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The impact of force, time, and rotation on the transfer of ammonium nitrate: a reductionist approach to understanding evidence dynamics

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A.P. Gibson: Conceptualisation, Project administration, Supervision, Writing – review & editing

R.M. Morgan: Project administration, Supervision, Writing – review & editing

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Declaration of competing interest

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Abstract

Empirical studies evaluating the conditions under which the transfer of forensic materials occurs can provide contextual information and offer insight into how that material may have been transferred in a given scenario. Here, a reductionist approach was taken to assess the impact of force, time, and rotation on the transfer of an explosive compound. An Instron ElectroPuls™ E3000 material testing instrument was used to bring porous and non-porous surfaces adulterated with an ammonium nitrate into direct contact with a human skin analogue, controlling for the force of contact, duration of contact, and rotation applied during contact. Quantifiable amounts of ammonium nitrate were recovered from all of the recipient surfaces demonstrating that ammonium nitrate is readily transferred from one surface to another, even when contact occurs for a short duration with a relatively low force. More particulates were transferred from non-porous surfaces onto the human skin analogue, but the amount of ammonium nitrate transferred did not depend upon the force of contact, duration of contact, or the amount of rotation applied. However, when contact occurred and involved rotation, a greater transfer of ammonium nitrate was observed compared to those contacts occurring without rotation being applied. This approach complements more commonly-used holistic experiments that test multiple interacting variables in a realistic setting by isolating these variables, allowing them to be examined individually. This can be utilised to better understand the individual impact that specific variables have on the transfer of trace evidence in relevant crime reconstruction contexts.

Keywords

Forensic science; Evidence dynamics; Experimental studies; Crime reconstruction; Explosives; Instron ElectroPuls

1. Introduction

The need for data to underpin the evaluation and interpretation of trace materials has been highlighted in a series of high-profile reports in the United States [1], Canada [2], and United Kingdom [3-6]. Establishing the significance of trace materials relies on having an evidence base that can support source, activity and offence level propositions [7]. When identifying competing propositions, a number of factors are important, such as the circumstances of the case, availability of empirical support, observations that have been made and the expertise of the scientist [8]. This study sought to generate data that can be used to provide support for level 2 (activity) propositions in an attempt to answer "how" a trace was deposited by incorporating transfer properties.

Particle traces can address a wide range of questions facing the forensic investigator and contribute to crime reconstructions [9]. Given the principle of contact and transfer (**Fig. 1**), empirical studies assessing the conditions under which transfers of specific traces occur can provide contextual information and offer insight into how that trace may have been transferred in a given scenario [10].

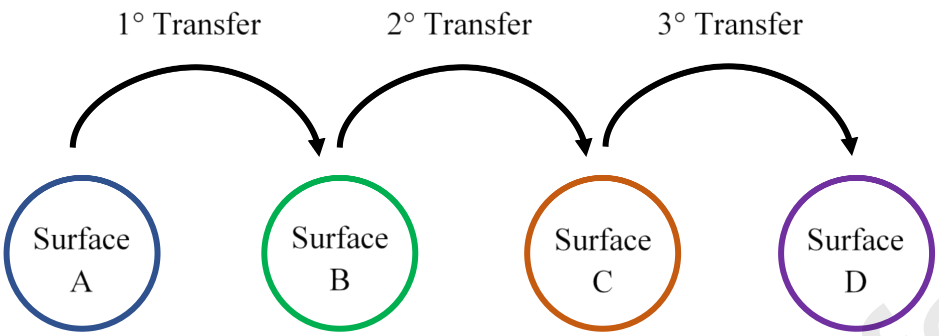

Fig. 1. Overview of primary (1°), secondary (2°), and tertiary (3°) transfer. This is predicated on sufficient trace being available for transfer.

Use of explosive materials by criminals and terrorist groups poses a significant threat to society through impacting public safety, political stability, and the global economy [11]. The direct handling of explosive materials by individuals has been shown to result in a significant transfer of that material onto their hands [12]. Once acquired onto the hands, the subsequent transfer of these explosive residues onto various surfaces is therefore likely to occur when that individual comes into contact with them. As such, it is important to understand the dynamics of how explosive materials may have been transferred onto various surfaces through contact and handling. Transfers resulting from illicit activities is of relevance to crime reconstructions and can provide valuable intelligence that can inform an investigation [9].

With respect to other forensic materials, there is a relatively small literature base pertaining to the transfer and persistence of explosive traces. Previous studies have assessed the transfer and persistence of explosive materials onto the hands of individuals through direct handling [12], in consecutive fingerprints [13], and in hair [14] under controlled conditions. There have also been, studies that have sought to offer insights into the transfer and persistence of traces have typically adopted experimental designs that seek to mimic forensically relevant scenarios [15-18]. However, this approach is unable to separate individual variables within a specific scenario to establish the mechanics of what is being observed. A reductionist approach that seeks to assess each variable one at a time in a controlled and repeatable manner offers a complementary approach that can identify how each individual variable impacts on others in a complex system. These data can then be incorporated with data derived from 'real world' studies to develop models that can be used to underpin inference and evaluation of specific traces.

The ElectroPuls™ is a state-of-the-art dynamic instrument for material testing produced by Instron®. It applies a force to a sample and measures the resulting change in length, allowing material properties such as stress and strain to measured [19]. These devices, of which those produced by Instron® are the most common, are frequently used in the automotive, biomedical, and construction industries to assess the mechanical properties of newly developed materials [20]. The ElectroPuls™ E3000 provides a range of dynamic and static loads up to 3,000 N, as well as providing torsional forces [19]. All are highly controllable with great precision and reproducibility [21-23]. In this reductionist experimental study, an Instron ElectroPuls™ E3000 was used to bring either a porous or non-porous surface adulterated with an explosive residue into direct contact with a human skin analogue (recipient surface), controlling for the force of contact, duration of contact, and rotation applied during contact. The amount of explosive residue transferred onto the recipient surface was then measured to isolate the individual impact that force, time, and rotation have on the percentage of the residue transferred. This can aid in developing an understanding of the proportion of explosive particulates transferred, through direct handling of explosive compounds and subsequent contact surfaces as well as innocent transfer arising from contact with contaminated surfaces, under different testing parameters.

