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TNO report

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Impact of drone propeller blades on avian feet

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Samenvatting

Sinds enige tijd onderzoekt de Nationale Politie de mogelijkheid om met getrainde roofvogels drones op een gecontroleerde manier te onderscheppen. Onder andere de American Bald Eagle blijkt hiervoor geschikt.

De onderzoeksvragen vanuit de Nationale Politie zijn als volgt:
1. Kunnen roofvogels gewond raken aan hun poten als ze een “commercially off the shelf” (COTS) drone (small UAV) onderscheppen?
2. Kunnen roofvogels gewond raken aan hun poten als ze een professionele zwaardere categorie drone onderscheppen?
3. Welke beschermingsmaatregelen voor de poten van roofvogels zouden kunnen worden toegepast mocht blijken dat dit nodig is?

Voor dit onderzoek is een eenvoudige testopstelling gebouwd om in een laboratorium-omgeving op veilige wijze hogesnelheid filmopnames te maken van de interactie tussen een roofvogelpoot of surrogaat hiervoor en een draaiende propeller. Er zijn verschillende surrogaatmaterialen beproefd en er zijn testen uitgevoerd met drukfolies en met verschillende beschermingsmaterialen. Hieruit is duidelijk geworden dat bescherming geboden dient te worden tegen zowel snijwerking van de propellerbladen als tegen botbreuk door de propellerinslag. Uit theoretische analyse van de inslag blijkt dat de sleutel voor het succesvol beschermen van de poot ligt in de verlenging van de contacttijd met de propeller: naarmate deze contacttijd langer is, is de optredende contactkracht kleiner en daarmee ook het gevaar voor snijverwonding en botbreuk. Verder kan op basis van theorie en experimenten worden geschat dat snijverwonding bij een veel lagere contactkracht kan optreden dan botbreuk. De bescherming tegen snijverwonding is dus van primair belang.

Als eerste werd aangetoond dat het mogelijk is om een zodanig goede bescherming tegen snijverwonding aan te brengen, dat een poot bij inslag bezwijkt door breuk maar zonder snijverwonding. De volgende stap was dus het bieden van bescherming tegen botbreuk. De toelaatbare belasting, waarbij nog net geen breuk optreedt, kon verhoogd worden door de contacttijd met de propeller te verlengen door de poot te omhullen met een buffermateriaal. Er is een beschermingsmaatregel gedemonstreerd die bij een bepaald belastingniveau een testresultaat zonder snijverwonding of botbreuk geeft en zonder welke de poot bij diezelfde inslagcondities breekt. Deze beschermingsmaatregel betreft het omhullen van de te beschermen pootdelen met een stoot-dempende binnenlaag van 2-mm dik EPDM-rubber en met een snijbestendige buitenste laag van 1-mm dik Steelskin®, een flexibel weefsel van miniatuur-staalkabel en Dyneema® hoge-sterkte vezel. Ook andere materiaalcombinaties zijn denkbaar. In algemene zin bestaat de beschermingsmaatregel uit een enkele millimeters dikke binnenlaag van buffermateriaal en een dunne (maximaal 1-mm dikke) snijbestendige buitenste laag. De binnenlaag zorgt voor een grote afname van de contactkracht door vergroting van de contacttijd tussen propeller en poot en voorkomt daarmee botbreuk (tot een bepaald belastingniveau).

Vanaf een bepaald belastingniveau zal de poot inclusief deze beschermingsmaatregel van snijbestendige omhulling en dempende binnenlaag bezwijken. Dit hangt onder andere af van de massa, de diameter en het toerental van de propeller.

Voor beantwoording van de onderzoeksvragen zijn de relevante drones onderverdeeld in twee typen: *low-end professional* drones *en high-end professional* drones. Speelgoed drones zijn licht en goedkoop (maximaal enkele honderden Euro's) en zijn niet relevant voor deze studie. De high-end professional drones wegen meer dan 2-kg en hebben een draagvermogen van meer dan 1-kg. Ze kosten in de ordegrootte van enkele tienduizenden Euro's en vergen een uitgebreide training om goed te kunnen besturen. *High-end professional* drones worden voornamelijk gebruikt door bedrijven en overheden voor inspectie (zoals bruggen, hoogspanningsleidingen en windturbines) en voor fotografie en video.

Het antwoord op de onderzoeksvragen luidt als volgt:

1. Als we COTS drones interpreteren als *low-end professional* drones, dan is het onwaarschijnlijk dat de poten van roofvogels verwond raken bij onderschepping van zo'n drone. Voor de American Bald Eagle kunnen we het risico op verwonding van de poten bij onderschepping van zo'n drone verwaarlozen.

2. Als we een professionele zwaardere categorie drone interpreteren als *high-end professional* drone, dan is het waarschijnlijk dat onbeschermde poten van roofvogels verwond raken bij onderschepping van zo'n drone. De onbeschermde poot van een American Bald Eagle kan bij onderschepping van een drone met een nylon propeller met een diameter van circa 0.4-m snijverwondingen oplopen in de schubben van been en tenen en er kunnen nagels worden afgeslagen. Minder sterke en kleinere vogels lopen hierbij bovendien het risico op botbreuk of amputatie van onbeschermde benen of tenen.
Indien de propeller diameter groter is dan circa 0.4-m kunnen ook onbeschermde benen of tenen van een American Bald Eagle breken of geamputeerd worden.

3. Voor een *high-end professional* drone die gerepresenteerd wordt door een nylon propeller met een diameter van circa 0.4-m kan de poot van een American Bald Eagle optimaal beschermd worden door een snijbestendige dunne en flexibele laag om snijverwonding in de schubben te voorkomen. In de praktijk worden de benen en de bovenste delen van de tenen al bedekt met leer, zodat er al een zekere mate van bescherming tegen snijverwonding aanwezig is op de betreffende plaatsen.
De benen en tenen van minder sterke en kleinere vogels dienen aanvullend beschermd te worden tegen botbreuk en amputatie. Dit kan worden gerealiseerd met een combinatie van een buitenste snijbestendige laag en een binnenste flexibele bufferlaag (bijv. rubber). Ook hier geldt dat in de praktijk de benen en de bovenste delen van de tenen van roofvogels al bedekt zijn met leer. Dit biedt al een zekere (niet-optimale) bescherming tegen zowel snijverwonding als botbreuk of amputatie omdat het relatief dikke leer zowel de functie van snijbestendige laag als die van bufferlaag vervult.

Indien de propeller diameter groter is dan circa 0.4-m dienen ook de benen en tenen van een American Bald Eagle aanvullend beschermd te worden tegen botbreuk of amputatie. Dit kan worden gerealiseerd met een combinatie van een buitenste snijbestendige laag en een binnenste flexibele bufferlaag (bijv. rubber). In dit project is niet bepaald tot welke propellerdiameter deze beschermingsmaatregel voldoende is om de poten van een American Bald Eagle te beschermen.

Summary

For some time now the National Police is investigating the possibility of intercepting drones with trained birds of prey in a controlled manner. Amongst others, the American Bald Eagle is found to be suitable for this purpose.

The research questions from the Dutch national Police are as follows:
1. Can the feet of birds of prey get injured by the intercept of a commercially off the shelf (COTS) drone (small UAV)?
2. Can the feet of birds of prey get injured by the intercept of a professional heavier drone?
3. What protection measures for the feet of birds of prey could be applied in case this would appear to be necessary?

For this study, a simple test set-up in a laboratory environment has been constructed in order to create high speed video recordings of the interaction between the foot of a bird of prey (or surrogate material for this) and a rotating propeller in a safe way. Several surrogate materials have been tested and tests have been performed with pressure foils and with different protective materials. It has become clear that protection should be provided against both cutting action of the propeller blades and against bone fracture due to the propeller impact. Theoretical analysis of the impact indicates that the key to successful protection of the leg is to prolong the contact time with the propeller. As this contact time is longer, the occurring contact force is smaller, and as a result the risk of cutting wounds and bone fracture is smaller. On the basis of theory and experiments it can be estimated that cutting injury can occur at a much lower contact force than bone fracture. So protection against cutting wounds is of primary importance.

First it has been shown that it is possible to apply such a good protection against cutting injury, that the bone fractures without penetration of the propeller blade into the cut-resistant layer. The next step was therefore to provide protection additional protection against fracture. The permissible load at which bone fracture is just prevented could be increased by extending the contact time with the propeller by adding a buffer material to the foot. A protection measure has been demonstrated that provides a test result without cutting or fracture, whereas without this measure bone fracture would occur. This protective measure consists of the encapsulation of the legs and toes of the feet with an impact-absorbing inner layer of 2-mm thick EPDM rubber and with a cut-resistant outer layer of 1-mm thick Steelskin®, a flexible woven fabric of miniature wire rope and Dyneema® high- strength fiber. Also other material combinations are conceivable. In general terms, the protection measure consists of a few millimeters thick inner layer of buffer material and a thin (up to 1-mm thick) cut-resistant outer layer. The inner layer provides a large decrease of the contact force by increasing the contact time between propeller and foot and thereby prevents fractures (up to a certain impact level).

Above a certain impact level, the combination of cut-resistant casing and absorbing inner layer will fail to protect the foot. This depends amongst others on the mass, the diameter and the rotational speed of the propeller.

In order to answer the research questions, the relevant drones are subdivided into two types: low-end professional drones and high-end professional drones. Toy drones are light and cheap (up to a few hundred Euros) and are not relevant to this study. The high-end professional drones weigh more than 2 kilograms and have a load carrying capacity of more than 1 kg. They cost in the order of tens of thousands of Euros and require extensive training to be able to control them properly. High-end professional drones are primarily used by businesses and governments for inspection (such as bridges, power lines and wind turbines) and for photography and video.

