Evaluation of the drone-human collision consequences

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1. Introduction

The rapid development of unmanned aircraft systems (UASs) and the related technologies in recent years has led to their massive expansion throughout the world. The increasing availability and decreasing costs have enabled an exponential growth and utilisation of these systems even by the general public. However, the lack of experience in controlling these devices has raised questions related to the safety of the operation and the elimination/mitigation of injuries caused by non-professional use.

The introduction of new legislation related to the safety of the operation of the UASs has proved to be a global challenge for aviation authorities, which have so far focused only on the protection of aircraft and persons on board [44]. Due to the lack of experience regarding the application of the UAS and the lack of knowledge about the risks of the operation, it was necessary to introduce new legislation. The focus was in particular to the protection of persons and property on the ground or in the potential impact zone in the event of an accident.

Current legislation and regulations in the EU [1, 2, 3, 4, 5] and the US [6, 7] lay down criteria allowing even untrained members of the public without significant experience to fly these aircraft. The operational limits are defined by the maximum take-off mass (MTOM), the threshold kinetic energy (KE) or the potential injury that can occur due to the collision. These criteria have historically been mostly derived from military studies. However, the application of these established procedures is problematic due to the different nature of the UAS characteristics (design, materials, dimensions, speed) and leads to significant limitations of the UAS operations, especially for small UAS (sUAS) up to 2 kg.

The aim of the contribution was to assess and practically verify various methods used for the safety assessment of the collision of a sUAS and which are currently being developed or used to regulate the possibilities of flying these machines. The results of the work presents a suitable basis for aviation authorities, as they offer a practical validation of the existing procedures and identify the ambiguities between these methods. An example is the application of alternatively proposed models of human vulnerability (automotive criterions, blunt criterion). The results show a high inconsistency with the current set limits and identify significant gaps in knowledge in the field of ground risks posed by UAS. This fact poses a problem especially for the category of the “harmless” UAS. While these sUASs should be operated without restrictions, the resulting level of risk should be still acceptable.

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2. Analysis of current knowledge

Studies often utilise a probabilistic approach where a long series of estimates and assumptions are made \([8, 9, 10, 11, 12, 13]\). In general, the issue can be divided into several parts. The first is the identification of the worst-case scenario of impact (kinetic energy, orientation, approach angle). The second is the evaluation of the collision consequences for a human (energy transition/absorption, human vulnerability, resulting injury). The third is practical testing with an anthropomorphic test device (ATD), a post mortem human surrogate (PMHS) or a computational modelling to obtain the base datasets for the evaluation and assessment of the potential consequences. Consideration is given to generalisation of the results that would lead to the creation of predictive models, threshold values or test procedures with a high degree of accuracy and validity.

At first, the aim is to define the configuration that is the most dangerous to humans. This can be determined by the maximum attainable kinetic energy of the UAS and the least favourable configuration of the impact to the human body. As the worst-case scenario can be considered the impact of the centre of gravity (CG) of the UAS on the CG-affected part of the human body. This scenario leads to the maximum transition to the KE of the UAS. Dynamic tests have shown \([14, 16, 18, 19]\) a significant reduction in the transferred energy even in cases of a slight displacement of the impact site. However, even in these cases, some of the kinetic energy is dissipated in the deformation and bending of the UAS. Thus, stiffer and denser structures transfer more kinetic energy and presents higher risks.

The researchers have attempted to predict a general relationship between the parameters of the UAS (MTOM, maximum speed) and KE at terminal velocity \(v_{\text{term}}\) \([11, 13, 14]\). This approach is problematic from several aspects. The first is the limited set of data used for determination of the relationship, whether linear or polynomial fitting. The second is the subsequent use of \(\sigma v^2\) or \(3\sigma v^3\) for the 95% and 99.7% confidence interval, respectively, and finally the rapid development of UAS technologies. The resulting relationships therefore often show a low level of correlation and lead to overly conservative limitations.