2. Materials and Methods

2.1 Transfer and Recipient Surfaces

Unfinished medium-density fibreboard (MDF) (a porous transfer surface) and stainless steel (non-porous transfer surface) were sourced from local vendors. Each surface type was cut into 1 x 1 cm^2 squares (MDF: n = 36; stainless steel: n = 36), placed into individual plastic holders, and affixed with Blu Tack®. This was to prevent cross contamination as well as the trace being exposed to the environment, thereby minimising any loss of the trace. Chamois (*R. rupicapra*) leather (Amazon, UK) was selected as a human skin analogue for the recipient surface as it has been shown to simulate both the mechanical and frictional contact behaviour of human skin [24,25]. In order to reproduce the oil content of human skin, the leather was preconditioned by wearing under clothing for a period of eight hours to transfer dermal oils onto the recipient surface. The leather was then cut into 1 cm^2 circles (n = 72), each stored in a 5 mL glass vial with a plastic lid.

2.2 Application of Ammonium Nitrate to Transfer Surface

Ammonium nitrate was selected as the explosive compound for this study due to its relative safety and stability. A working solution of ammonium nitrate with a concentration of 1,000 mg/L was prepared by weighing out 500 mg of ammonium nitrate (99.0% purity; Sigma Aldrich, Gillingham, Dorset, U.K.) and diluting to volume with methanol (HPLC grade; Sigma Aldrich, Gillingham, Dorset, U.K) in a 0.5 L volumetric flask. The approximate centre point of each of the transfer surfaces (MDF and stainless steel) was spotted with 100 μL of the working solution and left uncovered for thirty minutes to allow the solvent (methanol) to evaporate and the solute (ammonium nitrate) to recrystallize onto the surface.

2.3 Instron ElectroPuls™ E3000

An Instron ElectroPuls™ E3000 (Instron, High Wycombe, UK) was used to independently control the contact force (in newtons), duration of contact (in seconds), and rotation (in degrees) applied during contact, in order to assess their impact on the amount of ammonium nitrate transferred onto a recipient surface, a human skin analogue, following the controlled contact with a porous and non-porous surface adulterated with ammonium nitrate. The variables tested were contact force, duration of contact, and rotation applied during contact (**Table 1**).

Table 1
The control factors and variables tested in each experimental run.

Experiment	**Control Factors**			**Variables**	
	Force (N)	Rotation (°)	Recipient Surface	Transfer Surface	Time (s)
1	150	0	Leather *(Human skin analogue)*	MDF *(Porous)*	2
2					60
3					150
4					300
5				Stainless Steel *(Non-porous)*	2
6					60
7					150
8					300

Experiment	**Control Factors**			**Variables**	
	Time (s)	Rotation (°)	Recipient Surface	Transfer Surface	Force (N)
9	30	0	Leather *(Human skin analogue)*	MDF *(Porous)*	10
10					60
11					120
12					240
13				Stainless Steel *(Non-porous)*	10
14					60

15					120
16					240
Experiment	**Control Factors**			**Variables**	
	Time (s)	Force (N)	Recipient Surface	Transfer Surface	Rotation (°)
17	30	150	Leather *(Human skin analogue)*	MDF *(Porous)*	90
18					180
19					270
20					360
21				Stainless Steel *(Non-porous)*	90
22					180
23					270
24					360

Operation of the ElectroPuls™ E3000 was controlled through Instron WaveMatrix™ software (*version 1.8.383.0*). For dynamic and static loading, the ElectroPuls™ E3000 was fitted with a ±250 N Dynacell (dynamic load cell) with a load weighing accuracy of ±0.5% of measured load or ±0.0005% of the load cell capacity (whichever is greater). Using the auto-tune function in the software, the stiffness value for both sample surfaces (MDF and stainless steel) was established to be 1.446 N/m. Once the instrument had been tuned, a three-step method was created to deliver precise and reproducible contact between the surfaces (**Fig. 2**). The first step involved establishing a ramp waveform which controlled the speed at which the two surfaces were brought into contact with one another (0.05 mm/s). The second step related to the hold waveform which dictated the time and force which the two surfaces were held under compression. The final step was a ramp waveform which dictated the speed at which the two surfaces were pulled apart from one another (0.05 mm/s).

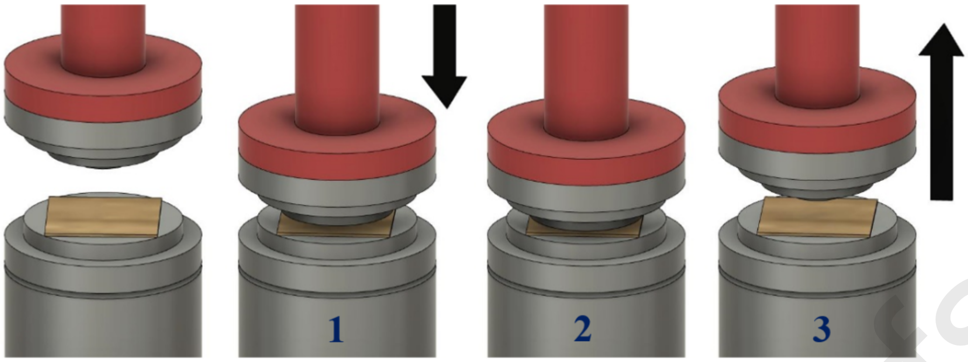

Fig. 2. Three-step method used when assessing the amount of ammonium nitrate transferred onto the recipient surface as a function of force and time. (1) The surfaces were brought into contact with one another at a speed of 0.05 mm/s until the defined contact force had been obtained (2) The two surfaces were held under the compression for the defined duration of time (3) Contact between the two surfaces was removed at a speed of 0.05 mm/s.

For the torsional testing the ElectroPuls™ E3000 was fitted with a ±5 kN Dynacell with a load weighing accuracy of ±0.5% of measured load or ±0.0025 N capacity (whichever is greater), with a torsional range of ±25 Nm. For these tests, the three-step method remained in place but with an additional rotation applied on the constant force hold (step 2) (**Fig. 3**). This rotation was applied in degrees per second. The angular velocities for each rotation (90°, 180°, 270°, and 360°) were as follows: 3°/s; 6°/s; 9°/s; 12°/s, with the hold waveform modified to apply these angular velocities over the duration of the hold time (30 s).

