Application of biomechanical modelling to police shooting reconstruction

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Abstract: When investigating officer-involved shootings, scientific input provides an unbiased perspective to case evidence that assist both the objectivity and credibility of associated reconstructions. This paper demonstrates this by detailing the reconstruction of a recent shooting where multiple scientific tools and methodology were implemented. In order to differentiate between different possible narratives, tools such as synthetic bones, ballistic soap, human dynamic testing as well as human body numerical modelling were used. These tools show how the narrative available can be tied to the injuries reported through the use of a model supported by simple yet robust laboratory testing. In the exemplary case presented, the method was shown to exonerate the response of a police officer who discharged their weapon in self-defence while trying to subdue a violent suspect.

Keywords: officer-involved shooting; biomechanics; modelling; reconstruction; ballistics; wound path; forensics; police; scientific; homicide; pistol; injury; abrasion.

Reference to this paper should be made as follows: Desmoulin, G.T. (2019) 'Application of biomechanical modelling to police shooting reconstruction', *Int. J. Forensic Engineering*, Vol. 4, No. 3, pp.169–180.

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1 Introduction

Police officer-involved shootings can sometimes come under public scrutiny. However, when doubt is cast on the circumstances surrounding officer inflicted injuries and death, it is important to seek out scientific input. With the help of the scientific method, various narratives can be tested against and either rejected or accepted to a specific degree of confidence.

Methods and materials have been developed over the years to assist in the reconstruction of such incidents in order to answer questions regarding the circumstances of how specific injuries occurred. Ballistic soap (Fackler and Malinowski, 1988; Sellier and Kneubuehl, 1994), synthetic bone (Sterzik et al., 2017) and numerical modelling methods (Raul et al., 2007) are all tools that can be used to provide authorities with fact based answers.

This can be demonstrated using a recent case where doubt was cast on the circumstances surrounding fatal discharges from a police officer semi-automatic pistol. In this case, the family of the deceased did not believe their loved-one had been treated fairly as they suggested the officer had discharged their firearm unnecessarily and with ill intent. The media seemed to support this view and public street demonstrations were organised to protest the lethal use-of-force.

To analyse this incident, the injuries and wound paths were first examined before performing a shooting reconstruction and the necessary associated tests to complete a thorough investigation. After these tasks were completed, a scientific opinion on the likely circumstances leading up to the fatal incident could be provided.

2 Case presentation

2.1 Incident

Following a domestic dispute 911 call, two officers were dispatched to the scene of a domestic dispute where they learned that the alleged assailant had fled the domicile. Officers then split up to look for the individual. Shortly after, one of the officers spotted the suspect and gave chase on foot. Witnesses stated the officer instructed the suspect to stop on multiple occasions as he ran away.

When the officer caught up with the suspect, the officer attempted to arrest the suspect by using ‘hands-on’ physical force. Simultaneously, the officer instructed the suspect to get down on the ground, without success. Using a foot sweep technique the officer did get the suspect to the ground. However, with the officer being physically smaller than the suspect, the officer struggled to control the suspect and handcuff him. However, the officer offered more details, claiming that while the suspect laid on the ground, he managed to secure the suspect’s left arm while kneeling over him.

An eyewitness described seeing the struggle from a distance and compared it to a wrestling match. However, no witness was able to provide more visual details for the rest of the intervention due to the sheltered nature of the alley it occurred in.

While struggling to get a hold of the suspect’s right hand and apply the second handcuff, the officer noticed that his backup firearm located in a level 1 ankle holster had come unholstered and laid on the ground approximately 60 cm from the suspect’s head. During the subsequent struggle for control, the officer stated that the suspect reached for the backup weapon. The officer then swatted the backup weapon away from the suspect's hand to thwart his attempt to reach the weapon. However, by doing so, the officer moved from his position of dominance on top of the suspect and let go of the suspect's left hand.