This report answers all three research questions as follows:

1. If we interpret a COTS drone as a low-end professional drone as defined in section 2.3, then it is unlikely that the feet of birds of prey get injured while intercepting a COTS drone. For an American Bald Eagle we can neglect the risk of feet injury while intercepting a COTS drone.

2. If we interpret a professional heavier drone as a high-end professional drone as defined in section 2.3, then it is likely that the unprotected feet of birds of prey get injured while intercepting a professional heavier drone. An unprotected American Bald Eagle might suffer from incisions into its scales while intercepting a drone with a nylon propeller with large diameter (around 0.4-m) and might lose a talon (nail). The unprotected toes or legs of less sturdy bird feet might suffer in addition from bone fracture or amputation of the toes or legs.

If the drone has a larger propeller (larger than around 0.4-m and accompanying larger propeller blade weight), it is possible that the unprotected toes and legs of an American Bald Eagle might also fracture or be amputated.

3. For a high-end professional drone threat level represented by nylon propellers with large diameter (around 0.4-m), the feet of an American Bald Eagle can be optimally protected by one of several types of commercially available thin and flexible cut-resistant material to prevent incisions into its scales. In practice the legs and the upper parts of the toes of the feet might be covered by relatively thick leather, already providing a certain (non-optimal) protection against incisions of the parts covered by this leather.
The legs and toes of less sturdy bird feet have to be protected against bone fracture and leg or toe amputation as well. This can be provided by a combination of an exterior cut-resistant layer and an interior flexible buffer layer (e.g. rubber). Again, in practice the legs and the upper parts of the toes of the feet of the intercepting birds of prey might be covered by relatively thick leather. This provides a certain (non-optimal) protection against both incisions and bone fracture (or amputation) of the parts covered by this leather, because the relatively thick leather acts as a of combination of a cut-resistant layer and a buffer layer.

For a higher threat level, i.e. a high-end professional drone with larger and heavier propellers (diameter > around 0.4-m), the feet of an American Bald Eagle can be protected against fracture and amputation by a combination of an exterior cut-resistant layer and an interior flexible buffer layer (e.g. rubber). In this project it has not been determined up to what threat level (up to what propeller diameter) this protection measure will be adequate for an American Bald Eagle.

Contents

1 Introduction

For some time now the Dutch National Police is investigating the possibility of intercepting drones with trained birds of prey in a controlled manner. Amongst others the American Bald Eagle appears fit for this purpose.

The research questions from the Dutch national Police are as follows:
1. Can the feet of birds of prey get injured by the intercept of a commercially off the shelf (COTS) drone (small UAV[1])?
2. Can the feet of birds of prey get injured by the intercept of a professional heavier drone?
3. What protection measures for the feet of birds of prey could be applied in case this would appear to be necessary?

Chapter 2 describes the laboratory test set-up made by TNO and gives a record of all performed tests with accompanying propeller blade types and avian feet surrogate materials. Chapter 3 explains the momentum-impulse principle which gives guidance to protection solutions. Chapter 4 discusses the results so far and makes a synthesis between the experimental results and observations from Chapter 2 together with the theory and insights from Chapter 3. Chapter 5 gives the conclusions and recommendations.

The DVDs accompanying the hardcopy version of this report contain all high-speed video footage from the tests (test matrix: see Annex B).

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[1] *UAV: Unmanned Aerial Vehicle*

2 Test set up and laboratory experiments

2.1 Introduction

It turned out to be very difficult to obtain real or surrogate avian feet, especially the feet of an American Bald Eagle or another relevant bird of prey. Moreover, according to literature (see Annex A), dried (dead) avian feet which can be relatively easy obtained are rather useless for testing because these dried feet can have significantly different mechanical properties than fresh avian feet which are more difficult to obtain. For these reasons we initially have used two types of surrogate materials for avian feet: PVC foam core material and synthetic bone made from a solid foam (see Section 2.2).
Two “threat levels” have been used: a light drone with accompanying propeller blades made from plastic and a heavier and stronger nylon propeller driven by a separate motor instead of using a complete drone (see Section 2.3).
Next this Chapter describes all performed tests but not exactly in the order they were executed. A distinction can be made between preliminary tests to get a feel for proportions and phenomena (Section 2.4), the tests with successful protection measures (Section 2.5) after incorporation of the momentum-impulse principle (as explained in Chapter 3), tests with real avian feet (Section 2.6) and all other laboratory tests (Section 2.7). These other tests include try-outs with inserting loose objects into rotating propeller blades. Finally, high-speed video footage made by TNO of drone intercepts by a bird of prey, filmed indoors in a horse riding school (in cooperation with the Dutch National Police and the firm Guard From Above), is discussed (Section 2.8).

2.2 Bird of prey feet and surrogate materials

The feet of birds of prey (see figure 1) include toes and legs covered by scales. Talons are the “nails”. Usually the bird of prey’s talons and toes are the parts of the foot that strike the propellers first. Since the talons (nails) can regrow, the parts to be protected are the toes and the legs.

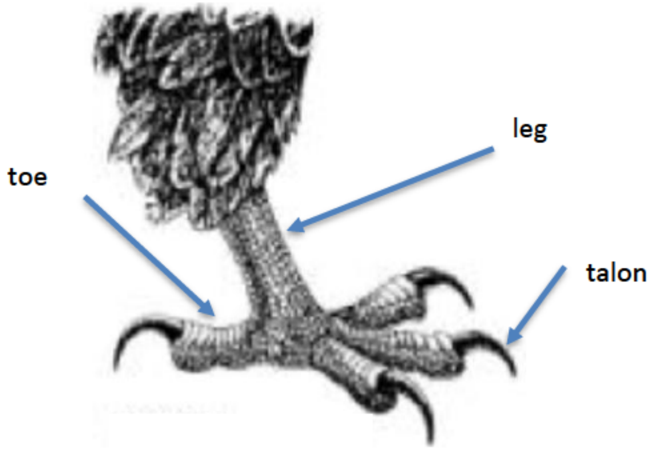


Figure 1: Leg, toes and talons (nails) of an American Bald Eagle [ICWDM, 2016].

As will be substantiated in the following Sections of this report, it is not necessary to provide additional protection for the feet (legs and toes) of an American Bald Eagle during intercept of a light drone like the one shown in figure 2. Moreover, the leather casing on the bird of prey's legs shown in figures 2 and 3 (yellow arrows) already offers some additional protection on top of the natural protection offered by the scales covering the toes and legs.

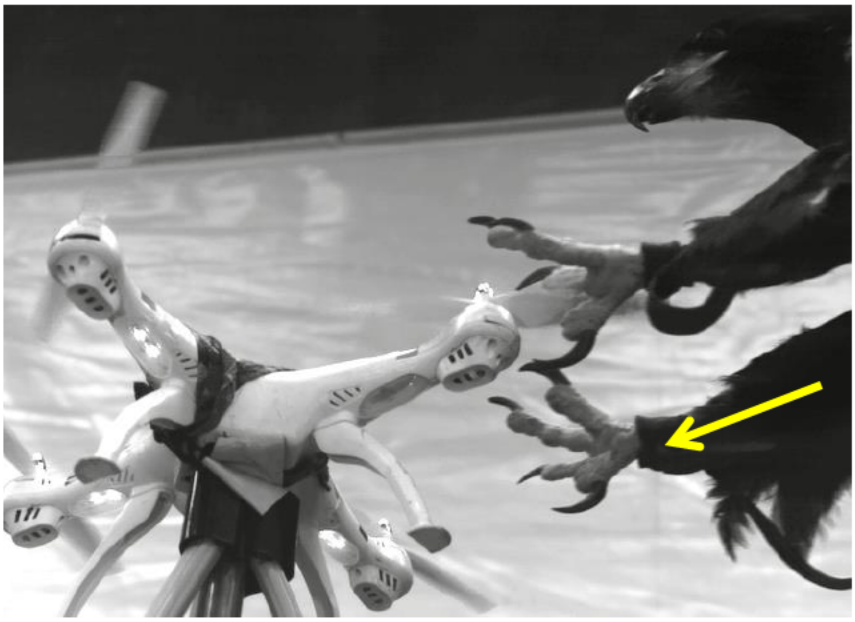


Figure 2: Still from high speed video footage (see Section 2.8); yellow arrow: leather casing.

Figure 3 gives a close-up of a foot of an American Bald Eagle. The bone of both toes and legs is covered by scales consisting of nail-like material (keratin). These parts are quite sturdy as they have to withstand the bites of certain types of prey. The foot bones of a big bird of prey like the American Bald Eagle can be roughly compared with the tibia of a cat, which can be obtained as a bone surrogate shown in figure 4. Since avian bone surrogates are not yet available we have used the feline tibia of figure 4 which is one of the two bones that make up the lower rear leg of a cat. It has a shaft diameter of around 7-mm. This cross-section roughly corresponds to that of the bones in the leg and toes of an American Bald Eagle. This surrogate bone has been supplied by the Swiss company Synbone. Synbone has not provided mechanical properties of this material, although they claim that the properties of their veterinary surrogate bones closely reflect the mechanical properties of real bones.

Figure 3: Close-up view of the toes and talons of an American Bald Eagle; yellow arrow: leather casing.