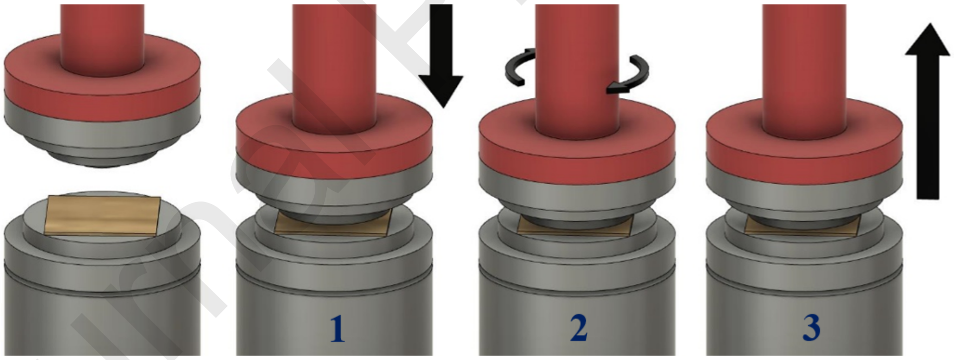

Fig. 3. Method used when assessing the amount of ammonium nitrate transferred onto the recipient surface as a function of the amount of rotation applied during contact. (1) The surfaces were brought into contact with one another at a speed of 0.05 mm/s until compression at 150 N was achieved (2) The two surfaces were held under the compression at 150 N for 30s during which a rotation was applied with an angular velocity of either 3°/s, 6°/s, 9°/s, or 12°/s depending on the extent of rotation assigned (3) Contact between the two surfaces was removed at a speed of 0.05 mm/s.

The transfer and recipient surface were affixed to compression discs (platens) using double-sided tape. The compression platen with the transfer surface was physically attached to the Dynacell™ dynamic load cell and the compression platen with the recipient surface was magnetically attached to the static load cell (**Fig. 4**). Each contact force, duration of contact, and amount of rotation during contact were assessed in triplicate for both surface types (porous and non-porous). For each run, the load registered by the Dynacell™ dynamic load cell was recorded.

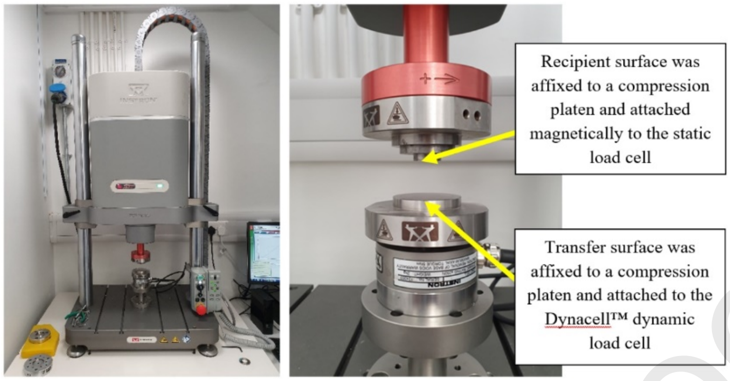

Fig. 4. Instron's ElectroPuls™ E3000 system (left) and annotated close-up picture of the load cells highlighting the placement of the transfer and recipient surfaces (right).

2.4 Extraction of Ammonium Nitrate from Recipient Surface

To each of the recipient surfaces, 1 mL of methanol was added. Each sample was then placed on a Cole-Parmer™ Stuart™ See-Saw Rocker at 70 revolutions per minute (rpm) for 15 minutes. Following this time, the leather samples were wrung dry using a pair of forceps (cleaned with methanol between samples) and the solution transferred into a 2 mL screw cap autosampler vial. Each sample was analysed and quantified using liquid chromatography as described in **Section 2.5**. The extraction efficiency of the method employed was assessed by spotting five leather samples with 100 µL of the stock solution (1,000 mg/L) of ammonium nitrate and quantifying the amount of ammonium nitrate recovered following extraction.

2.5 Quantification of Ammonium Nitrate in the Extracts

All analyses were performed on a Shimadzu Prominence UFLC (Ultra Fast Liquid Chromatography) System with ultraviolet (UV) detection. With respect to ammonium nitrate, the nitrate ion (NO_3^-) absorbs UV radiation and is therefore amenable to UV detection [26]. The analytical method used was adapted from the Environmental Protection Agency Method 8330B [27] and the detector wavelength optimised for the analysis of ammonium nitrate (see **Table 2**). The analysis of a standard solution of ammonium nitrate yielded a single Gaussian peak on flat baseline with a corresponding retention time of 1.8 minutes. As this was a targeted study to quantify the amount of ammonium nitrate transferred onto a recipient surface, the method employed is not amenable to mixtures, or instances in which other unretained compounds in a given sample may interfere with signal obtained from the detector.

Table 2
Chromatographic system and method used to quantify the percentage of ammonium nitrate transferred onto each recipient surface.

Liquid Chromatograph	Shimadzu Prominence UFLC
Detector Column	UV-Vis (SPD-20A)
Column Flowrate	Acclaim™ Explosive E2 (3.0 x 150 mm, 3 µm, 120 Å)
Flowrate	0.3250 mL min^{-1}
Mobile Phase	48:52 (v/v) of Methanol/Water
Gradient	Isocratic
Injection Volume	2.0 µL
Temperature	30°C
Detection	214 nm

In order to quantify the amount of ammonium nitrate present in each extract, a ten-point calibration curve was established (concentration range: 1 mg/L to 1,000 mg/L). Each of the ten calibration standards were injected onto the column in triplicate and the areas of the resultant peaks recorded. The peak areas were then plotted against the concentration of each calibration standard and the linearity evaluated (**Fig. 5**). The resultant R^2 coefficient of determination (0.999) indicted a linear relationship between concentration and the peak area over the range tested. Two calibration checks were performed to assess the reliability of the calibration curve in quantifying ammonium nitrate. This was carried out using two independently prepared solutions at concentrations of 350 and 800 mg/L. The accuracy, with respect to determining the true concentration of ammonium nitrate in a sample, was determined to be 99.1% and 99.6% respectively. Using the established calibration curve (y = 2.941(x) + 5.193), the concentration of ammonium nitrate in each extract was calculated by correlating its resultant peak area to a concentration.