As the officer pivoted back towards the suspect, he stated that he unholstered his primary firearm and noticed the suspect was getting up and lunging toward him with both hands reaching for his primary firearm. As he believed his life to be in danger, the officer discharged his firearm twice, in quick succession. Both rounds hit the suspect. One bullet penetrated around the navel area while the second bullet was found to have penetrated the back of the neck, in a downward trajectory. Subsequently, the officers claim to have applied handcuffs to the suspect and provided chest compressions until medical support arrived at the scene.

Considering the description of the arrest comes solely from the officer involved, the family and media challenged this version of events and suggested that the suspect had been handcuffed prior to the firearm discharge. Witnesses confirmed hearing both the handcuffs rattling prior to hearing the firearm discharge and described the two gunshots as happening in quick succession.

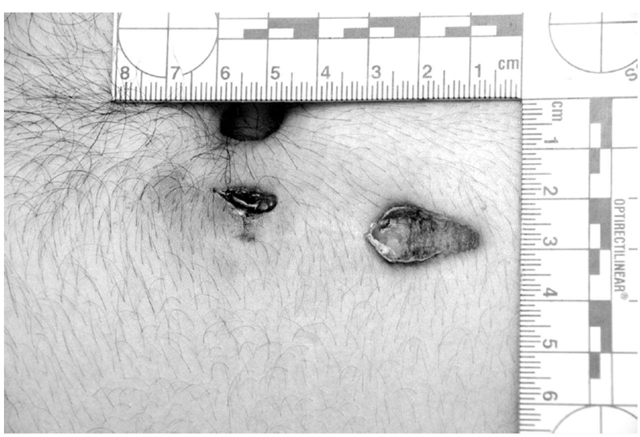
2.2 Injuries

Below are injuries of significance to the forensic biomechanical engineering analysis. The information presented originates from the medical examiner of the municipality where the incident occurred or from literature where otherwise noted.

The results of the autopsy revealed that the suspect was a male measuring 184 cm tall, weighing 82 kg and was in his early thirties.

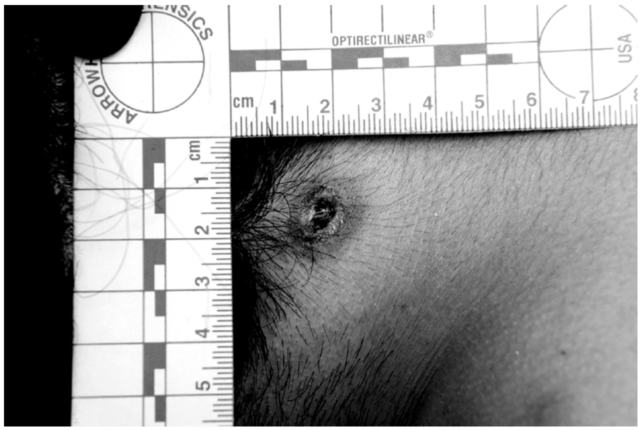
The medical examiner documented the gunshot wound to the abdomen, seen in Figure 1, as having an entrance wound 71 cm from the top of the head just left of and superior to the navel. The bullet was recovered from the left buttock 84.5 cm from the top of the head resulting in a 13 cm change in height. The trajectory of the bullet was described to have travelled backward, downward, and slightly left. It was noted that the bullet had just passed through the sacrum before coming to a stop in the soft tissue of the buttock.

Figure 1 Abdominal entry wound



Another entry wound, seen in Figure 2, was found on the back of the neck, 6 mm left of the posterior midline and 20 cm from the top of the head. The bullet was described to have travelled downward, frontward and minimally rightward and was recovered midline in the diaphragm.