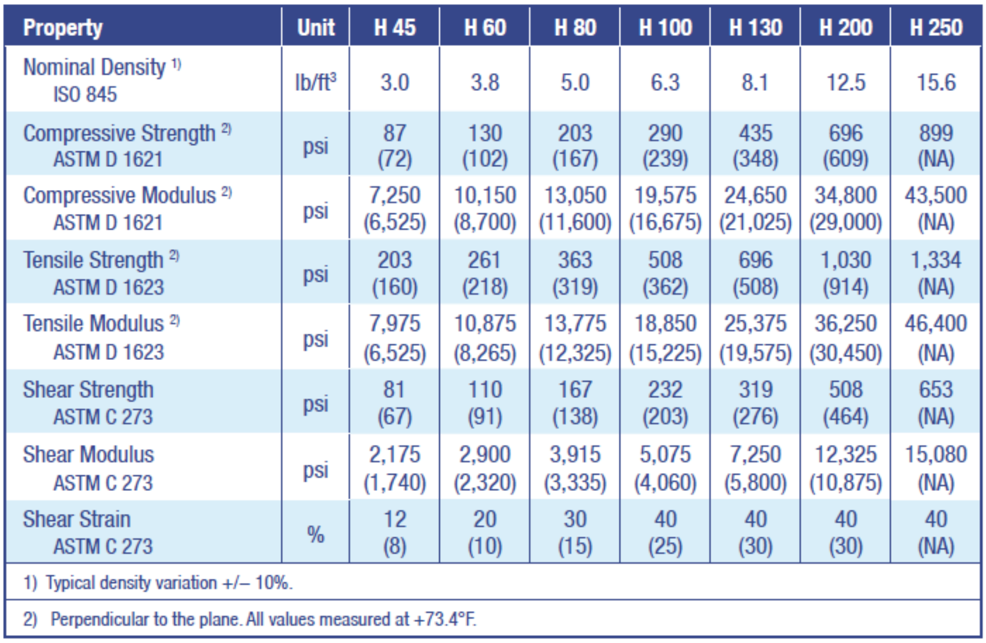
Figure 4: Feline tibia surrogate made from a solid foam [Synbone, 2016].

The preliminary experiments made use of PVC foam core material from Divinycell. We have used two types of this foam: the one with the lowest density (H45, green colored) and the one with the highest density (H250, yellow colored). Table 1 gives specifications of these PVC foam cores as tested by TNO in 2009 and table 2 gives a number of properties of these PVC foam cores supplied by Divinycell. For the propeller impact tests, TNO cut bars from the available foam blocks with a cross-section of around 20-mm (circular) for the low density (green colored) H45 foam and with a cross-section of around 16-mm by 16-mm (square) for the high density (yellow colored) H250 foam.

Table 1: Specifications of Divinycell PVC foam core material (source: TNO)

Type	length [mm]	width [mm]	thickness [mm]	weight [gram]	density [kg/m^3]	areal density [kg/m^2]
Divinycell H45 70	399	405	71	563	50	3.48
Divinycell H250 50	365	367	50	1607	240	12

Table 2: Properties of Divinycell PVC foam core material [DIAB, 2006].
Conversion to SI-units: 1 psi = 6.89 kPa.



Property	Unit	H 45	H 60	H 80	H 100	H 130	H 200	H 250
Nominal Density 1) ISO 845	lb/ft³	3.0	3.8	5.0	6.3	8.1	12.5	15.6
Compressive Strength 2) ASTM D 1621	psi	87 (72)	130 (102)	203 (167)	290 (239)	435 (348)	696 (609)	899 (NA)
Compressive Modulus 2) ASTM D 1621	psi	7,250 (6,525)	10,150 (8,700)	13,050 (11,600)	19,575 (16,675)	24,650 (21,025)	34,800 (29,000)	43,500 (NA)
Tensile Strength 2) ASTM D 1623	psi	203 (160)	261 (218)	363 (319)	508 (362)	696 (508)	1,030 (914)	1,334 (NA)
Tensile Modulus 2) ASTM D 1623	psi	7,975 (6,525)	10,875 (8,265)	13,775 (12,325)	18,850 (15,225)	25,375 (19,575)	36,250 (30,450)	46,400 (NA)
Shear Strength ASTM C 273	psi	81 (67)	110 (91)	167 (138)	232 (203)	319 (276)	508 (464)	653 (NA)
Shear Modulus ASTM C 273	psi	2,175 (1,740)	2,900 (2,320)	3,915 (3,335)	5,075 (4,060)	7,250 (5,800)	12,325 (10,875)	15,080 (NA)
Shear Strain ASTM C 273	%	12 (8)	20 (10)	30 (15)	40 (25)	40 (30)	40 (30)	40 (NA)

1) Typical density variation +/– 10%.

2) Perpendicular to the plane. All values measured at +73.4°F.

Despite their low strength, the PVC foam materials are useful to illustrate the fact that the standard plastic propellers of the more common types of drones pose a negligible threat to the feet of birds of prey (see Section 2.4).

2.3 Drones and drone propellers & test set-up

Small drones (UAVs) don’t pose a great risk of injury because the propellers are small and don’t rotate with nearly as much momentum (momentum: see Chapter 3) as the propellers of bigger drones. Big drones pose a great risk of injury because the propellers are larger and typically made of more rigid material, such as nylon or carbon fiber. We can subdivide the small drones into “toy” drones and “low-end” professional drones as explained further in this section. “Toy” drones are light and cheap (less than a few hundred Euros) and are irrelevant for this study because their propeller blades are weak (fracture easily) and are less dangerous to avian feet than the propeller blades of “low-end” professional drones that have been studied in this project.

For the purpose of this project we make a distinction between two types of relevant drones:

Type 1.
Low-end professional drones are commercially available at various stores and store chains. These drones weigh around 2-kg or less and have a maximum payload of around 1-kg. They have a price tag of several thousands of Euros at maximum. Learning how to operate these kind of drones is relatively easy. Low-end professional drones are used by national authorities and business as well as by hobbyists. The first seven models in Table 3 (above the red line) are representative examples of low-end professional drones.

Type 2.

High-end professional drones are available only at specialized stores. These drones weigh more than 2-kg and have a maximum payload of more than 1-kg. The price tag is of the order of several ten thousands of Euros. It takes extended training to be able to operate these drones. High-end professional drones are mainly used by national authorities and business for inspection (e.g. bridges, power transmission lines, wind turbines) and professional photography and video. The last three models in Table 3 (below the red line) are representative examples of high-end professional drones.

Table 3: Select list of commercially available drones [Remote, 2016].

Model	Weight	Payload	Flight time	Range	Max speed	Camera	Operating conditions	Price
Parrot BeeBop	0.4 kg	0 kg	12 mins	250 m (extendable)	29 mph	Yes (14MP)	Dry conditions only	£700-900 (RTF)
Blade 350 QX2	1 kg	0.2 kg	10 mins	1,000 m	32 mph	Yes	Dry conditions only	£200-300 (RTF)
3DR IRIS+	0.9 kg	0.2 kg	16 mins	800-1,000 m	40 mph	Yes	Dry conditions only	£500-600 (RTF)
DJI Phantom 2 Vision +	1.2 kg	0.2 kg	25 mins	600 m	33 mph	Yes (14MP)	Dry conditions only	£800-1,200
DJI Phantom 3 Professional	1.2 kg	0.3 kg	28 mins	1,900 m	35 mph	Yes (12MP)	Dry conditions only	£1,000-1,200
Walkera Scout X4	1.7 kg	0.5-1.0 kg	25 mins	1,200 m	40-50 mph	Yes	Dry conditions only	£700-900
Yuneec Q500 Typhoon	1.1 kg	0.5 kg	25 mins	600 m	54 mph	Yes (12MP)	Dry conditions only	£900-1,100 (RTF)
SkyJib-X4 XL Ti-QR	15 kg	7.5 kg	15 mins	3,000-25,000 m	24 mph	Yes	Wind	£7,500-8,000
Altura Zenith ATX8	3.1 kg	2.9 kg	45 mins	1,000 m	44 mph	Yes	Light rain/ snow	£15,000-20,000
MicroDrones MD4-1000	2.65 kg	1.2 kg	88 mins	5,000 m	26 mph	Yes	Light rain/ snow	£20,000-30,000

TNO bought a YUNEEC Q500G Typhoon Quadcopter (see figure 5) as a representative for a low-end professional drone. This drone weighs 1.13-kg without battery and payload (1.7-kg with battery and payload).

The standard propeller (diameter: 330-mm) has two blades made from plastic with a thick middle section with an aluminum threaded insert for assembly onto the drone, see figure 6. A single blade weighs 6.3-gram, much less than the total weight of the propeller (23-gram) divided by 2 (2 blades per propeller). This weight for a single blade is important to correctly calculate (estimate) the momentum imparted by a striking propeller blade.

Figure 5: YUNEEC Q500G Typhoon Quadcopter.

Figure 6: YUNEEC propeller.

Figure 7 shows the YUNEEC Q500G Typhoon Quadcopter in the test set-up. The drone is placed inside a safety box to prevent injury of personnel by flying debris; the front part and the first half of the top of the safety box are closed by polycarbonate transparent plastic plates. The rear half of the top of the safety box has to remain open for the large airflow resulting from the operation of the drone and to insert the test objects into the propeller. The high-speed camera is positioned in front and the test is illuminated by the light source shown left in figure 7.

For test #1 through #44 (test matrix: see Annex B) the objects to be impacted by the propeller blades are manually inserted; these objects have a vertical orientation and are moved from top towards bottom. From test #45 onwards, the vertically orientated test objects are moved sideways from the right into the spinning propeller blades and hence impacted at the largest radius of the propeller.

Figure 7: Test set-up with light source, high-speed camera and safety box around the YUNEEC Q500G Typhoon Quadcopter.

After the preliminary tests, the YUNEEC Q500G Typhoon Quadcopter with accompanying propeller blades turned out be too low a threat to properly assess the interaction with protected surrogate avian feet because it will not damage the test objects. So a second “drone” was a set-up with a brushless DC[2]-motor and an APC nylon propeller (see figure 8) with a diameter of 410-mm and a weight of 44-gram. Compared to the hard plastic propellers of the YUNEEC drone, these nylon propellers are stronger and sturdier and won’t easily fracture upon impact. The propeller has two blades with a full nylon middle section. The weight of a single blade is estimated at 20-gram (the complete propeller weighs 44-gram). The propeller is driven by a brushless DC-motor, fed by a power source outside the safety box.