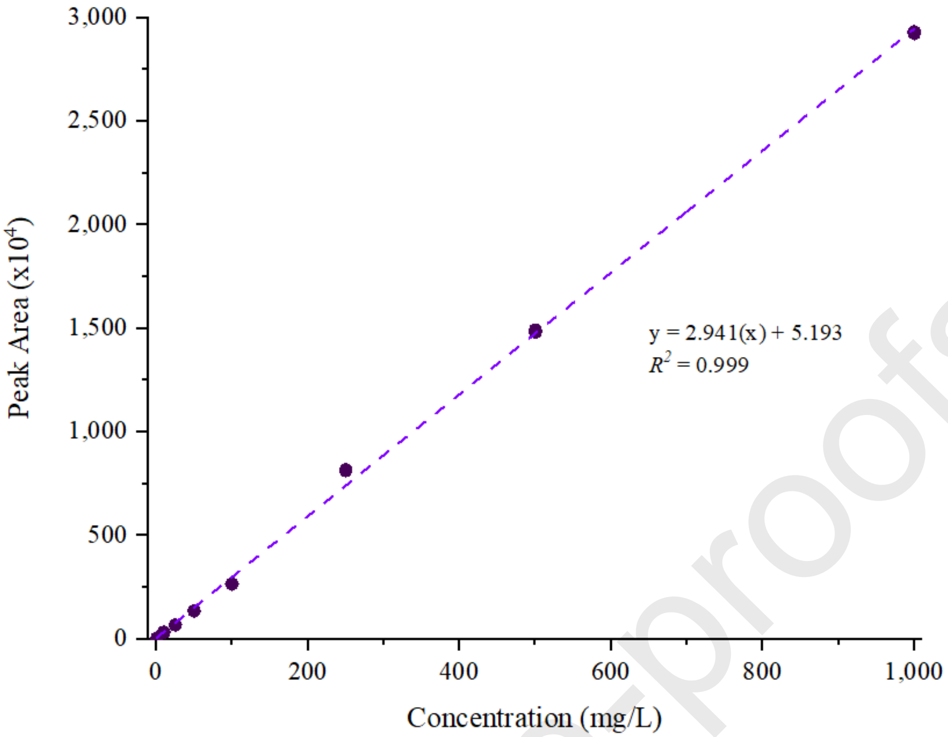

Fig. 5. Ten-point calibration curve of ammonium nitrate (reference standard).

2.6 Negative Controls

A series of negative controls were carried out to ensure that the response obtained from the analysis was a direct result of ammonium nitrate being detected and not a background contaminate present on the transfer and recipient surfaces. Methanol washes of each surface type were analysed along with a methanol blank and water blank. No measurable response at 1.8 minutes was observed in any of the negative controls.

2.7 Statistical Analyses

A one-way analysis of variance (ANOVA) was conducted to determine if the mean amount of ammonium nitrate transferred significantly ($p < .05$) differed with increasing force of contact, duration of contact, or extent of rotation applied during contact. Regression models were then fitted to sample data to assess if a relationship existed between the three contact parameters (contact force, duration of contact, and extent of rotation applied over contact time) and the amount of ammonium nitrate transferred. Based on these models, a two-sample *t*-test (assuming unequal variances) was conducted to compare the mean amount of ammonium nitrate transferred when contact involved rotation, to those contacts that did not involve rotation. Finally, in order to assess the impact of surface type on the transfer of ammonium nitrate, a two-sample *t*-test (assuming unequal variance) was performed. This was to ascertain if the mean amount of ammonium nitrate transferred onto the recipient surface significantly ($p < .05$) differed when the contact occurred with either a porous or non-porous surface. Cohen's *d*, the standardised mean difference, was used to measure the effect size. The means plus or minus one standard deviation are presented throughout. An alpha level of .05 (5%) was used for all statistical tests.

3. Results

3.1 Accuracy of Instron ElectroPuls™ Test Methods

As this is the first reported use of Instron's ElectroPuls™ for application to forensic science, it is important to demonstrate the repeatability and reproducibility of the process. Therefore, the following aspects were assessed:

- load accuracy – the load achieved in relation to the method;
- load consistency – fluctuations in load across the hold period;
- rotational accuracy- the rotation angle achieved in relation to the method;
- hold time accuracy- the length of time under prescribed load in the method.

In all tests, the load delivered was within 1.6% of the load requested. In the experimental setup, the actuator needed to be lowered down on to the sample, meaning it had to travel in free space before contact with the two surfaces occurred. As a consequence, the initial load at the point of contact was slightly higher than the load requested by the method. This was followed by an automatic adjustment by the instrument to compensate for this and is likely to be the reason for the small variation in loads observed. Once the hold level was reached, the load during the entire hold period was stable to within <±0.5%: 10.03 ± 0.03 N; 60.60 ± 0.04 N; 121.13 ± 0.07 N; and 242.03 ± 0.13 N. In the same way, the set rotation rates of 3°/s, 6°/s, 9°/s, and 12°/s were constant ($R^2 < .99$). The duration of the hold periods was confirmed by the time length of the hold step. **Table 3** demonstrates that the hold time for each test achieved the desired time within an average of 0.09 ± 0.01 seconds over the hold length.

Table 3
The actual hold times as compared to each of the four programmed times. %CV denotes coefficient of variation expressed as a percentage.

	Actual hold time (s)							
Programmed hold time (s)	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Avg. ± SD**	**%CV**
2.00	2.11	2.09	2.11	2.09	2.10	2.09	2.10 ± 0.01	0.47
60.00	60.10	60.09	60.08	60.10	60.09	60.09	60.09 ± 0.01	0.01

150.00	150.08	150.07	150.09	150.08	150.08	150.11	150.09 ± 0.01	0.01
300.00	300.12	300.09	300.09	300.10	300.06	300.08	300.09 ± 0.02	0.01

3.2 Extraction Efficiency

The extraction efficiency of the method employed to recover the ammonium nitrate transferred onto the recipient surface was determined to be 26.1 ± 0.6% (**Table 4**). As such, the measured amount of ammonium nitrate in each sample was adjusted, accounting for the extraction efficiency, to provide a more accurate representation of the actual amount of ammonium nitrate that was transferred. Although a relatively low recovery was obtained, this was not unexpected, as other studies have also highlighted the difficulties of recovering explosive compounds from porous surfaces [28]. Despite this, the extraction method provided consistent results (%CV = 2.3%) and as such, enabled meaningful comparisons with respect to the transfer of ammonium nitrate (expressed as a percentage) under different testing parameters.

Table 4
The recovery efficiency of the extraction technique employed prior to analysis in order to assess the average amount of ammonium nitrate recovered during this process as well as the repeatability of the extraction method employed.

Leather Sample	Conc. Spotted (mg/L)	Conc. Recovered (mg/L)	Amt. Lost in Extraction (mg/L)	Recovery (%)	Avg. Recovery ± SD (%CV)
1	1000.0	260.7	739.3	26.1	26.1 ± 0.6 (2.3%)
2	1000.0	254.3	745.7	25.4	
3	1000.0	265.8	734.2	26.6	
4	1000.0	268.7	731.3	26.9	
5	1000.0	257.1	742.9	25.7	

3.3 The Impact of Force on the Transfer of Ammonium Nitrate

As the surface area of contact remained constant, the pressure was considered to be the best representation of force. The surface area for each sample was 1 cm^2 and therefore the pressures exerted ranged from 100 kilopascals (kPa) (when 10 N was applied) to 2,400 kPa (when 240 N was applied). As the average pressure of contact during a handshake for adult males is between 550 kPa and 690 kPa [29], the pressures assessed are representative of real-world scenarios.

