To validate a numerical model its response is generally required to fall within the experimental corridors.

The validation approach suggested in this research relies solely on cadaver tests. An alternative method to assess the performance of surrogates is through live animal experiments. These two approaches are considered complementary: while PMHS provide the closest resemblance in terms of morphology (Bir, Viano, & King, 2004), pigs are better at replicating pathophysiological responses [26] but validation using live animal models introduces additional complexity and relying solely on single biomechanical injury metrics may not provide a comprehensive solution. The physiology of live animal models is a highly complex system with numerous interrelationships and dependencies, and relying solely on a simple and easily measured metric may not capture the full range of outcomes accurately. Previous research has compared the results of ballistic impact experiments using PMHS and pigs [27]. Recent study compared the behaviour of PMHS and both living and dead pigs in a ballistic setting (Bourget D. , 2020).

In this study, the simplified finite element model of the human thorax, SurHUByx FEM, was compared to experimental data obtained on PMHS to ensure that its behaviour was consistent with established biomechanical corridors (Bir, Viano, & King, 2004). The validated SurHUByx FEM was then used to create its physical twin, SurHUByx, which was also validated against the same experimental corridors. The results showed that both the numerical and physical surrogates had a consistent mechanical response to the experimental data in terms of force time, displacement time curves and VCmax values. However, because each human behaviour is different, biomechanical corridors were used to evaluate the models and no conclusion can be drawn regarding which model has a closer dynamic response to the human body. Nevertheless both of these FE models can be enhanced in terms of biofidelity.

After validation, SurHUByx was used to replicate impact cases and create injury probability risk functions based on data from local sensors embedded in the physical surrogate. The replication cases showed that SurHUByx could record local data which could be linked to a probability of injury. The creation of the injury probability curves relay on statistics as it is recommended by McMurry et al. [29]. However, it is important to use the probability curves with caution because only a few impact cases were replicated. The non-definition of the 95% prediction bounds of the injury risk curves confirms this limitation. To build accurate probability injury risk functions, a large amount of experimental data is needed, as shown in a previous study [30].

To improve the probability injury risk function developed in this study, further research is needed to find and replicate impact cases. Once enough cases are replicated, these curves could be used to assess protection using local information without the need for living animals or cadavers. Currently, sensors embedded in the surrogate can be used to compare different body armour systems using local data. Future research could focus on developing a way to measure the VC response without affecting the surrogate behaviour. In addition, creating twin surrogates dedicated to blunt ballistic impacts for various anthropometry, as in the crashworthiness field, could also be pursued.

5. CONCLUSION

A simplified version of the HUByx model, a biofidelic finite element model of the human thorax, was created by simplifying its structure to form SurHUByx FEM. The reverse engineering method was used to find manufacturable materials available in the industry with consistent properties to the initial ones, and their corresponding material laws were implemented in the code. The SurHUByx FEM behaviour was validated by numerically replicating cadaveric impact cases. The geometry and materials of SurHUByx FEM were used to create SurHUByx, its physical twin, which was then compared to the Bir et al. biomechanical corridors. The results showed good agreement with cadaveric experiments in terms of sternal force, displacement, and VCmax values, thereby validating SurHUByx. Local sensors were included in the surrogate internal organs and ribs, and impact cases involving less lethal weapons and firearms with soft armours were replicated. Injury reports and recorded data were used to construct injury risk functions for the heart, lungs, and ribs. While this study validated the method used to build SurHUByx and proved its ability to predict injuries, additional impact cases need to be recreated to enhance the accuracy of the probability injury risk functions.

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References

[1] S. Roth, F. Torres, P. Feuerstein and K. Thoral-Pierre., «Anthropometric Dependence of the Response of a Thorax FE Model under High Speed Loading: Validation and Real World Accident Replication» Computer Methods and Programs in Biomedicine, vol. 110, n° 12, pp. 160-170, 2013.

[2] M. Chaufer, R. Delille, B. Bourel, C. Marechal, F. Lauro, O. Mauzac and S. Roth., «Enhancement of a Human Thoracic FE Model for Blunt Impact and Related Trauma» Computer Methods in Biomechanics and Biomedical Engineering, vol. 24:sup1, pp. 310-311, 2021.

[3] A. Bracq, R. Delille, B. Bourel, C. Maréchal, G. Haugou, F. Lauro, S. Roth and O. Mauzac., «Numerical Recreation of Field Cases on a Biofidelic Human FE Model Involving Deformable Less-Lethal Projectiles» Human Factors and Mechanical Engineering for Defense and Safety, 2019.

[4] N. Nsiampa, «Development of a Thorax Finite Element Model for Thoracic Injury Assessment» 8 th LS-DYNA User Conference, 2011.

[5] D. S. Cronin, M. C. Bustamante, J. Barker, D. Singh, K. A. Rafaels and C. Bir, «Assessment of Thorax Finite Element Model Response for Behind Armor Blunt Trauma Impact Loading Using an Epidemiological Database» Journal of Biomechanical Engineering, vol. 143, n° 13, 2021.