Figure 8: APC nylon propeller driven by a brushless DC-motor, shown in safety box.

The set-up with the large nylon propeller (see figure 8) is considered representative for a “type 2” class drone, i.e. a high-end professional drone.

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[2] DC: direct current

2.4 Experiments with unprotected PVC foam and synthetic bone

The first series of experiments (test number #1 through #44) were intended to get a feel for the impact phenomena and to check how well the test set-up functions. The complete test matrix is given in Annex B. The first ten tests (#1 through #10) were conducted with the YUNEEC drone, all subsequent tests were conducted with an APC nylon propeller driven by a brushless DC-motor.

Test #3 through #5 with the low density (green colored) H45 PVC foam result in incisions into the foam and in slicing the foam. Figure 9 shows the retrieved test materials from test #4 and #5:

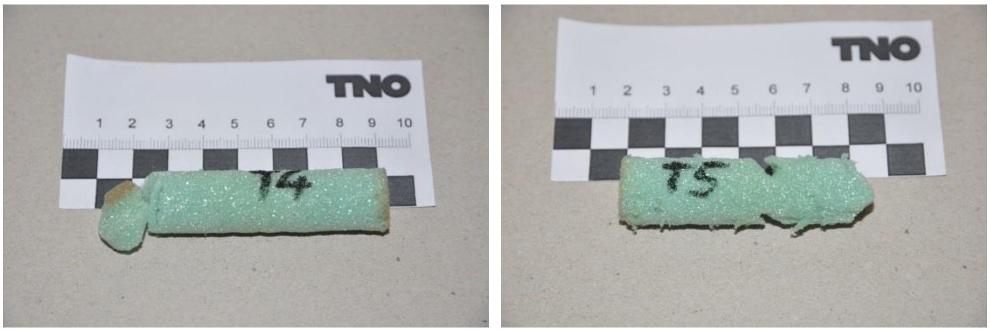

Figure 9: Low density PVC foam; results for test number *#4 (left) and #5 (right).*

The tests (#6 through #10) with the stronger high density (yellow colored) H250 foam resulted in multiple stalls of the drone motor and in one test (#10) the propeller broke after multiple hits against the foam. In all these tests the foam only suffered from minor incisions. Figure 10 shows the impacted foam (with incision) together with the fractured plastic propeller blade (from the YUNEEC drone) for test number #10:

Figure 10: High density *PVC foam: results for test number #10*

Test number #12 shows that the high density (yellow colored) H250 PVC foam is now sliced (instead of only damaged by incision) due to the impact. The propeller blade is heavier, has a higher speed ("full throttle" for #12) and does not fracture, as compared with test number #10. A thin layer of leather wrapped around the foam (test number #14) gives the same result (slicing).

A number of tests (#18 through #23) have been performed with pressure foils wrapped around the H250 foam, at "medium" rotational speed to prevent slicing of the foam. These foils change in color due to pressure. Only test number #19 gave a useful result because (as partly witnessed by the high-speed video footage) the propeller struck the foil only once; the other tests with pressure foils suffered from multiple impacts onto the pressure foil. The pressure foil of test number #19 indicated a pressure of 130-MPa over an area of 12-mm^2, corresponding to an impact force of 1560-N (see also Section 4.2).

Test number #13 and #17 used a synthetic bone taped at the H250 PVC foam bar, in such a way that the propeller blade impacts the bone. Both tests use a different side (end) of the non-symmetric synthetic bone, see figures 11 and 12. In both cases, the bone fractures where it is impacted by the propeller blade. Figure 11 shows the bone before and after impact for test number #13, figure 12 shows another (but identical) bone before and after impact for test number #17. Figure 11 indicates that the bone can also fracture by bending besides cleavage fracture. It should be kept in mind that figure 11 shows the end-result of multiple impacts with the first two impacts resulting in cleavage fracture at the impact positions.

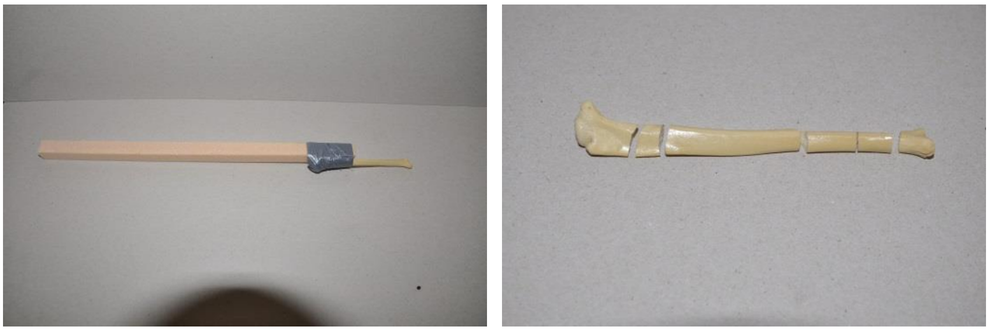

Figure 11: Feline tibia surrogate before and after test *#13.*

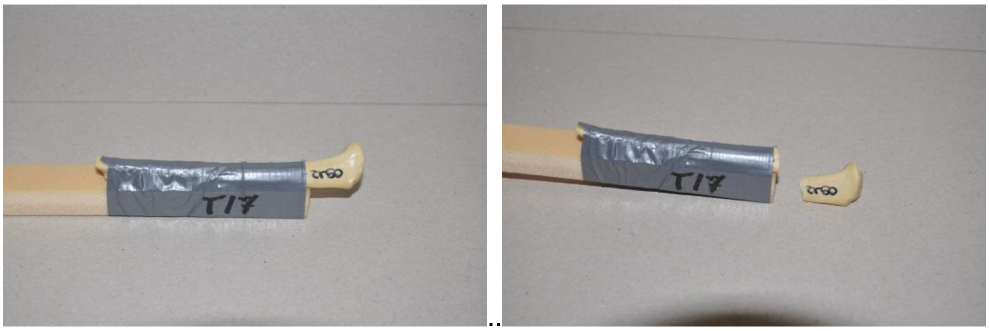

Figure 12: *Feline tibia surrogate before and after test #17.*

2.5 Experiments with successfully protected synthetic bone

These tests have been performed by moving the vertically orientated test objects sideways from the right into the spinning propeller blades.
Tests #46 and #47 show that it is possible to protect the feet against incision to a contact force that is high enough to cause fracture of the bone. This is accomplished by a flexible lightweight existing textile-like solution (around 1-mm thick). This cut-resistant material is called Steelskin® and consists of a mesh of thin steel cutting cables (miniature wire rope) and a weave of Dyneema fibers, see figure 13. It was developed during the last decade for law enforcement personnel and military personnel by the Belgian manufacturer Bekaert together with DSM Dyneema [Press release, 2005][3].

Figure 13: Steelskin® *cut-resistant material.*

The protection level can be further increased by wrapping the leg and toes in a buffering layer (such as 2-mm thick rubber) before protecting it by an external layer of Steelskin®. As a result, as witnessed by tests #48 (see figure 14) and #49, the bone of a protected toe or leg can now withstand a propeller blade impact that would cause the bone to fracture in case it was unprotected or only protected against cutting. The buffer layer must always be accompanied by the cutting protection to prevent the buffering material from being cut, because the latter could lead to loss of bone fracture protection.

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[3] *Steelskin® is patented by NV Bekaert SA (Belgium) under number WO/2010/092151 (publication date 19.08.2010).*

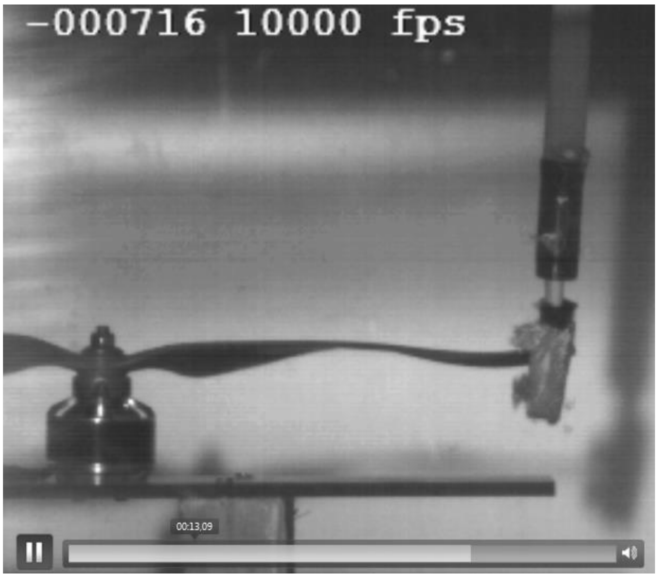

Figure 14: *Video still from test #48; feline tibia surrogate (synbone) protected by Steelskin® plus rubber.*

2.6 Experiments with real avian feet

These tests, #54 through #60, have been performed by moving the test objects sideways from the right into the spinning propeller blades. These tests were performed using the fresh feet of birds slaughtered the evening before.

Test #54 shows how the unprotected middle toe of a turkey suffered a deep incision by the tip of the propeller blade. The toe was pushed aside by the impact.
Test #55 shows how the unprotected leg of a turkey suffered incisions (chipping off from its scales) by the tip of the propeller blade whilst the leg was being held in position. Despite multiple impacts and an almost standstill of the propeller blade, the leg was not fractured.
Test #56 shows how the unprotected toes of a turkey suffered incisions (chipping off from its scales) by the tip of the propeller blade followed by fracture of one or two toes, whilst the leg was being held in position. The toes had a “parallel” orientation relative to the propeller blades instead of a perpendicular orientation (see high-speed video footage).