The second approach of dealing with collision is to evaluate the consequences of a collision for humans generally. An impact of the UAS or its parts can cause a variety of mechanical injuries (blunt impact, lacerations, penetration) or other non-mechanical injuries (burns, over-pressure). In this study, only the blunt trauma injury is considered, while other types of injury are not taken into account, similarly as in \([16, 17, 18, 19, 21]\). An Abbreviated Injury Scale (AIS) is used as a standardised method to assess the severity of injury. An anatomical coding system developed by the Association for the Development of Automotive Medicine \([22]\) is used. This system is commonly used to classify the severity of an injury and corresponding threat to the life (from AIS 1 – minor injury, AIS 3 – serious injury to AIS 6 – fatal injury). Most of the currently used models are based or derived from the military research on the protection of people from projectiles and fragmentation caused by either explosions \([23, 24]\), falling debris \([25]\), or non-lethal ammunition \([26]\). More recent studies also use the automotive industry standards \([5, 14, 27]\).

From the studies mentioned above, the KE alone has shown to be a good predictor of the resulting blunt trauma injury. The KE thresholds and probability models have been designed to determine the probability of a fatal injury (PoF) from the military research (falling debris and explosions). The oldest energy threshold was defined at value of 58 ft-lbs (79 J). It was first introduced by a German officer Röhne during the World War I, generally used by the German army as an energy value that “removes a person from the battlefield” \([28]\). Current research shows \([23, 25]\) that the agreement with measured empirical data is still relatively high. Furthermore, it is very close to the proposed limit within the EU legislation (80 J of transmitted energy). The main study in the area of the KE vulnerability models is represented by Feinstein et. al. \([23]\), who evaluated the effects of glass, bullets, balls and blunt objects (spherical concrete projectiles) hitting the skin, lower abdomen, chest, limbs and skull (PMHS, animals).

The Range Commanders Council (RCC), based their standards on Feinstein’s results, RCC 321 (inert debris) \([25]\) and RCC 323 (UASs) \([29, 30]\), and defined two main energy thresholds (11 ft-lbs (14.9 J) and 25 ft-lbs (33.9 J)). The 14.9 J threshold presents a value “designed to afford protection against injury levels of an Abbreviated Injury Scale (AIS) of level 3 or worse” \([25]\). The threshold was originally defined by Zaker et al. \([31]\). However, its use is nowadays based on a precedent and serves as an effective and conservative criterion for the protection of the public. The 33.9 J threshold is derived directly from the Feinstein study. Both of these threshold values are considering an impact to the head. In case that the same principles would be used for thorax impact, the resulting value would be 14 ft-lbs (19 J). Several studies \([24, 32]\) tried to broaden the base database, providing further tests with animals and PMHS, or used weighted exposed areas to create a PoF for a given posture or public assembly \([14, 24]\). However, the crash test data obtained from this research and other studies \([14, 16, 18, 19]\) for the impact of the UAS with an ATD or a PMHS shows a low correspondence between the PoF based on these studies and the resulting injury. The probable reason is that the projectiles material characteristics and impacting speeds, used for these studies, differ from the fragile and elastic structures of an UAS or the corresponding contact area at impact. Furthermore, it has been shown \([14, 19]\) that impacts, even with a slight offset of the CG, can lead to a significant decrease (up to 73%) of the transferred KE to the impacted body part \([14]\).

Other research \([21, 33]\) is based on a theoretical evaluation of the collision severity through the blunt criterion (BC). The BC also implements, apart from the KE, the ratio of the colliding masses, the body characteristics and contact area. Thus, it should have a better predictive ability than the KE. Sturdivan et al. \([26]\), and Bir et al. \([34]\) determined the probability curves of sustaining injuries at different AIS levels for the thorax and the abdomen (on PMHS and animals). In comparison to the Viscous criterion (automotive criterion for the evaluation of a thorax injury) the BC serves as a predictive measure. Thus, the severity evaluation can be computed even with limited information about the impacts. Based on the original dataset, the use of BC is limited for very low velocities (below 3 m/s), thus, it does not consider the rate at which is the energy absorbed by the body \([26]\).