Ammonium nitrate was readily transferred from both porous and non-porous surfaces onto the recipient surface, with non-porous surfaces consistently transferring more ammonium nitrate than porous surfaces.

The average percentage of ammonium nitrate transferred onto the recipient surface following contact with a porous surface was 11.5 ± 1.9%. For contact with non-porous surfaces this was 38.8 ± 2.3%. The amount of transfer was significantly different between the porous and non-porous surfaces ($t(22) = 30.24$, $p < .001$, $d = 13.47$), but the amount of ammonium nitrate transferred did not depend on the force of contact (non-porous surfaces: $R^2 = .17$, $F(1, 10) = 2.12$, $p = .176$ and porous surfaces: $R^2 = 0.08$, $F(1, 10) = 0.88$, $p = .371$) (**Fig. 6**).

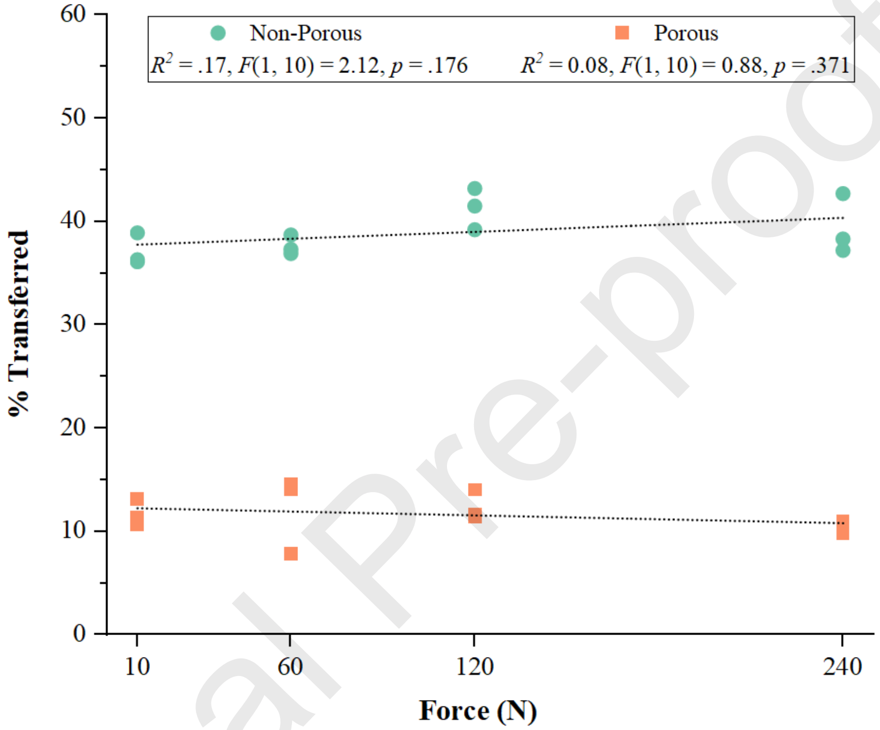

Fig. 6. The percentage of ammonium nitrate transferred onto the recipient surface following contact with an adulterated porous or non-porous surface at four different contact forces. No trend was observed.

3.4 The Impact of Time on the Transfer of Ammonium Nitrate

The contact times selected in this study provide a range, from a brief contact (2 s), such as that involved by brushing against a surface or a handshake, to an extended contact (300 s), in order to encompass a wide range of contact scenarios that might be encountered throughout routine day-to-day activities.

As was observed with force, non-porous surfaces consistently transferred more ammonium nitrate than porous surfaces ($t(22) = 15.26$, $p < .001$, $d = 7.33$). The average percentage of ammonium nitrate transferred onto the recipient surface following contact with a porous surface was 11.4 ± 3.0% and 34.0 ± 3.9%) from contact with an adulterated non-porous surface. The amount of ammonium nitrate transferred did not depend on contact time (non-porous surfaces: $R^2 = 0.02$, $F(1, 10) = 0.22$, $p = .653$ and porous surfaces: $R^2 = 0.08$, $F(1, 10) = 0.86$, $p = .374$) (**Fig. 7**).

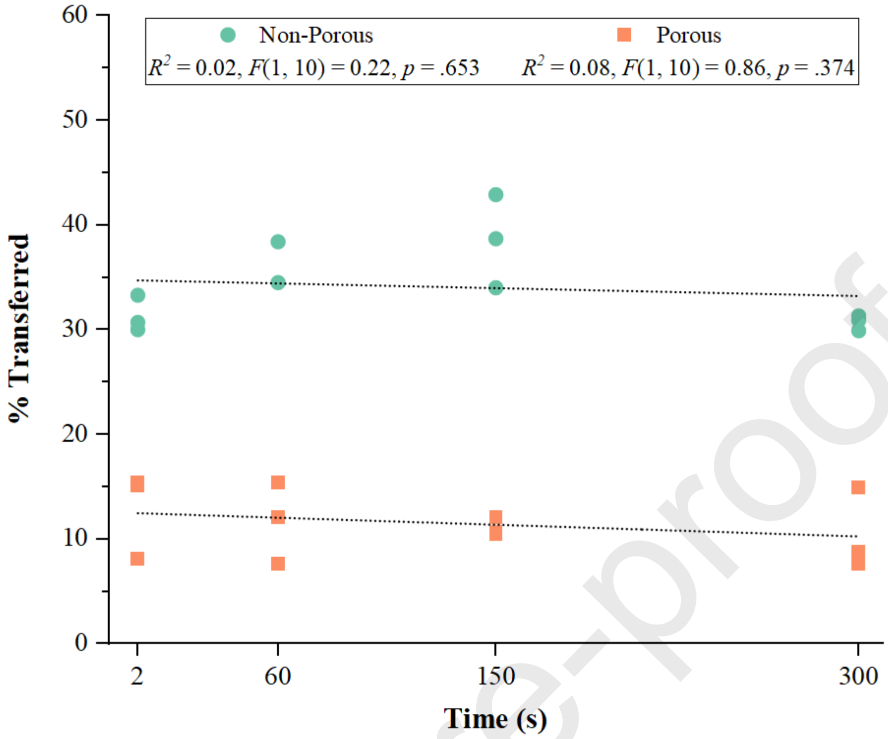

Fig. 7. The percentage of ammonium nitrate transferred onto the recipient surface following contact with an adulterated porous or non-porous surface at four different contact times. No trend was observed.