[6] National Institute of Justice, «Ballistic Resistance of Body Armor NIJ Standard-0101.06» 2008.

https://doi.org/10.52202/080042-0041

[7] J. Read, R. Hazael and R. Critchley, «Soft Tissue Simulants for Survivability Assessment - A Sustainability Focussed Review» Applied sciences, vol. 12, n° 14954, p. 14, 2022.
[8] C. R. Bass, R. S. Salzar, S. R. Lucas, M. Davis, L. Donnellan, B. Folk, E. Sanderson and S. Waclawik, «Injury Risk in Behind Armor Blunt Thoracic Trauma» International Journal of Occupational Safety and Ergonomics, vol. 12, n° 14, 2006.
[9] Y. Wenmin, X. Yao, Y. Wang, Y. Jin and W. Wei, «Experimental Study of the Mechanical Response of a Physical Human Surrogate Thoracic Model Impacted by a Rubber Ball» Journal of Physics, vol. Conf. Ser. 1507, n° 1102032, 2020.
[10] K. Sedberry and S. Foley, «Modular Human Surrogate for Non-Lethal Weapons (NLW) Testing» DSIAC Journal, vol. 6, n° 11, 2019.
[11] P. Biermann, E. Ward, R. Cain, B. Carkhuff, A. Merkle and J. Roberts, «Development of a physical Human Surrogate Torso Model (HSTM) for ballistic impact and blast» Journal of Advanced Materials, vol. 38, n° 11, pp. 3-12, 2006.
[12] M. Bolduc and B. Anctil, «Improved Test Methods for Better Protection, a BABT Protocol Proposal fo STANAG 2920» chez Proc Personal Armour System Symp, 2010.
[13] J. C. Roberts, A. C. Merkle, P. Biermann, E. E. Ward, B. Carkhuff, R. Cain and J. V. O'Connor, «Computational and experimental models of the human torso for non-penetrating ballistic impact» Journal of Biomechanics, n° 140, pp. 125-136, 2007.
[14] M. Chaufer, R. Delille, B. Bourel, C. Marechal, F. Lauro, O. Mauzac and S. Roth, «Development of a simplified human thoracic FE model for blunt impact and related trauma» chez 27th Congress of the European Society of Biomechanics, Porto, 2022.
[15] C. Bir, D. Viano and A. King, «Development of Biomechanical Response Corridors of the Thorax to Blunt Ballistic Impacts» Journal of Biomechanics, vol. 37, pp. 73-79, 2004.
[16] M. Kobayashi and P. F. Mellen, «Rubber Bullet Injury Case Report With Autopsy Observation and Literature Review» Forensic Med Pathol, vol. 30, n° 13, pp. 262-267, 2009.
[17] W. Wood Garrett, M. B. Panzer, C. R. Bass and B. S. Myers, «Viscoelastic Properties of Hybrid III Head Skin» SAE International Journal of Materials and Manufacturing, vol. 3, n° 11, pp. 186-193, 2010.
[18] R. A. Mrozek, B. Leighliter, C. S. Gold, I. R. Beringer, J. H. Yu, M. R. VanLandingham, P. Moy, M. H. Foster and J. L. Lenhart., «The Relationship between Mechanical Properties and Ballistic Penetration Depth in a Viscoelastic Gel» Journal of the Mechanical Behavior of Biomedical Materials, vol. 44, pp. 109-120, 2015.
[19] O. Mauzac, C. Paquier, E. Debord, F. Barbillon, P. Mabire and J. Jacquet, «A substitute of gelatin for the measurement of dynamic back face deformation» chez Personal armour systems symposium, Quebec, Canada, 2010.
[20] A. Bracq, G. Haugou, B. Bourel, C. Maréchal, F. Lauro, S. Roth and O. Mauzac., «On the Modeling of a Visco-Hyperelastic Polymer Gel under Blunt Ballistic Impacts» International Journal of Impact Engineering, n° 1118, pp. 78-90, 2018.
[21] P. Wahl, N. Schreyer and B. Yersin, «Injury Pattern of the Flash-Ball, A less-lethal weapon used for law enforcement: report of two cases and review of the literature» The Journal of Emergency Medicine, vol. 31, n° 13, pp. 325-330, 2006.
[22] E. Riffault, «Etude des traumatismes dus à l'impact de balles» Ministère de l'intérieur, Direction générale de la police nationale, Direction de la logistique de la police, Paris, France, 1983.
[23] «Lésions par balles avec et sans dispositif de protection» Contrat I.R.O. - D.R.E.T. 80715, 1984.
[24] M. Giglio, A. Manes and A. Gilioli, «Investigations on sandwich core properties through an experimental–numerical approach» Composites: Part B, vol. 43, n° 12, pp. 361-374, 2012.
[25] T. Kanehira, H. Mutsuda, S. Draycott, N. Taniguchi, T. Nakashima, Y. Doi and D. Ingram, «Numerical re-creation of multi-directional waves in a circular basin using a particle based method» Ocean Engineering, vol. 209, n° 1107446, 2020.
[26] N. Prat, F. Rongieras, E. Voiglio, P. Magnan, C. Destombe, E. Debord, F. Barbillon, T. Fusai and J. Sarron, «Intrathoracic pressure impulse predicts pulmonary contusion volume in ballistic blunt thoracic trauma» The Journal of Trauma, n° 169, pp. 749-755, 2010.
[27] N. Prat, F. Rongieras, H. d. Freminville, P. Magnan, E. Debord, T. Fusai, C. Destombe, J.-C. Sarron and E. J. Voiglio, «Comparison of thoracic wall behavior in large animals and human cadavers submitted to an identical ballistic blunt thoracic trauma» Forensic Science International, n° 1222, pp. 179-185, 2012.
[28] D. Bourget, «Scaling of animal and PMHS thoracic BABT data to live human data» *Proceedings of the Personal Armour Systems Symposium 2020,* p. 10, 2020.
[29] T. L. McMurry et G. S. Poplin, «Statistical Considerations in the Development of Injury Risk Functions» *Traffic Injury Prevention,* vol. 0, pp. 1-9, 2015.
[30] N. Dau, J. Cavaneugh and C. Bir, «Evaluation of Injury Criteria for the Prediction of Commotio Cordis from Lacrosse Ball Impacts» Stapp Car Crash Journal, vol. 55, n° 110, pp. 251-279, 2011.