The Alliance for System Safety of UAS through Research Excellence research (ASSURE) \([14, 16, 17, 18, 19]\) has used for the evaluation automotive criteria and limits \([36, 37]\). These criteria are derived from a wide range of empirical data and are commonly used during the certification procedures of vehicles for the occupant safety in the event of an impact. However, despite their high explanatory power and extensive validation, the difference in the impact masses, velocities or materials used for the interior of the vehicle and those used for the construction of the UASs means that the transition has to be taken with certain caution. This is confirmed by the available empirical data from the UAS tests with PMHS \([19]\). The results show differences between the assumed probabilities of skull fractures based on automotive standards \([36]\) and the observed injuries.

The application of automotive based vulnerability models within the legislation would require a definition of detail standardised test procedures and evaluation of each UAS by the producer. While the tests could be required only on the devices developed with an aim to operate above uninvolved people, the corresponding costs would be significantly higher than in the case of application of the generalised KE threshold values.

A third option for the risk assessment is an experimental testing with an ATD, a PMHS or computational modelling to obtain basic datasets for an evaluation and assessment of possible consequences.

The ASSURE A4 Report \([14]\) with 26 tests with a DJI Phantom 3 Standard impacting an ATD (FAA 50th male Hybrid III). Thanks to the instrumentation of the ATD, various automotive criteria were used for the evaluation of the severity of the injury. The highest estimated probability of an AIS 3 neck injury was observed at a vertical impact with \(v_{\text{term}}\) of 13.1 m/s and a KE of 105 J. Overall, the tests showed a very low
probability for a skull fracture. Among other things, these tests also showed that ATDs are able to distinguish the stiffness, structure and transmission of the energy of the impacting object.

Another example is Koh [27], who used practical tests to validate models using the Finite Element Method (FEM). A simplified ATD device was used (50th percentile male Hybrid III head attached with springs to a solid surface) for the evaluation of the severity of an impact with the head. Only the mass (from 305 up to 5100 g), drop height (3–30 m) and head acceleration were recorded. The UASs were dropped with the use of electromagnet and impacted the simplified ATD with its bottom side. For sUASs under 2 kg (the scope of this study), the resulting Peak Head Acceleration and HIC15 correlated with an increasing KE.

The largest up to date dataset was presented in the ASSURE A14 Report [16, 18, 19] (315 tests in total). The tests were performed with different UASs (multi-rotor, fixed wing, influence of a parachute), under various impact scenarios and with different impact partners – a simplified ATD [16] (Head and neck of 50th male Hybrid III fixed to a solid surface), an ATD [18] (FAA 50th male Hybrid III) and a PMHS [19]. However, the detailed data and tests results were available only for 149 tests, which are used for the purpose of this study. In the PMHS tests, a difference was observed between the measured acceleration with redundant accelerometers (up to 33%), probably due to the position of the sensor assembly and the resulting cranial deformation on impact. In addition, the measured values in the PMHS tests were higher than in the same ATD tests. Furthermore, differences were identified between the simplified ATD and ATD. The rigidity of the simplified apparatus mount provides a markedly different response than the ATD.

Two types of the human FEMs (Humanetics FAA Hybrid III 50th Percentile Male Dummy FE model, version 1.2.2 for LS-DYNA with virtual sensors) and Total Human Model for Safety (THUMS) were also used in the above study. Three UAS models were used to simulate a collision with the ATD (Phantom 3, eBe-1 - Precision Hawk - fixed wing).

In general, lower head kinematic values were identified for the FEM (THUMS) and ATD (Hybrid III) against the PMHS (lower by approximately 30%). The decreased kinematic response can be accounted for by the different aim of the design (automotive car crashes) and the corresponding validation for these purposes. The difference between the ATD and THUMS model can be also attributed to the damping effects of the biological material models (lower magnitude of force and extended duration of the impulse transfer). However, based on the published data, the computational modelling shows a need for validated data to further improve the accuracy of the resulting simulations. Still, the outcomes proved that it can be already used with great advantage to determine the critical sUAS orientation and the impact conditions for the ATD or PMHS testing [18] to limit the time and financial costs of the testing.