3.5 The Impact of Rotation on the Transfer of Ammonium Nitrate

As well as force and time, contact is also likely to involve rotation; a variable that has not previously been independently assessed with respect to the transfer of forensic materials. Again, non-porous surfaces consistently transferred more ammonium nitrate than porous surfaces ($t(22) = 27.80$, $p < .001$, $d = 12.33$). The average percentage of ammonium nitrate transferred onto the recipient surface following contact with a porous surface with rotation applied was 22.2 ± 2.3%. For contact with non-porous surfaces this was 51.6~~7~~ ± 2.7%. Although the amount of ammonium nitrate transferred did not depend upon the extent of rotation applied (non-porous surfaces: $R^2 = 0.13$, $F(1, 10) = 1.54$, $p = .244$ and porous surfaces: $R^2 = 0.19$, $F(1, 10) = 2.37$, $p = .155$) (**Fig. 8**), contact which involved any amount of rotation resulted in a significantly larger transfer of ammonium nitrate (non-porous: $t(34) = 11.63$, $p < .001$, $d = 4.11$; porous surfaces: $t(34) = 12.09$, $p < .001$, $d = 4.27$) when compared to contacts occurring without rotation (**Fig. 9**).

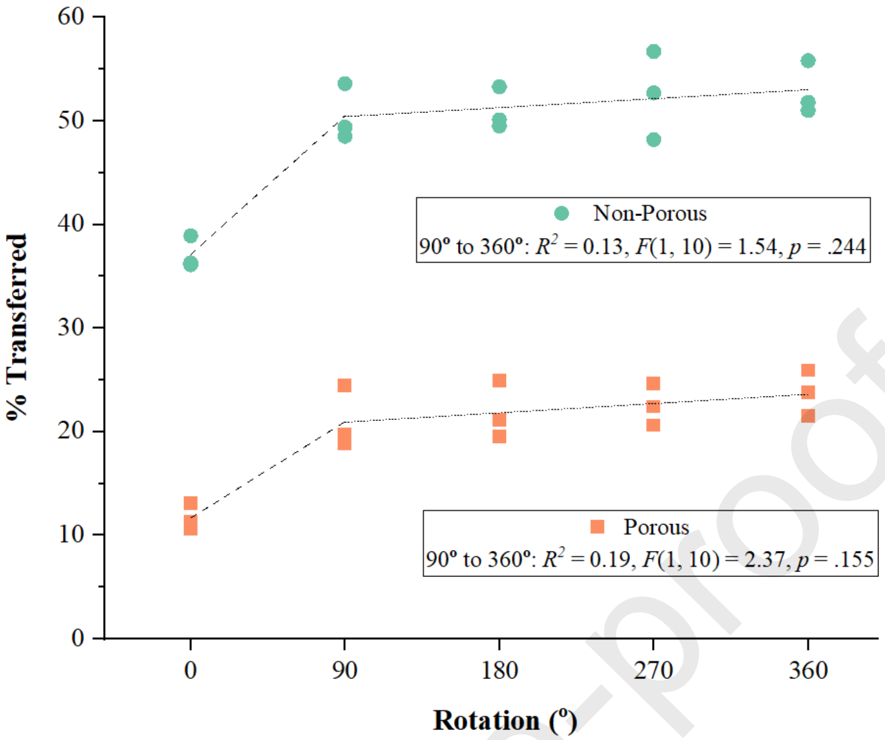

Fig. 8. The percentage of ammonium nitrate transferred onto the recipient surface following contact with an adulterated porous or non-porous surface without rotation and with four rotations applied during contact. The application of rotation during contact was significant; however, no trend was observed with additional rotation applied.

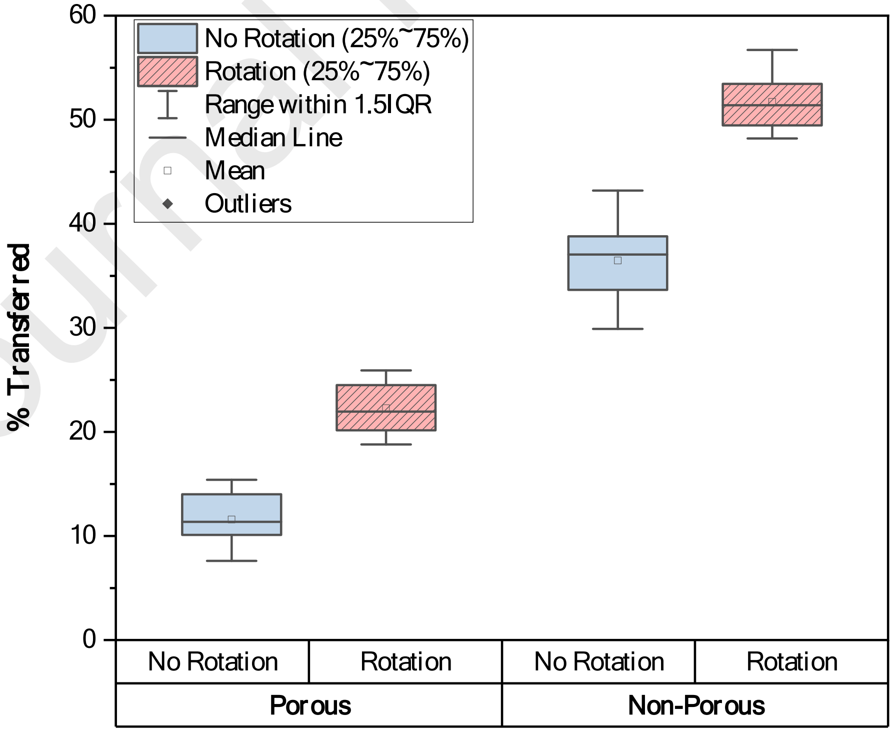

Fig. 9. Box plot comparing the amount of ammonium nitrate transferred onto a recipient surface from an adulterated porous or non-porous surface across contacts occurring without rotation and those with rotation.

4. Discussion

We have demonstrated a reliable and repeatable method to assess the transfer of particulates from one surface to another, in a manner that ensures accurate control over the contact force, duration of contact, and amount of rotation applied over the duration of contact. This is the first reported study on the use of the ElectroPuls™ E3000 for forensic applications and opens up the opportunity for using similar devices to isolate and explore fundamental aspects of transfer in forensic research.