Test #57 shows that the Steelskin® protected middle toe of a rooster remained intact (left part of figure 15) until the Steelskin® protection was whacked away by the propeller blade. The unprotected toe was cut to the bone after the first subsequent impact and was cut through the bone (fractured) at the second subsequent impact (right part of figure 15).

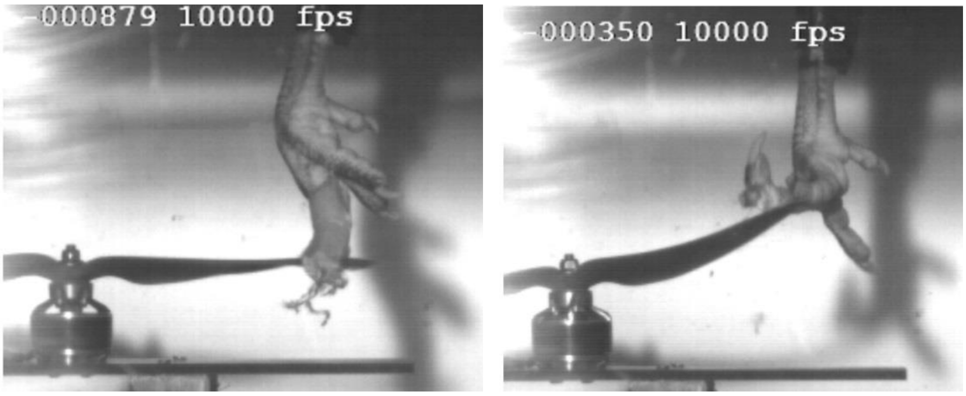

Figure 15: Video stills from test *#57; left: intact rooster toe (protection in position);* right: amputated rooster toe (after loss of protection).

Test #59 shows the amputation of the nail of a rooster's toe. This indicates that the nail might be lost in case the nail (instead of a toe or leg) hits the propeller blade first.
Test #60 shows that the Steelskin® plus rubber protected middle toe of a rooster remained intact until the complete protection was whacked away by the propeller blade. The tip of the unprotected toe was amputated.

2.7 All other laboratory tests

For test #1 through #44 the objects to be impacted by the propeller blades of the drone were manually inserted; these objects had a vertical orientation and were moved from top towards bottom. From test #45 onwards, the vertically orientated test objects were moved sideways from the right into the spinning propeller blades and hence impacted at the largest radius of the propeller (highest linear velocity of the blade).

Test number #24 through #40 were trials to investigate the effects of positioning disturbing elements into the spinning propeller blades. These disturbing elements were rubber bands, coats of mail (hauberks) and aramid wires with steel rings. In all these cases, the velocity of the propeller blades was so much higher than the velocity of the disturbing elements, that these elements were pushed away over and over again from the propeller blades upon impact, until they didn't hit the propeller blades anymore.
Test number #62 and #63 again were trials to investigate the effects of positioning disturbing elements into the spinning propeller blades. Test number #62 used shoe-laces with nuts and #63 used loose strings connected to a single nut. In both tests, again these elements were pushed away over and over again from the propeller blades upon impact, until they didn't hit the propeller blades anymore.

Tests #50 through #53 tested a soft-wooden stick with and without D3O shear thickening polymer wrapped around it. The unprotected wooden stick fractured (test #51) whereas the soft-wooden stick with D3O stopped the propeller blade without fracture of the wood (tests #50 (see figure 16), #52 and #53). Tests #52 and #53 used a Steelskin® layer in addition, to prevent incision of the D3O layer. As witnessed by the high-speed video footage from test #53, care must be taken to properly attach this cut-resistant layer to prevent it from being whacked away by the impacting propeller blade.

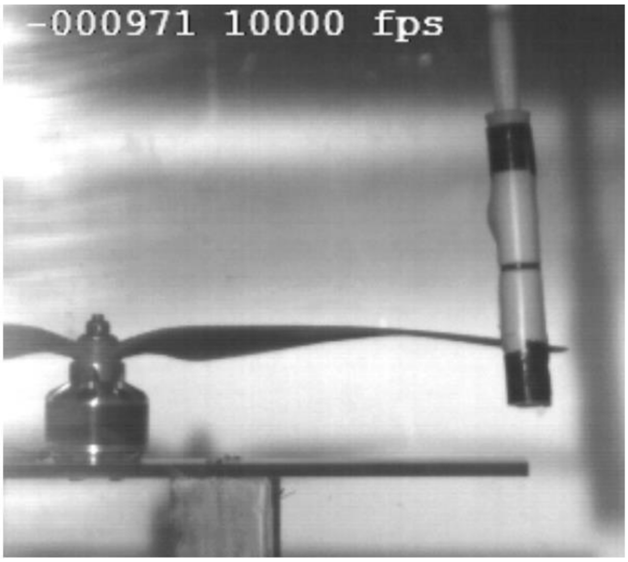

Figure 16: Video still from test #50: a soft-wooden stick protected by D3O shear thickening polymer remains intact after 6 consecutive impacts and temporarily stops the propeller at the 6th impact.

2.8 High speed video from drone intercepts by a bird of prey

The DVDs accompanying the hardcopy version of this report contain high-speed video footage made by TNO of drone intercepts by a bird of prey, filmed indoors in a riding school (in cooperation with the Dutch National Police and the firm Guard From Above) on Monday 23 may 2016. The six intercepts are named 1A, 1B, …6A, 6B with A for frontal footage and B for footage from below. The Dutch National Police has additional high-speed video footage. Figure 17 gives an impression of the test set-up:

Figure 17: Test set-up and approaching bird during indoor drone intercepts.

The first two intercepts (videos 1A, 1B, 2A and 2B) show a variety of orientations of propeller blades relative to the legs and toes of the bird. As stated previously, a perpendicular impact between propeller blade and leg or toe is considered worst case because the impacted area is minimal for perpendicular impact. Consequently, the impact pressure exerted on the bird’s leg or toe is maximal for perpendicular impact.

The third and fourth intercept show the potential danger of propeller blade impact on the feathers. Video 3A (see still image in figure 18) shows the rear propeller turning through the feathers (without feathers being lost). Video 3B shows how the frontal propeller was initially arrested against a feather shaft but later started turning again. Also videos 4A and 4B show the turning of the propeller blades through the feathers, including initial arrest and resumed rotation. The risk of feather shaft fracture is estimated to be subordinate to the risk of feet injury, see Section 4.8.

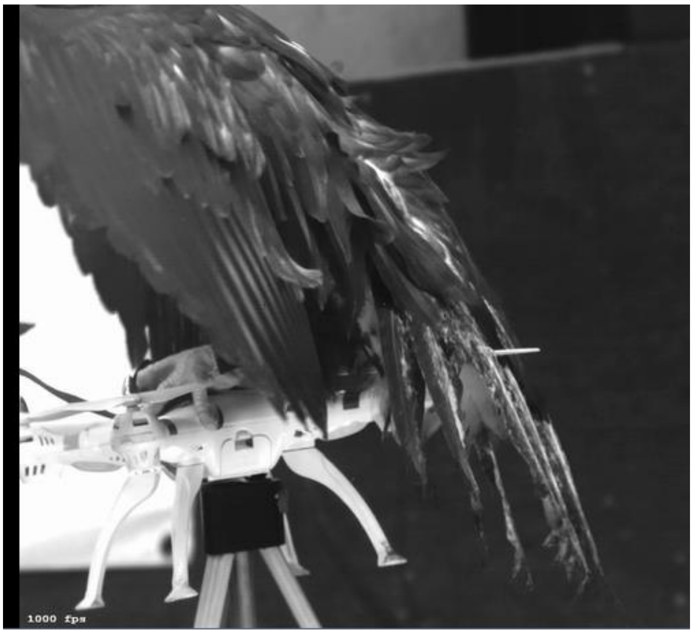

Figure 18: Still from video 3A.

3 Momentum-impulse principle

3.1 Theory of momentum-impulse principle

The momentum-impulse principle is another way of formulating Newton’s second and third law combined. For our propeller impact analysis, it states that the momentum (in Dutch: impuls) of the striking propeller blade is converted into an impulse (in Dutch: stoot) onto the object obstructing the free rotation of the blade:

$$\mathrm{m} \cdot \Delta \mathrm{v} = \mathrm{F} \cdot \Delta \mathrm{t} \quad (1)$$

Figure 19 visualizes the momentum-impulse principle. The contact force ‘F’ and the time interval ‘t’ (Δt in equation (1)) can be exchanged against each other within the same “budget” of the momentum, i.e. m·v (m·Δv in equation (1)). A truck impacting a pile of hay big enough to stop the truck will result in an undamaged truck thanks to the low contact force (and long interaction time). A truck impacting a concrete wall on the other hand will result in a crushed cabin due to the large contact force (and short interaction time).

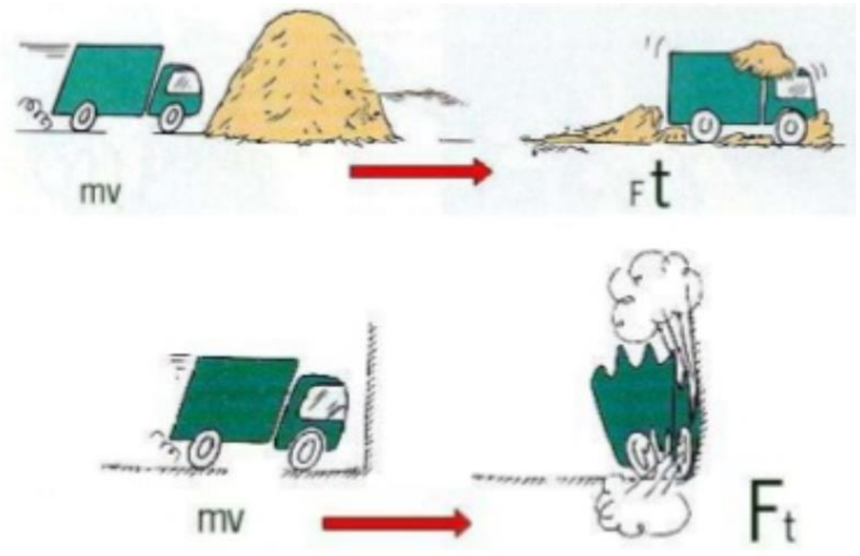

Figure 19: Visualization of the momentum-impulse principle: the contact force ‘F’ and the time interval ‘t’ can be exchanged against each other.