2.2. Regulation and used limiting values for sUASs in the USA

The UASs in the USA are regulated by the Code of Federal Regulations (CFR) 14 part 107 [6]. Currently, there is a limit of 122 m for their operation, with a maximum speed of 44 m/s and an upper weight limit of 25 kg. A newly proposed rule by the Federal Aviation Administration (FAA) [7] is considers the creation of three categories of permissible operations over people based on the risk of injury. In consideration to the ground risks, it contains the MTOM thresholds of 250 g and two energy thresholds of 14.9 J and 33.9 J.

An additional condition is that the sUASs have to be operated without any exposed rotating parts that could lacerate the human skin upon impact with a person. These conditions were based on the conclusions of the ARC [15, 20]. The 250 g presents an already used limit for the registration of sUASs.

The mass threshold was derived with a standard aviation risk assessment formula used in consideration of manned aircraft safety [15]. An acceptable risk level was achieved with a series of assumptions to estimate the probability of a lethal event occurring per a sUAS flight hour. The energy threshold limit of 80 J served as the basis [32]. Solving for mass and velocity, this energy equates to an object weighing 250 g traveling at a $v_{\text{term}}$ of 25 m/s.

The energy thresholds are used instead of the recommended level of the resulting injury (1% of AIS 3 and 30% of AIS 3) by ARC [20]. The threshold values are taken from RCC 321 with an aim to be consistent with the existing commercial space safety regulations. However, the limits are intentionally defined as an injury more severe than an injury that would result from a transfer of 14.9 J, resp. 33.9 J, of KE from a rigid object. “The FAA proposal for using injury avoidance as a threshold, rather than an impact kinetic energy threshold alone, considers the disparity between impacts from metallic fragments and small unmanned aircraft. The performance-based standards intend to encourage development of testing methodologies and other means of compliance that account for the transfer of kinetic energy that may occur upon impact from small unmanned aircraft” [7].

3. Data and methods

As has been shown above, the current determination of the ground risks or the potential severity of a resulting injury is largely taken from different fields and various criteria or threshold values are adopted without clearly defining their limitations. Significant differences in the predicted injury severity together with the different base datasets on which are the various human vulnerability models are based, makes the comparison or even the identification of the “most suitable” model rather challenging.

Especially, when the available datasets are missing basic information necessary for the application of different criteria than those selected in the given study (such as the impacting velocity [27], contact area [14, 16, 18, 19]). Therefore, it was decided to prepare and perform dynamic tests of sUASs (up to ca. 2 kg) to obtain an additional dataset of the validated collision dataset on which the human vulnerability models could be compared and confirmed.

Five sUASs were used for the evaluation, three multi-rotor quadcopters and two fixed wing airplanes (Figure 1). The selection of particular UAS was done with an aim to show the differences in resulting impact consequences. The multi-rotor aircrafts had a plastic frame which is the most common material for this type of sUAS. Similarly, the fixed-wing aircrafts had a foam fuselage and wings.

The first quadcopter had a 3D printed frame and weighted exactly 250 g. The second was a toy grade quadcopter (680 g) with a low-
resolution camera and prop guards. The last multirotor aircraft was the Phantom 2 vision+ (1242 g). For the fixed-wing category, a flying wing (similar to the eBee+ with a weight of 600 g) and a pusher airplane with a camera commonly used for photogrammetric measurements (1300 g) were used. A Hybrid III 50th Percentile Male was used as a collision partner for the frontal crash tests. The ATD was instrumented with head accelerometers and load cells in the upper and lower neck. The tests were documented with 2 high speed cameras (frame rate 900 and 2500 fps) and the velocity was determined through a velocity gate and subsequently verified by the high-speed footage. Additionally, the area of impact was measured to enable the utilisation of the BC.

The impact scenarios were defined based on the conclusions from other studies [14, 16, 17] and the worst-case scenarios defined by The European Union Aviation Safety Agency (EASA). The multi-rotor UASs were released from a height of 40 m and collided with the top of the head of the ATD in a levelled position with their bottom side. The reason why the UASs were not accelerated with pneumatic actuators or elastic band is to minimise the effects of the rapid acceleration on the UAS structure.

The authors believe that the acceleration should be gradual to eliminate the introduction of stress or bending in the UAS structure prior to the impact, similarly as in automotive testing. The impacts were aimed to be CG-to-CG. The height was decided based on the findings in [17] to enable the aircraft to achieve near $v_{term}$.