Figure 2 Neck entry wound

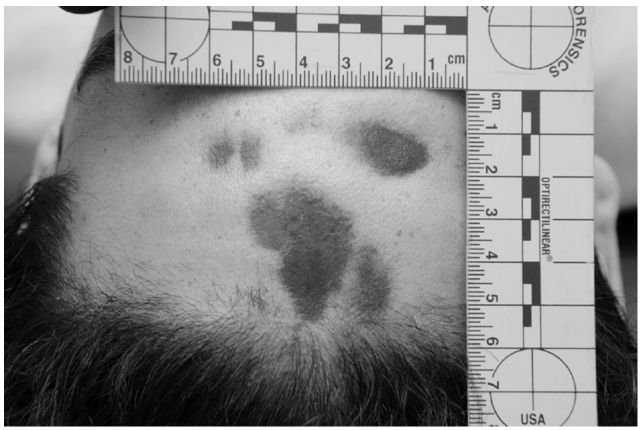


The medical examiner reported that the bullet caused multiple fractures as it passed through the spine. The posterior cervical spinous processes at levels C5–C7 were fractured, the left transverse processes of C6–C7, and the left lateral aspect of the vertebral body of C7 were also fractured. Correspondingly, the spinal cord was nearly transected at the C6–C7 level. Further, there was evidence of perforation of the aortic arch and near transection of the proximal left subclavian artery as well as sequential heart injury in multiple locations. The medical examiner described the injury as causing catastrophic paralysis with some possible function retained at the diaphragm and arm levels. The paralysis would have occurred quickly and cut most input from the central nervous system to the rest of the body below the site of injury.

Figure 3 Suspect's elbow abrasions

The suspect also presented with multiple abrasions to the elbows (Figure 3) and forehead (Figure 4). These kinds of abrasions are known to occur when a portion of the skin is removed via tangential contact with a surface of sufficient friction (i.e., rubbing). Abrasions are relevant from a biomechanical engineering perspective when determining movement patterns as they provide an independent source of forensic information regarding contact with an object (Reddy and Lowenstein, 2011).

Figure 4 Suspect's forehead abrasions



3 Reconstruction method

The most complete validation of a reconstruction is performed at full-scale. As such, a reconstruction was performed using a fully validated mathematical model.

When performing a biomechanical reconstruction, it is important to perform a series of key steps (Nahum and Gomez, 1994). First, defining the mechanism of the injury takes priority and was performed in this case with photographs and the medical examiner's report. The second component of a biomechanical reconstruction involves understanding and documenting the circumstances surrounding and leading up to the injury. However, due to the potentially biased nature of officer statements, objective testing and biomechanical analyses were performed in order to confirm or deny the details of the incident.

With this as foundation data, a physics-driven model's output was analysed and compared to sources of information including the suspect's injuries, the timing between shots, and the conclusions of the medical examiner.

4 Ballistic testing

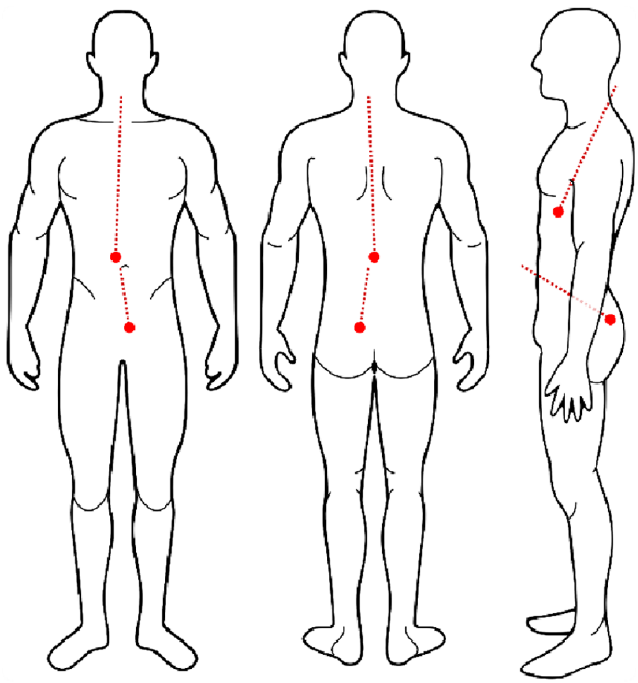
To properly quantify the contribution of the bullet penetration through the muscle and bone involved with the suspect's injuries, ballistic testing was designed and performed.