3.2 Application of momentum-impulse principle

The momentum of the propeller blade equals the product of half of the mass ‘m’ of the blade and the blade’s change in velocity ‘Δv’, so the momentum is ½·m·Δv. The factor ½ results from the fact that for the rotating propeller blade the momentum has to be integrated over the radius of the blade, changing equation (1) into equation (2):

$$\frac{1}{2} \cdot \mathrm{m} \cdot \Delta \mathrm{v} = \mathrm{F} \cdot \Delta \mathrm{t} \quad (2)$$

When a collision with the propeller causes the blade to stop spinning, Δv equals the velocity ω·r; 'ω' is the rotational speed (in rad/s) and 'r' is the propeller radius. The linear velocity of the blade at any radius 'r' can be calculated from the rotation velocity 'RPM' (in rounds per minute) using equation (3):

$$\mathrm{v} = \frac{2\pi \cdot \mathrm{RPM}}{60} \cdot \mathrm{r} = \omega \cdot \mathrm{r} \qquad (3)$$

So we have three parameters for the propeller blade determining the impulse (½·m·Δv= ½·m· ω·r) at impact in case the blade stops spinning as a result of the collision:

1. mass 'm' (of one blade),
2. radius 'r' of the propeller and
3. rotational speed 'ω'.

So a spinning propeller blade has a given momentum (½·m·Δv= ½·m· ω·r), regardless of the impact location. According to equation (2) the contact force 'F' is maximal at the tip of the propeller blade since the contact time interval Δt is inversely proportional to the distance between impact location and rotation axis (the center of the propeller). For example, the contact force 'F' at the propeller blade tip is twice as high as at the middle of the blade, because Δt is inversely proportional to the linear velocity 'v' and thus inversely proportional to the distance between impact location and rotation axis.

3.3 Implications of momentum-impulse principle for protection

Equation (2) gives a clear direction how to offer protection against impact. The leg or toes of a bird of prey's foot can suffer from cutting injury or can suffer from fracture due to the impact by a propeller blade. In both cases (scale incision or bone fracture), it is ***pressure*** (force 'F' divided by area 'A') that determines whether or not cutting injury or fracture takes place. The tolerable loading conditions are expressed in allowable tensile stress (tensile strength) of leg or toes in case of cutting and allowable shear stress (shear strength) of leg or toes in case of fracture, as explained in Annex A. So equation (2) can be interpreted as follows to serve as a guide to offer protection:

1. Diminish contact force 'F';
2. Increase contact area '**A** '(and hence decrease the pressure F/A).

Measure 1. can be realized as follows:

1a. Diminish **mass** 'm' (this is a given by the propeller blade);
1b. Diminish velocity drop Δv (this is a given by the **rotational speed** and **radius** of the propeller);
1c. Increase the interaction time interval **Δt**.

From the threat side (red colored), the drone and propeller blade type determine the severity of the impact. These are the **blade mass**, the **rotational speed** and the **propeller diameter**. The higher the values of these three parameters, the more difficult it is to prevent cutting or fracture of legs and toes.
The measures we can take to increase protection (blue colored), independent of drone and propeller blade type, are the contact area (**A↑**) and the interaction time interval (**Δt↑**). This can be accomplished in both cases by adding a buffering material to the leg or toes. The resulting reduction in pressure helps to prevent both cutting injury and fracture of legs and toes.

Remark: the contact area can also be increased (A↑) if the leg or toes are hit by the propeller blade at an angle. The precautionary principle leads us to assume perpendicular impact between blade and leg or toes as a worst case scenario.

4 Discussion of results

4.1 Low-end professional drones: tests with the YUNEEC drone

The tests with the YUNEEC drone (see Section 2.4) illustrate the fact that the standard plastic propellers of low-end professional drones pose a negligible threat to the feet of birds of prey. These tests were conducted with PVC foam materials in order to be able to assess impact damage. The H250 (yellow) PVC foam suffers from superficial incisions during tests #8 through #10 at maximum momentum transfer (the propeller blade comes to a halt). In contrast the H45 (green) PVC foam suffered from deeper cuts during tests #4 and #5 at much smaller momentum transfer (the propeller blades kept spinning, although temporarily slowed down).
These test results are consistent with the mechanical properties given for the foam in table 2. For incisions to occur, the pressure determined by the contact force divided by the contact area has to be larger than the tensile strength of the foam. The yellow foam has a tensile strength of 9.2-MPa and the green foam has a tensile strength of only 1.4-MPa. The scales of an American Bald Eagle have a tensile strength of at least around 30-MPa (see Annex A), three times as large as for the H250 foam with only superficial incisions. So from a mechanical point of view it can be explained that live intercept tests such as those described in Section 2.8 with comparable impact conditions do not result in scale incisions.

4.2 High-end professional drones: estimate of contact force

The contact force in test #19 with foam and pressure foil is estimated at 1560-N (130-MPa pressure over an area of around 12-mm^2), based on the color intensity and colored area of the pressure foil after the interaction between blade and surrogate leg. This result is used in Section 4.3. During the other tests with pressure foils on a surrogate leg represented by a H250 PVC foam bar with a cross-section of 16-mm by 16-mm, the inserted test object was hit multiple times, making interpretation of the pressure foil difficult.
Additional tests using pressure foils are recommended to validate the reproducibility since the performed test series so far only gave one valid result (from test #19).

4.3 High-end professional drones: cleavage fracture of unprotected surrogate bone

The tests with unprotected surrogate bone (tests #13, #17 and #45) show cleavage fractures. Since the Swiss company Synbone claims that the properties of their veterinary surrogate bones closely reflect the mechanical properties of real bones, we assume a shear strength of around 50-MPa (1/3rd of the tensile strength of bone, see Annex A). With a cross-section of around 38-mm^2 this requires a contact force of around 1900-N to fracture the surrogate bone. The contact forces in tests #13, #17 and #45 are estimated based on the contact force of test #19 that was established using a pressure foil (see Section 4.2). Since the impact locations for tests #13 and #17 were at a similar propeller blade radius as for test #19 and

because these tests had comparable deceleration of the propeller blade at impact, the contact forces for tests #13 and #17 are derived and estimated from test #19 by correcting for the rotational speed. For test #45 in addition a correction has to be made for the impact location (at maximum radius instead of half the radius). In this way, the contact forces are roughly estimated at 2500-N for test #13, 1800-N for test #17 and 4100-N for test #45. Of course this is only an approximation of the real contact forces, since test #19 (pressure foil) was performed with H250 PVC foam and not a surrogate bone. Nevertheless, it explains that these tests all resulted in a cleavage fracture (at first or second impact) of unprotected surrogate bone with estimated contact forces roughly around or significantly above the allowable contact force (shear strength multiplied by the cross-section) of the test object.
It is recommended to perform additional tests using pressure foils since the performed test series so far only gave one valid result for pressure foil measurements.

4.4 Cut-resistant protection (surrogate bone)

Tests #46 and #47 used one (#46) or two (#47) layers of Steelskin® cut-resistant protection wrapped around the surrogate bone at the impact position. Using the same approach as above (Section 4.3), the upper limit of the contact forces can be estimated at around 3200-N for test #46 and 2500-N for test #47 whereas it is estimated that it would take around 1900-N to break the surrogate bone by cleavage fracture. We use the term “upper limit” here, because the high-speed video footage shows a longer contact time for the propeller blade at impact (at bone fracture) for tests #46 and #47 compared to test #45. Hence, according to the momentum-impulse principle (see Chapter 3) the contact forces in tests #46 and #47 will be lower than the above calculated values. Moreover, the contact area between impacting blade and impacted object will probably be a bit larger than is the case with the unprotected (bare) bone. Nevertheless, in both test #46 and $47 the surrogate bone fractures (at 6th and at 2nd impact respectively) without the propeller blade cutting through the Steelskin®. Apparently, the contact force is roughly equal to or larger than the allowable contact force (shear strength multiplied by cross-section) of the test object in tests #46 and #47.

4.5 Protection against fracture (surrogate bone)

Tests #48 and #49 both used a single layer of Steelskin® cut-resistant protection wrapped around 2-mm thick EPDM rubber which in turn was wrapped around the surrogate bone. In accordance with the momentum-impulse principle as explained in Chapter 3 the contact forces in tests #48 and #49 are significantly decreased with a corresponding longer contact time. Consistent with expectations from the theory of Section 3.1 the high-speed video footage shows a temporary stop of the propeller blade (i.e. maximum momentum transfer) and the bone remains intact in both tests despite multiple impacts. These tests are conducted at around half the maximum rotational speed of the APC nylon propeller (around 3000-rpm) at maximum propeller radius (around 20-cm).

4.6 Tests with real avian feet

The tests with real avian feet (tests #54 through 60) demonstrated the adequacy of the protection offered by the combination of Steelskin® an rubber to prevent cutting of the scales or fracture of the bones. These tests were performed with avian feet that likely have inferior mechanical properties and less favorable dimensions (scale thicknesses, bone diameters) compared to those of an American Bald Eagle, so the use of these tests can be considered to be conservative (i.e. on the safe side).
As long as the Steelskin® remains in place the scales of the test objects will not suffer from incisions. Unprotected turkey toes or legs will suffer from incisions and chipping off of pieces of scale (tests #54 through #56).
The bone in the unprotected leg of a turkey does not fracture (test #55), but the bone in an unprotected toe of a turkey can fracture (test #56). As long as the complete protection package (Steelskin® plus rubber) remains in place, even the toe of a rooster remains intact (does not fracture); after loss of protection the rooster toe is amputated. This follows from tests #57 and #60. Test #57 shows that even protection by only the Steelskin® layer (without rubber) saves a rooster toe from fracture during the first two impacts (before the protection is whacked away).