The UASs were turned off but the motion of the rotors was not restricted in any way. To ensure the determined impact orientation and precision of the impact, the UASs were led by nylon wires that were attached to steel guiding wires by specially designed clips during the fall.

Different scenarios were used for the fixed-wing aircrafts. The decision was based on a series of controlled flight tests where various conditions were simulated (similarly as in [16]). Based on these tests, it can be confirmed that steeper impact angles have to be considered for the fixed-wing UASs. This is in correspondence with the ASSURE findings [16], where an angled tests were performed with an impact angle of 58°. However, steeper impact angles mean that the evaluation of the worst-case scenario for fixed-wing sUAS should also encompass the potential impact into the thorax area.

The selected scenarios were the following: The UAS starts from a controlled levelled flight and then continues into a rapid descent with a maximum throttle and subsequently impacts the temporal area of the ATD's head with the frontal part of the UAS fuselage. The starting height of the descent was set to approximately 40–50 m to achieve the maximal velocity. The impact angle was set to 58°.

4. Data results

In total, 8 tests were performed – one with the 250 g quadcopter; two with the larger toy quadcopter; two with the Phantom 2 vision+; one with the flying wing and two with the pusher fixed-wing. The 680 g quadcopter was tested with full assembly and with camera removed to observe effects of the increased contact area. The tests with the Phantom 2 were also performed in different configurations to observe the differences in the achieved velocity. The first was performed with removed propellers and camera and the second with re-attached propellers, but without camera. Due to wind gusts during the fixed wing impacts, the desired impact orientation was not fully achieved and the impacting velocity had to be decreased. The flying wing impacted the ATD at 45° instead of 58°. The push fixed-wing aircraft shifted its course slightly before impact and collided with the neck of the ATD with its wing near the fuselage. Therefore, a second test was performed with adjusted impact orientation (impact angle of 0° – horizontal impact) due to the wind conditions and pilot limitations. For the second test, the desired impact orientation was achieved (Figure 2).

The KE and all the measured parameters during the impact were used for the prediction of the resulting injury severity. Although all the measured impacts were performed as the UAS impact to the head of ATD, the assessment and computations for the fixed wing UASs were also made for the thorax impacting configuration due to the possibility of steeper impact angles.

The following tables contain the aggregate values for the individual tests, derived evaluation criteria and the corresponding injury prediction. The probability of a fatality was determined based on the KE probability curves by RCC 321-07 [23, 25] and Jansser [24].

For the BC computation, following formulas (Eqs. (1) and (2)) were used [26, 34, 35, 42]:

$$ BC = \ln \left( \frac{1}{2} \frac{MV^2}{W^2T^2D} \right) $$

(1)

where $M$ [kg] is the mass, $V$ [m/s] is the velocity and $D$ [cm] is the diameter of the contact area of the SUAS, $W$ [kg] is the mass of the struck body and $T$ [cm] is the thickness of the body wall.

Furthermore, the BC was computed with the effective energy $E_{df}$ based on the conservation of momentum, where the ratio between the impacted body part and the UAS was taken into account [26, 33]. As not the whole body is accelerated during impact, the effective mass $W_{df}$ of the struck body part was used for the calculation of $E_{df}$ and then used instead of the $E_k$ for the BC calculation.

$$ E_{df} = \frac{1}{2} MV^2 \left( 1 - \frac{W}{W + W_{df}} \right) $$

(2)

The parameters for a 50th percentile male used for the computations – weight of 77 kg, effective mass of the head and thorax of 4.9 kg, resp. 16.2 kg, average combined thickness of the soft issue and skull of 1.3 cm, average combined thickness of the soft tissue and ribs of 3 cm.

The limits of the skull fracture probability (AIS 2) were estimated based on the Peak Head Acceleration [38, 43] and HIC$_{53}$ (FMVSS 208 [36, 37, 42] and Merzt [38, 39]). The probability of an AIS 3 neck injury was estimated through $N_{th}$ [36, 37, 42, 43] or modified $N_{ij}$, proposed in [40], in the case of the side impacts with the flying wing aircrafts. The results of the tests are shown in Tables 1 and 2.