In all scenarios, and under all of the testing parameters assessed, quantifiable amounts of ammonium nitrate were recovered on the recipient surface. This highlights that ammonium nitrate is readily transferred from one surface to another, even with low pressure (100 kPa when 10 N was applied across a 1 cm^2 surface) and short duration (2 s). A greater transfer of ammonium nitrate was observed when the transfer originated from an adulterated non-porous surface (**Fig. 10**). This was expected, and is in agreement with other studies that have assessed the impact of surface type on the transfer and recovery of forensic materials [30-33]. It is likely that this is due to the surface topography (as shown in the SEM micrographs of the surfaces (**Fig. 11**)) allowing particulates of ammonium nitrate to be retained within the pores of the MDF surface. Additionally, as the recovery surface (leather) was also porous, it is likely that this is what accounted for the low recovery observed in the extraction phase with direct spiked samples.

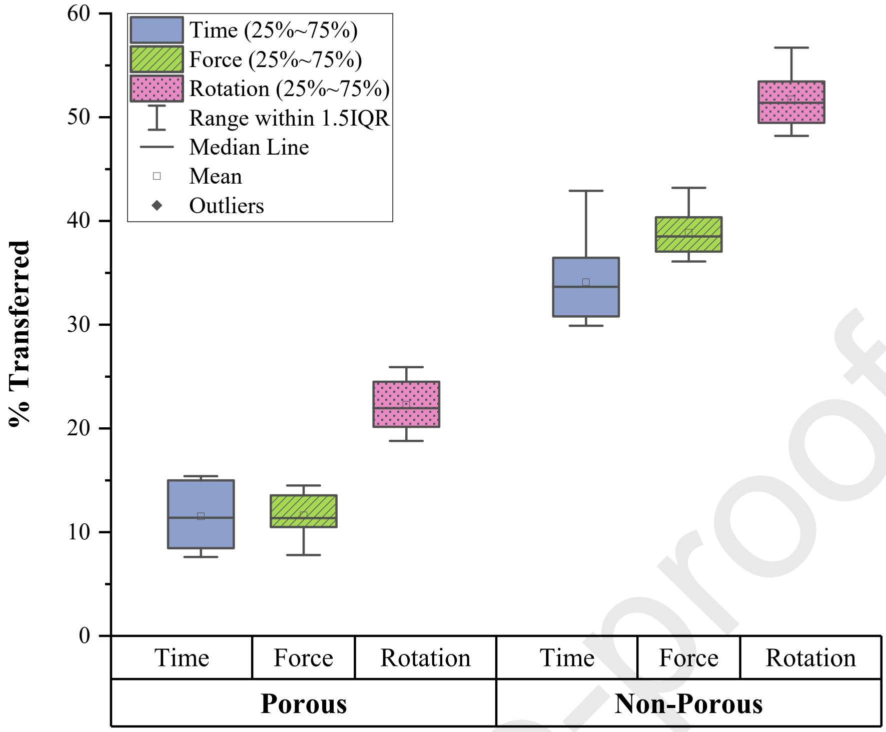

Fig. 10. Box plot comparing the amount of ammonium nitrate transferred onto a recipient surface from an adulterated porous or non-porous surface across different contact times, forces, and rotations.

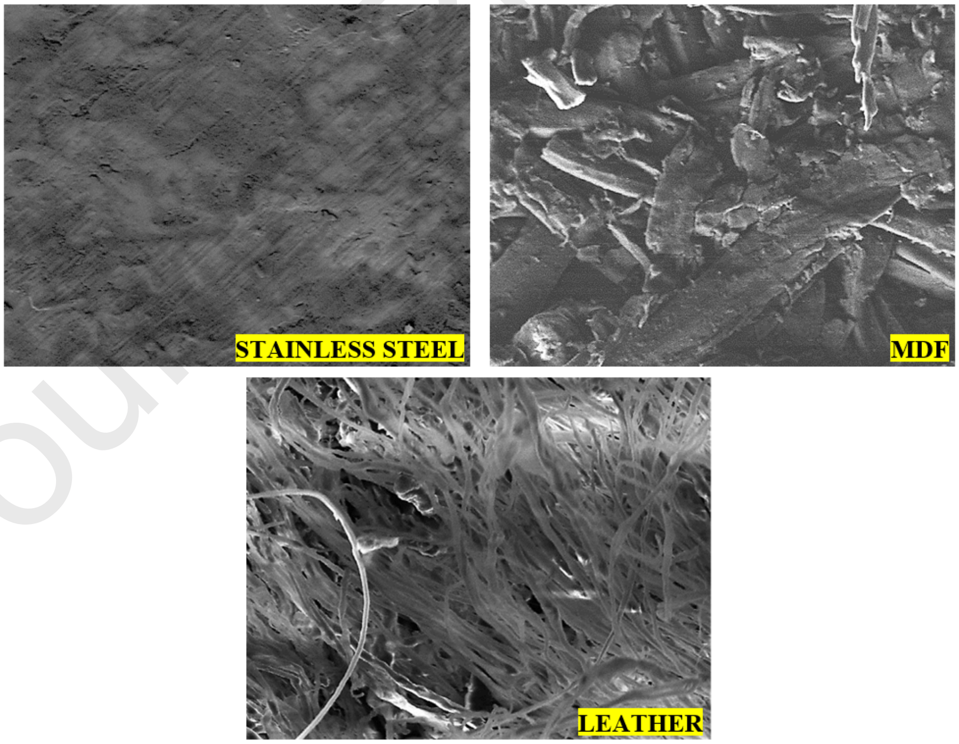

Fig. 11. SEM micrographs of the two transfer surfaces (top) and the recipient surface (bottom) at 500x magnification (HV = 18.0 kV; WD = 14 mm). Micrographs acquired using a Pemtron PS-230 scanning electron microscope (Pemtron, Seoul, South Korea) fitted with an Oxford Instruments X-act energy-dispersive X-ray

spectrometer system (Oxford Instruments, Abingdon, UK). Surfaces were sputter coated (time = 2 min; vacuum = 0.2 Torr; current = 0.2 mA) with gold prior to analysis using an SEM Coating Unit E5100 (Polaron Equipment, Hertfordshire, UK).

For both porous and non-porous surfaces, the force and duration of contact did not significantly impact the amount of ammonium nitrate transferred onto the recipient surface. This is in contrast to the work conducted by Gherghel et al., where an increase in transfer was observed with increasing contact times [34] and a decrease over time when contact involved friction [35]. However, these studies involved the transfer of volatile organic compounds (VOCs) rather than solid particulates, which is likely to account for the difference in findings. The impact of pressure has also been assessed with respect to the transfer of DNA, whereby, it was found that a larger portion of DNA is transferred with increasing pressure both directly from skin onto a surface [36] as well as between two surfaces [33]. Again, these findings contrast with the results presented here and further highlights the need to understand the different transfer dynamics of different forensic trace materials.