4.1 Method

Although ballistics can describe the kinematics of a bullet going through a homogenous material, the deceleration profile of a bullet going through multiple materials is more complex. Therefore, the bullet wound was modelled using synthetic materials and tested using live rounds in order to measure the force generated.

First, the human body was modelled for this test using ballistic soap (Concordia P. Llave of West Covina, CA) and bone simulant (SYNBONE AG, Malans, Switzerland). The dimensions of flesh and bone analogues were set to match the distances estimated from the autopsy report, which can be seen as illustrated by Figure 5.

Figure 5 Bullet trajectories through the body modelled from autopsy report (see online version for colours)



To reproduce the abdominal gunshot wound, the soft tissues were modelled with a soap block coupled with a 6 mm bone plate and a second soap block in order to represent the abdomen, sacrum, and buttocks respectively. The exact depth of the first block was adjusted between test shots in order to find the depth, which would result in a complete bone perforation representative of the incident.

Prior to testing, the soap was placed in an environmental control chamber regulated to 30°C for 24 h to best simulate tissue properties. The temperature was maintained during transport via interior vehicle environmental control and stacked in front of a regulated heat source at the shooting range, as can be seen in Figure 6. Immediately prior to testing, the temperature of the soap was measured using a DeWalt DCT414 Infra-red Thermometer as shown in Figure 7. The average temperature of the soap bricks measured throughout testing was 27.8 ± 1.5°C.

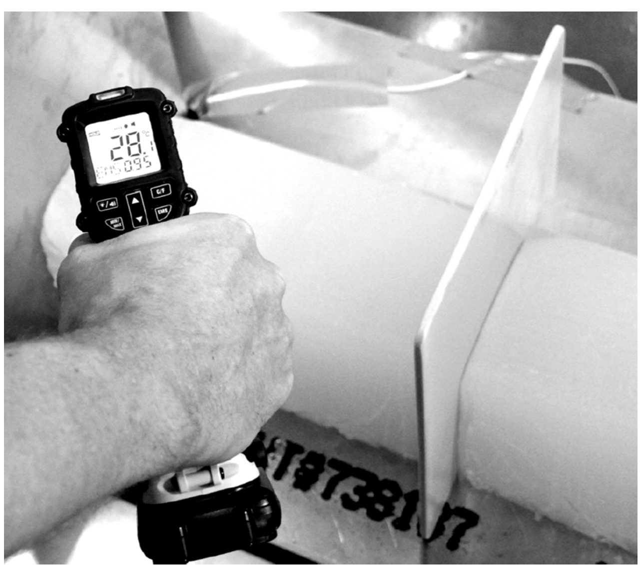
The tissue and bone analogue were placed on a mobile platform resting against a load cell (PCB, #208C05, Depew, NY). This load cell measured the resulting force profile caused by each bullet as it passed through the soft tissue and bone simulants.

A chronometer (Chrony F1-master series with LED lights with ± 0.5% tolerance which relates to approx. ± 1.5 m/s in this case) was also used to measure the muzzle velocity of the bullet (Shooting Chrony Inc., 2009).

The firearm used was the same make and model as the one fired by the officer in the incident, a Sig Sauer P229. The ammunition used was Remington Golden Saber 9 mm Luger 147 grain copper jacketed hollow-point bullet (#GS9MMC). This ammunition was considered sufficiently representative of the ammunition used by the officer (9 mm Luger).

Figure 6 Shooter's view through chronometer and to the target

Figure 7 Temperature measurement of the abdominal shot test



A second shooting test was also performed to examine the spread of rapidly fired shots. Therefore, in this dynamic test, the shooter was instructed to fire two rounds in 'quick succession' from a single-handed and non-outstretched arm position to a paper target approximately 42 inches away. This configuration was chosen in order to match the description provided by the officer in regards to relevant aspects of his shooting posture. This test was repeated three times.