Overall, the tests correlate with the tests performed in other studies [14, 16, 17, 18]. The energy-based criteria show significantly higher values of the predicted PoF in comparison to other vulnerability models. While the BC predicts lower values, it still leads to over conservative predictions of the severity due to the disregard in the elastic and frangible properties of UASs. All of the tests reached a KE higher than the 14.9 J (11 ft-lbs), which was also the case for the lightest 250 g quadcopter. Thus, a 250 g vehicle crossed the energy limit that was used for the definition of 250 g mass threshold of the "harmless" category, the category of UAS without any operational limits above uninjured people.

Furthermore, besides the Test 1 of the 250 g quadcopter, all the tests also crossed the 19 J (25 ft-lb) limit. Three of the tests led to a KE higher than 80 J, which should correlate with a fracture of the skull. Yet, the
acceleration; 13.34% or 1.30% based on HIC15). Overall, it can be said that the probability of a skull fracture for Test 4 ties by the automotive vulnerability models leads to different conclusions. show that for the low measured values, even the predicted probabilities of neck injury were observed at the Test 4. In case of the neck injury evaluation, the pusher's pusher, while the HIC15 413 did not reach the limit value for the Phantom 2. The difference between the current used model predicts a probability of 3.8%. As expected, Test 4 without the propellers showed the most severe impact with the highest probability of a skull fracture. Based on the CFD on the DJI Phantom 3 Standard [14], the rotors contribute between 30–40% of the total flat plate drag area. The difference between the attached and removed propellers from the same drop height presented a 12% change in the vimp and led to significantly higher measured values. This illustrates the importance of the accurate determination of the drag in the case of generalisations about UAS characteristics. The potential thorax injury could be assessed only with the KE and the BC. Due to the translation from the head impact, the necessary parameters for assessment of the automotive criteria (such as Viscous Criterion or Thoracic Trauma Index) could not be determined. Overall, the PoF curves predict a higher severity of injury than the BC, similarly as with the head injury prediction. However, it is important to note that even for the value of 0 Nij, the current used model predicts a probability of 3.8%. automotive models did not confirm a significant threat to the safety or a skull fracture apart from Test 4, where the KE reached 177.9 J. The low rate of absorption of the KE by the ATD head was also proven by the high-speed footage where the UAS displayed intensive bending and deformation of its structure. In the case of the fixed-wing aircrafts, the impact KE was not absorbed, instead, it had transformed into the translation and rotation movement of the ATD head. The foam construction of the aircrafts damped the impact even for the pusher fixed-wing aircraft with mirror-less camera right behind the nose area of the fuselage (Test 8). None of the tests crossed the automotive thresholds for the 3 ms head acceleration (limit of 60 g), HIC15 (700) or Nij (1). The highest measured values for head injury were observed at the Test 4 – the Phantom 2 without propeller. While the HIC15 413 did not reach the limit value for severe injury, the Upper Neck Compression Force was above the threshold value. In case of the neck injury evaluation, the pusher fixed-wing aircraft impact (Test 7) reached a value of 0.39 for the modified Nij. The tests also showed that for the low measured values, even the predicted probabilities of neck injury by the automotive vulnerability models lead to different conclusions (the probability of a skull fracture for Test 4–48.34% for peak head acceleration; 13.34% or 1.30% based on HIC15). Overall, it can be said that more complex criterions which consider the effects over time, such as HIC15 or Nij seem to be the more suitable for assessment. Furthermore, the predicted probabilities of neck injury are higher than for the skull fracture. However, it is important to note that even for the value of 0 Nij, the current used model predicts a probability of 3.8%.
consequences for thorax impact seems to be closer to the Janser PoF. While the results are limited, the predicted injury severity for thorax are significantly higher than those for the head impact. Thus, it stresses the necessity to further consider and assess the thorax impact for sUAS with steeper impact angles.