When contact involved rotation, a statistically larger transfer of ammonium nitrate was observed, compared to those contacts not involving a rotation. However, this was not dependent upon the extent of rotation applied. This suggests that any rotation at all will increase transfer, but once transfer has occurred, any additional rotation has no measurable effect. This is an important finding given that contacts, in most instances, will inherently involve an amount of rotation.

In order to build a robust empirical evidence base, a larger surface set should be assessed under similar testing conditions using a variety of surface types that one might encounter in a given day, and in certain scenarios. Additionally, the impact of these variables on the transfer of other evidence types (for example: gunshot residue, pollen, glass, fibres and drug residues) needs to be assessed in order to better understand transfer dynamics across a wide range of evidence types in order to aid and assist with forensic reconstructions. Other factors likely to impact upon the transfer of forensic materials, such as the particle size of the material being transferred and the electrostatic forces involved, are also important to consider in understanding evidence dynamics and warrant future investigation. Additionally, once transferred, the persistence of that material on a surface then becomes an important consideration.

Although the results of this study are akin to secondary transfer scenarios, this method can be expanded to include tertiary transfer scenarios. As such, this opens up an opportunity for having a powerful tool to assess the primary, secondary, and tertiary transfer dynamics of a number of different evidence types across different combinations of surface types.

This work provides a starting point for future studies in which controlled experimental studies addressing specific aspects of trace evidence dynamics can be conducted to better understand the individual impact that specific variables have on the transfer of trace evidence. Establishing the contribution of individual variables opens up possibilities for creating simulation models that can be adapted for specific crime reconstruction contexts.

5. Conclusion

This study sought to assess the impact of three variables, contact force, duration of contact, and the amount of rotation applied during contact, on the transfer of ammonium nitrate. Using the Instron's ElectroPuls™ E3000, a reliable and repeatable method was established to assess these variables independently by having automated control of the parameters in which the contact between the transfer and recipient surfaces occurred. The amount of ammonium nitrate transferred onto the recipient surface from both a porous and non-porous surface as a function of each of the three variables was then quantified. The results from this study have demonstrated that:

1) ammonium nitrate is readily transferred from both porous and non-porous surfaces over a range of contact forces, durations of contact, and rotations applied during contact;
2) a greater transfer of ammonium nitrate was observed when the transfer originated from an adulterated non-porous surface;
3) when contact occurred and involved rotation, a statistically larger transfer of ammonium nitrate was observed compared to contact not involving a rotation.

The results from this study provide empirical data on the independent impact of force, time, and rotation on the transfer of ammonium nitrate. This study highlights that when contact occurs, even with the smallest forces and shortest contact times, it is possible that detectable amounts of the explosive compound transferred can be recovered. These findings indicate that there is value for broader crime reconstruction endeavours in taking a reductionist approach when seeking to understand the mechanics of trace transfers. The potential such insights offer include the creation of simulation models where specific parameters can be adjusted for a given case in which the transfer of explosive residues, as well as other evidence types, may have occurred. The creation of such datasets will be valuable for modelling the movements of traces in order to enable more transparent and reproducible interpretations of pertinent trace materials in crime reconstructions going forward.

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Highlights

- Novel use of the Instron ElectroPuls™ for forensic applications
- Objective assessment of the impact of force, time, and rotation on trace transfer
- Transfer readily occurred across all test scenarios and conditions
- More particulates transferred from non-porous surfaces than porous surfaces
- Greater transfer was observed when contact involved rotation

Table 1
The control factors and variables tested in each experimental run.

Experiment	Control Factors			Variables	
	Force (N)	Rotation (°)	Recipient Surface	Transfer Surface	Time (s)
1	150	0	Leather *(Human skin analogue)*	MDF *(Porous)*	2
2					60
3					150
4					300
5				Stainless Steel *(Non-porous)*	2
6					60
7					150
8					300

Experiment	Control Factors			Variables	
	Time (s)	Rotation (°)	Recipient Surface	Transfer Surface	Force (N)
9	30	0	Leather *(Human skin analogue)*	MDF *(Porous)*	10
10					60
11					120
12					240
13				Stainless Steel	10

14				*(Non-porous)*	60
15					120
16					240

Experiment	**Control Factors**			**Variables**	
	Time (s)	Force (N)	Recipient Surface	Transfer Surface	Rotation (°)
17	30	150	Leather *(Human skin analogue)*	MDF *(Porous)*	90
18					180
19					270
20					360
21				Stainless Steel *(Non-porous)*	90
22					180
23					270
24					360

Table 2
Chromatographic system and method used to quantify the percentage of ammonium nitrate transferred onto each recipient surface.

Liquid Chromatograph	Shimadzu Prominence UFLC
Detector Column	UV-Vis (SPD-20A)
Column Flowrate	Acclaim™ Explosive E2 (3.0 x 150 mm, 3 µm, 120 Å)
Flowrate	0.3250 mL min^{-1}
Mobile Phase	48:52 (v/v) of Methanol/Water
Gradient	Isocratic
Injection Volume	2.0 µL
Temperature	30°C
Detection	214 nm

Table 3

The actual hold times as compared to each of the four programmed times. %CV denotes coefficient of variation expressed as a percentage.

	Actual hold time (s)							
Programmed hold time (s)	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Avg. ± SD**	**%CV**
2.00	2.11	2.09	2.11	2.09	2.10	2.09	2.10 ± 0.01	0.47
60.00	60.10	60.09	60.08	60.10	60.09	60.09	60.09 ± 0.01	0.01
150.00	150.08	150.07	150.09	150.08	150.08	150.11	150.09 ± 0.01	0.01
300.00	300.12	300.09	300.09	300.10	300.06	300.08	300.09 ± 0.02	0.01

Table 4
The recovery efficiency of the extraction technique employed prior to analysis in order to assess the average amount of ammonium nitrate recovered during this process as well as the repeatability of the extraction method employed.

Leather Sample	Conc. Spotted (mg/L)	Conc. Recovered (mg/L)	Amt. Lost in Extraction (mg/L)	Recovery (%)	Avg. Recovery ± SD (%CV)
1	1000.0	260.7	739.3	26.1	26.1 ± 0.6 (2.3%)
2	1000.0	254.3	745.7	25.4	
3	1000.0	265.8	734.2	26.6	
4	1000.0	268.7	731.3	26.9	
5	1000.0	257.1	742.9	25.7	