Based on these tests with real avian feet it is concluded that the legs and toes of an American Bald Eagle can be protected against both scale incisions and bone fracture (or toe or leg amputation) at impact by a large diameter (around 0.4-m) nylon propeller. This is representative for high-end professional drones. One possible protection measure is the combination of a cut-resistant outer layer like 1-mm thick Steelskin® and an inner buffer layer like 2-mm thick rubber. Tests #50 through #54 demonstrate the feasibility of using a shear thickening polymer like D3O instead of rubber as buffer layer.

Test #59 is performed with an insertion orientation enabling the propeller blade impact directly on the nail of a rooster. During the course of several impacts, the nail is eventually amputated. This implies that the nails of an American Bald Eagle can be amputated by a large diameter (around 0.4-m) nylon propeller as well. Since nails can regrow, this is not considered to be of grave concern.

4.7 Insertion of distortional objects

Various tests have been performed with insertion of distortional objects to try to decelerate or stop the propeller: leather belts, bundles of rubber bands, bundles of strings with steel washers, loose ring mail, shoe laces with nuts and a bundle of loose strings connected to a single nut. All these tests showed no or little distortion of the propeller (of a high-end professional drone) and all these objects were sooner or later whacked away by the spinning propeller. The high-speed video footage made by TNO of low-end professional drone intercepts by a bird of prey (see Section 2.8) however did show several cases of propeller disturbance by the leather belts connected to the feet of the bird.
For possible follow-on tests (with high-end professional drone propellers), it is recommended to improve the test set-up. A distortional object (e.g. a leather belt) has to be inserted in a controlled and reproducible way into the spinning propeller

and the rotation speed of the propeller has to be better adjustable. In this way, the potential of insertion of distortional objects to try to decelerate or stop the propeller can be better assessed.

4.8 Risk of feather shaft fracture

The high-speed video footage made by TNO of drone intercepts by a bird of prey (see Section 2.8) show the potential danger of propeller blade impact on the feathers. The feather shafts of an American Bald Eagle are estimated to have a tensile strength comparable with the strength of its bones (see Annex A). So the fracture resistance of a feather shaft can be roughly compared to that of a foot (leg or toe) bone with similar diameter. In combination with the test results with real avian feet (Section 4.6) this leads to the estimation that the risk of feather amputations from the American Bald Eagle is minor in case of the intercept of a low-end professional drone. High-end professional drones might pose a risk for the feathers (potential facture of feather shafts) because they can’t be protected like the legs or toes. In case of feather impact it is likely that multiple feathers will be impacted simultaneously and at angles other than perpendicular to the feather shafts. So the contact pressures will likely be limited (relative to feet impact) and the risk of feather shaft fracture is estimated to be subordinate to the risk of feet injury.

4.9 Other recommendations

It is recommended to establish the tolerable momentum below which no injury occurs for a protected foot of an American Bald Eagle. In this way, it can be estimated which combination of the three main threat level parameters, i.e. the propeller blade mass, the propeller radius and the rotational velocity, could be engaged without risk of foot injury in case of protected feet.

Possible future laboratory tests should make use of a better way of realizing the impact. The current manual insertion of test objects into the spinning propeller should be replaced by a mechanical solution. An improved upon test set-up might also be beneficial to better assess the potential of insertion of distortional objects (like a leather belt) to try to decelerate or stop a propeller prior to feet impact.

5 Conclusions and recommendations

5.1 Conclusions

This report answers all three research questions as follows:

Question 1: can the feet of birds of prey get injured by the intercept of a commercially off the shelf (COTS) drone (small UAV)?
Answer to question 1:

> If we interpret a COTS drone as a low-end professional drone as defined in section 2.3, then it is unlikely that the feet of birds of prey get injured while intercepting a COTS drone. For an American Bald Eagle we can neglect the risk of feet injury while intercepting a COTS drone.

Question 2: can the feet of birds of prey get injured by the intercept of a professional heavier drone?
Answer to question 2:

> If we interpret a professional heavier drone as a high-end professional drone as defined in section 2.3, then it is likely that the unprotected feet of birds of prey get injured while intercepting a professional heavier drone. An unprotected American Bald Eagle might suffer from incisions into its scales while intercepting a drone with a nylon propeller with large diameter (around 0.4-m) and might lose a talon (nail). The unprotected toes or legs of less sturdy bird feet might suffer in addition from bone fracture or amputation of the toes or legs.
>
> If the drone has a larger propeller (larger than around 0.4-m and accompanying larger propeller blade weight), it is possible that the unprotected toes and legs of an American Bald Eagle might also fracture or be amputated.

Question 3: What protection measures for the feet of birds of prey could be applied in case this would appear to be necessary?
Answer to question 3:

> For a high-end professional drone threat level represented by nylon propellers with large diameter (around 0.4-m), the feet of an American Bald Eagle can be optimally protected by one of several types of commercially available thin and flexible cut-resistant material to prevent incisions into its scales. In practice the legs and the upper parts of the toes of the feet might be covered by relatively thick leather, already providing a certain (non-optimal) protection against incisions of the parts covered by this leather.
> The legs and toes of less sturdy bird feet have to be protected against bone fracture and leg or toe amputation as well. This can be provided by a combination of an exterior cut-resistant layer and an interior flexible buffer layer (e.g. rubber). Again, in practice the legs and the upper parts of the toes of the feet of the intercepting birds of prey might be covered by relatively thick leather. This provides a certain (non-optimal) protection

against both incisions and bone fracture (or amputation) of the parts covered by this leather, because the relatively thick leather acts as a of combination of a cut-resistant layer and a buffer layer.

For a higher threat level, i.e. a high-end professional drone with larger and heavier propellers (diameter > around 0.4-m), the feet of an American Bald Eagle can be protected against fracture and amputation by a combination of an exterior cut-resistant layer and an interior flexible buffer layer (e.g. rubber). In this project it has not been determined up to which threat level (propeller diameter) this protection measure will be adequate for an American Bald Eagle.

For the American Bald Eagle, the conclusions can be repeated as follows.
This research has demonstrated that for intercepts of a low-end professional drone the unprotected feet of an American Bald Eagle will likely only suffer from incisions into its scales (or suffer no injury at all). Protection against incisions can be ensured by a cut-resistant layer. For high-end professional drones represented by a large diameter (around 0.4-m) nylon propeller, the feet of an American Bald Eagle can be protected against cutting injury or bone fracture (or amputation) by the combination of a cut-resistant layer plus a buffer layer (e.g. rubber). In this study it has not been established to which higher threat level (propeller diameter larger than around 0.4-m) this protection solution will be adequate.

5.2 Recommendations

For intercepts of a high-end professional drone it is currently unknown to which level of impact momentum the protection solution of a cut-resistant layer plus a buffer layer is adequate to prevent fracture or amputation of a toe or leg of an American Bald Eagle. It is recommended to determine the maximum allowable combination of propeller blade mass, propeller diameter and rotation speed for the protection solution of a cut-resistant layer plus a buffer layer. Of these three parameters, the propeller diameter is the most important.

For possible follow-on tests, it is recommended to improve the test set-up. A (fresh or surrogate) leg or toe (or a distortional object) has to be inserted in a controlled and reproducible way into the spinning propeller and the rotation speed of the propeller has to be better adjustable. This might also help to develop a more efficient distortion measure in the form of insertion of an object to try to decelerate or stop the propeller (e.g. a leather belt) before the propeller hits a foot of the bird of prey.

It is also recommended to selectively reproduce tests (e.g. threefold repetition) to validate the reproducibility of the tests. Also additional tests using pressure foils are recommended since the performed test series so far only gave one valid result for pressure foil measurements.

Finally, it is recommended to assess the injury risk for feathers as well, especially for impacts for which the feet are injured without protection.

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A Mechanical properties of scales and bones

The best validation test for drone propeller blade impact on a leg or toe of an American Bald Eagle would be to use the real leg or toe. For living or freshly slaughtered birds of this type, this is not a viable option for obvious reasons. Alternatively, the use of “dried” (long deceased / stuffed) American Bald Eagles is not only difficult and/or expensive, but also not very useful since the mechanical properties of dried avian feet can have large deviations from fresh (living or freshly slaughtered) avian feet.
It is important to use fresh avian feet (recently slaughtered) instead of dried avian feet. According to [McKittrick, 2012] the mechanical properties of the hard keratin scales (that in our case cover the leg and toes of the foot of the American Bald Eagle) are extremely sensitive to the amount of hydration, with stiffness and strength decreasing accompanied by an increase in toughness with increasing hydration. Following the precautionary principle, we assume a similar discrepancy between dried/old and fresh bones in the leg and toes.

So the next logical step is to use a more readily available substitute avian foot (leg and toes) for the validation impact tests. Section 2.6 describes the test results for the feet of a turkey and of a rooster. It is assumed that the scales and that the leg- and toe-bones of an American Bald Eagle are at least as strong as those of a turkey or rooster. In this way, the test results with a turkey or rooster foot can be considered a representative (and likely conservative) test for the foot of an American Bald Eagle.

We have not been able to find mechanical properties of the feet of an American Bald Eagle in open literature. However, a conservative estimate for these properties can be given by those of other avian feet or other animal or human parts with a comparable composition. The scales of the American Bald Eagle can be compared to other biological materials with a similar (keratin-based) composition like hoofs, horns and claws. Similarly, the bones in the leg or toe of an American Bald Eagle can be compared to other avian feet (e.g. a comparably big bird like a turkey) or the feline tibia[4] used in the tests described in Chapter 2 or human bones.