5. Discussion

The evaluation of the UAS ground risk presents a topic, which is still burdened by many unknowns. The correlation of the mass and resulting kinetic energy allows the utilisation of mass-based thresholds to great advantage. However, the limits currently used are based on a wide range of assumptions, simplifications and generalised UAS characteristics. Thus, they do not accurately represent the UAS ground risks. While the restrictive parameters enabled one to lay the basis for the operation rules to overcome the unknowns, there is a significant need to determine the limits that truly encompass the potential risks. The determination of the threshold values or standardised testing procedures for sUAS presents a crucial step in the integration into the National Airspace System (NAS), especially for the lightest sUAS, where operations above uninjured people are allowed. While the ASSURE research [14, 16, 17, 18, 19] proposes testing scenarios, injuries to the thorax for aircrafts with steeper impact angle are not considered. This disagrees with the tests performed in this study. Furthermore, all the vulnerability models show a higher potential of an injury with the same kinetic energy for the thorax than for the head (RCC 321 [25], Janser [24], Bir [34]).

Overall the provided dataset enables to show differences between currently used or proposed vulnerability models for ground risks and their corresponding shortcomings. The KE energy models were designed for hard, small objects with high velocity and thus leads to a significant overestimation of the PoF. This is clearly shown by the results of BC, that is in principle also based on KE but considers additional parameters. In agreement with the ASSURE findings, the automotive criteria seem to be the most suitable for the assessment. It is important to note, that the presented tests are rather limited and it is desirable to perform more dynamic tests. Furthermore, the resulting values for fixed-wing aircrafts were affected by the chosen test procedure, piloted impact to the ATD, and weather conditions. The planned impact angle of 58° was not achieved and for the pusher fixed-wing had to be modified to horizontal impact. These facts did not affect the KE and BC assessment but lead to a shift of the load from the head to upper neck.

While the ASSURE group performed a significant amount of testing, the cross validation of the tests results showed to be problematic even among the involved research organisations (NIAR vs UAH tests). Therefore, the future research should focus on broadening of the datasets with a clear aim for validation and repeatability. Furthermore, the automotive criteria and testing are rather time and cost demanding and it is not feasible or possible to perform the testing for all the sUAS on the market. A potential solution lies in the description and identification of the ratio of transferred KE during the impact. Suitable dataset for various sUAS types, frame structures and materials would enable to define parameters for given material or frame type and could be further applied for the regulation purposes.

6. Conclusion

The aim was to describe the proposed solutions and the main assumptions that led to the legislation and regulation of currently used sUAS. Additionally, various human vulnerability models were presented together with their limitations, base datasets and conclusions. The focus was on a potential limitations and characteristics which are crucial for their transition into the field of the UAS ground risks. Due to the large differences in the severity predictions and an inability to compare the prediction models on the currently available datasets, the dynamic tests with sUAS were performed to serve as a uniform dataset for the assessment. The test results are in agreement with other studies and indicate further knowledge gaps. While the mass or the corresponding kinetic energy presents an easily definable threshold, the available datasets and performed tests show limitations of its predictive ability for deformable and frangible structure of sUAS. When the kinetic energy threshold is set as an energy transferred to human from an impact with a rigid object, the issue lies in the missing information about the rigid object structure (such as the shape, material density and contact area), the transition ratios or definition of standardised testing procedures for the assessment. While the BC shows a better predictive ability than the pure kinematic energy quantification, even its application leads to a significant over-conservativeness and does not seem to be a suitable measure for the generalisation of the corresponding sUAS ground risk. The application of automotive vulnerability models has shown to be the most suitable approach. The automotive criteria have the highest correlation with the PMHS tests. However, even for the automotive vulnerability models, there is not, currently, a general agreement on the accuracy of used severity models for vehicle testing (Mertz, FMVSS 208). Additionally, more tests data are needed for generalisation and transition into the regulations. The testing is rather complex, time demanding and costly. Computational modelling could counter some of those aspects, but requires extensive datasets for the proper validation, such as structural analysis of the UAS, material properties and precise geometric characterisation. The currently proposed FEM models do not accurately predict the resulting effects of the impact in comparison to the performed PMHS tests.

Declarations

Author contribution statement

Z. Svatý, L. Nouzovský, T. Mičunek, M. Frydrýn: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

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