Scales:
Lacking direct data, the tensile strength of the scales of an American Bald Eagle is assumed to be comparable to horns, nails, claws and hoofs which are composed of hard keratin as well. Since the data found in open literature refers to “tame” animals, this likely results in a conservative estimate since the scales of an American Bald Eagle (a bird of prey) can withstand the bites of their preys.

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[4] *Although an avian bone is hollow and a cat’s or mammal’s bone is not, the approximate comparison remains valid because the resistance against fracture or cutting through the bone is determined by the bone’s cross-section (at comparable bone strength) and this cross-section (the amount of square millimeters of bone to be fractured or cut) is largely determined at the larger radii of the bone.*

[Tombolato, 2010] gives tensile strengths ranging from 6.5-MPa (equine hoof at 100%-RH[5]) to 137-MPa (oryx horn at 0%-RH). [Maloney, 1977] gives a tensile strength for human fingernail ranging from 30.8-MPa to 117.7-MPa. [McKittrick, 2012] gives tensile strengths for an ostrich claw ranging from 14-MPa (100%-RH) to 69-MPa (50%-RH) to 90-MPa (0%-RH). Since the long-term annual average RH-value in The Netherlands (averaged over all 4 seasons) lies between 80% and 85% [KNMI, 2016], the tensile strength of the scales of the feet of an American Bald Eagle operating in The Netherlands is estimated to be at least 30-MPa.

Bones:
Various unreferenced sources indicate a tensile strength of 150-MPa for human bone. [Ritchie, 2009] gives a value of “few hundred MPa” for the allowable stress at the onset of plastic deformation of human bone. [Newman, 1998] gives a “representative value of 144.5-MPa” for the bone strength of an adult rooster (white leghorn). [Tombolato, 2010] gives a tensile strength of 148-MPa for bovine femur bone (in Dutch: dijbeen van rund). Based on these data, the tensile strength of the bones in the leg and toes of an American Bald Eagle is estimated at 150-MPa.

Feather shafts:
Finally, because of the possibilities of drone propeller blade impact on feathers (see Section 2.8), the mechanical properties of feather shafts have been searched as well (in open literature). [Taylor, 2004] gives tensile strengths for an ostrich feather shaft ranging from 106-MPa (100%-RH) to 130-MPa (50%-RH) to 221-MPa (0%-RH). These values have a magnitude around that of bone material (i.e. around 150-MPa]. Other data referred to in [Taylor, 2004] suggest that at 65%-RH the tensile strength of feather shafts is around 200-MPa. So it is reasonable to assume that the feather shafts of an American Bald Eagle have similar mechanical strength.

For injury of the feet of an American Bald Eagle, we can make a distinction between scale incision (cut injury) and bone fracture (cleavage fracture). In both cases we have to assess the exerted pressure on the scales or bones.

Incisions:
By approximation, incision of a scale will take place if the contact force divided by the contact area is larger than the tensile strength of the scale. The use of the tensile strength instead of the shear strength is intentional: for an incision to start, the material of the scale has to be pulled apart. In reality, the stress conditions will be multi-axial, but the tensile stress will be dominant at the start of the incision. Perpendicular impact is a worst case situation because of the corresponding minimum contact area.

Fracture:
By approximation, cleavage fracture will take place if the contact force divided by the bone cross-section in the direction of cleavage is larger than the shear strength

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[5] *RH = relative humidity.*

of the bone.
Perpendicular impact is a worst case situation because of the corresponding minimum bone cross-section. The bone shear strength is chosen conservatively (on the safe side) to be 1/3rd of the bone tensile strength. The already conservative Tresca criterion states that the shear strength of a material can be derived from its tensile strength by dividing it by a factor of 2. Because bone tissue is known to be anisotropic (different properties at different orientations), the tensile strength of bone material is divided by 3 (instead of 2) to be on the safe side.

B Test Matrix

Note: Tests #1-10 with YUNEEC drone; tests #11-63 with an APC nylon propeller driven by a brushless DC-motor

Test number #	Description	Test object	HSV footage	rotation speed (rpm)
#1	camera test	-	-	-
#2	camera test	-	-	-
#3	drop PVC foam	H45 (green)	-	5000
#4	slow insertion of PVC foam with tie-wrap	H45 (green)	-	4950
#5	fast insertion of PVC foam with tie-wrap	H45 (green)	foam incisions and slices cut from foam	4400
#6	drop PVC foam	H250 (yellow)	-	4979
#7	fast insertion of PVC foam with tie-wrap	H250 (yellow)	wrong insertion, propeller blade breaks	5000
#8	manual vertical insertion of PVC foam	H250 (yellow)	motor stalls, superficial foam incisions	4633
#9	manual vertical insertion of PVC foam	H250 (yellow)	motor stalls, superficial foam incisions	4959
#10	manual vertical insertion of PVC foam	H250 (yellow)	motor stalls, propeller blades break, superficial foam incisions	4945
#11	nylon propeller: rpm measurement	-	-	5921
#12	manual vertical insertion	H250	slices cut	5940

#13	manual vertical insertion	synbone taped on H250	impact on thinnest side, fracture at 1st full impact	5732
#14	manual vertical insertion	H250 with thin leather	slices cut	5750
#15	failed	-	-	-
#16	failed	-	-	3586
#17	manual vertical insertion	synbone taped on H250	impact on thickest side, fracture at 2nd impact	4072
#18	manual vertical insertion	pressure foil + H250		-
#19	manual vertical insertion	pressure foil + H250		3528
#20	manual vertical insertion	pressure foil + H250		3156
#21	manual vertical insertion	pressure foil + H250		2940
#22	manual vertical insertion	pressure foil + H250		3600
#23	manual vertical insertion	thin leather + pressure foil + H250		3156
#24	drop	bundle of rubber bands	no distortion, eventually whacked away	2912
#25	drop	bundle of rubber bands	no distortion, eventually whacked away	2830
#26	drop	bundle of rubber bands	no distortion, eventually whacked away	4477
#27	drop	bundle of aramid strings with steel washers	no distortion, eventually whacked away	2941
#28	drop	bundle of rubber bands	no distortion, eventually whacked away	2608
#29	drop	bundle of rubber bands	no distortion, eventually whacked away	2500
#30	drop	bundle of aramid strings with steel washers	no distortion, eventually whacked away	2608
#31	drop	leather belt	temporary propeller slowdown, eventually whacked away	2238
#32	drop	leather belt	no distortion, eventually whacked away	477
#33	drop	bundle of rubber bands	no distortion, eventually whacked away	2158
#34	drop	bundle of rubber bands	no distortion, eventually whacked away	2979

#35	drop	ring mail + thin leather + H250	temporary propeller slowdown, eventually whacked away	1442
#36	drop	ring mail + thin leather + H250	temporary propeller slowdown, eventually whacked away	2362
#37	drop	loose ring mail	little distortion, eventually whacked away	2325
#38	drop	loose ring mail	little distortion, eventually whacked away	2678
#39	drop in center	loose ring mail	little distortion, eventually whacked away	2205
#40	drop in center	loose ring mail	temporary propeller slowdown, eventually whacked away	2307
#41	failed	-	-	-
#42	failed	-	-	-
#43	failed	-	-	-
#44	drop	loose ring mail	temporary propeller slowdown, eventually whacked away	4166
#45	manual insertion sideways	unprotected synbone	bone fractures at 2nd impact	4651
#46	manual insertion sideways	Steelskin + synbone	Steelskin is not cut, bone fractures at 6th impact	3578
#47	manual insertion sideways	double Steelskin + synbone	Steelskin is not cut, bone fractures at 2nd impact	2799
#48	manual insertion sideways	Steelskin + rubber + synbone	bone remains intact, propeller temporarily stops spinning at 3rd impact	3114
#49	manual insertion sideways	Steelskin + rubber + synbone	bone remains intact, propeller temporarily stops spinning at 4th impact	3103
#50	manual insertion sideways	D3O on soft-wooden bar	six consecutive impacts; initially the propeller slows down and finally the propeller is stopped by the object; object remains intact	3370
#51	manual insertion sideways	unprotected soft-wooden bar	propeller slows down at each impact; soft-wooden bar breaks at 4th impact	2962

#52	manual insertion sideways	Steelskin + D3O + soft-wooden bar	propeller stops at and after 2nd impact; soft-wooden bar remains intact	3116
#53	manual insertion sideways	Steelskin + D3O + soft-wooden bar	propeller slows down at both impacts; Steelskin is lost at 2nd (last) impact; soft-wooden bar remains intact	3117
#54	manual insertion sideways	unprotected middle toe of turkey foot	incision	3418
#55	manual insertion sideways	unprotected turkey leg	multiple pieces of scale are chipped off (multiple impacts); eventually the propeller is almost stopped	3333
#56	manual insertion sideways	unprotected turkey toes	multiple pieces of scale are chipped off and finally one or two toes are fractured; significant propeller slowdown at toe fracture.	3813
#57	manual insertion sideways	Steelskin + rooster toe	toe remains intact under protection (first 2 impacts) but is amputated after protection is lost (3rd and 4th impact); strong propeller deceleration at 4th impact.	3991
#58	manual insertion sideways	-	(failed impact)	2970
#59	manual insertion sideways	rooster's nail	nail is amputated during the course of several impacts	3076
#60	manual insertion sideways	Steelskin + rubber + rooster toe	toe-tip is amputated (after multiple impacts) after loss of protection	3921
#61	failed	-	-	-
#62	manual insertion sideways	shoe laces with nuts	little distortion, eventually whacked away	2926
#63	manual insertion sideways	loose strings connected to a single nut	little distortion, eventually whacked away	4240

Distribution list

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