4.2 Results

Shots with appropriate penetrations through synthetic bone and the second soft tissue block matched the injury descriptions on half of the trials performed. On average, the obtained muzzle velocities of the rounds were 296.1 ± 2.3 m/s. The average total distance penetrated into the soap and through synthetic bone was 0.27 ± 0.01m, and average force from these trials was 1551 ± 54 N. These tests allowed for the force of the round to be added to the model for increased accuracy.

Results for the dynamic shooting test showed that the second shot landed, on average, higher and to the left of the first bullet.

5 Modelling

5.1 Model preparation

The model used for this case was an Ellipsoid MADYMO model. All MADYMO models consist of rigid bodies with mechanical (inertial) properties, which are connected by joints (TASS International, 2010). The inertial properties of the rigid bodies and the range of motion of the joints are based on biomechanical data. Furthermore, the joint characteristics and mechanical properties of the various model segments have been tuned and validated using human volunteer and postmortem human subject responses in a variety of impact tests (TNO, 2013). The models' geometry and mechanical properties are dependent on the type and size of the model used.

The human body model was scaled to match the height and weight of the suspect involved in this case, with the scaling approach having been validated by the developers of the model (TASS International, 2017).

To obtain appropriate initial conditions, the statements supplied by the officer involved was tested using human surrogates. The situation was reenacted and filmed using minimal instructions in order to observe the body positions most likely to have occurred during the incident as shown in Figure 8. The body positions and approximate velocity involved in the altercations were then reproduced from the findings of video analysis. A list of the important initial parameters used can be found in Table 1. These parameters were generated from a combination of video analysis, chronometer results, static shooting tests, the autopsy report, calculations, dynamic shooting pattern test and literature regarding the skin-ground coefficient of friction.

Figure 8 Re-enactment of incident with key measurements using individuals of similar height as the suspect

Table 1 Model initial parameters

Human parameters	*Value*	*Units*
Torso angle (w.r.t. horizontal)	36.1	deg
Shoulder angle (w.r.t. Torso)	89.2	deg
Elbow angle (w.r.t. forearm)	118.6	deg
Forward velocity (upper body)	1.6	m/s
Coefficient of friction (w.r.t. ground)	0.5	n/a
Bullet parameters	*Value*	*Units*
Velocity	294.65	m/s
1st bullet angle (w.r.t. horizontal)	6.5	deg (+*y*)
1st bullet angle (w.r.t. vertical)	1	deg (–*z*)
1st bullet height (w.r.t. ground)	829	mm (+*z*)
1st bullet distance (w.r.t. hand)	304.8	mm (+*x*)
1st bullet distance (w.r.t. mid-line)	20.58	mm (+*y*)
2nd bullet angle (w.r.t. horizontal)	6.5	deg (+*y*)
2nd bullet angle (w.r.t. vertical)	0	deg
2nd bullet height (w.r.t. ground)	847	mm (+*z*)
2nd bullet distance (w.r.t. 1st bullet)	12.7	mm (+*z*)
2nd bullet distance (w.r.t. 1st bullet)	12.7	mm (–*y*)

5.2 Results

At the onset, the model was placed in the position identified in preliminary testing, shown in Figure 10, and imparted with an initial horizontal velocity as measured from the video analysis. The model's initial position was also set to coincide with the moment where the first bullet is fired. Through officer testimony it is reasoned but not confirmed that this first gunshot led to the abdominal injury. At 4 ms into the model run, this bullet reaches the suspect in the abdominal area in an angle that would agree with an impact through the pelvis terminating in the buttock, as suggested by the medical examiner's report.

Following the impact from the first bullet, the model's initial momentum carries the modelled suspect forward. The impact of the first bullet also contributes in a forward lean of the torso.

At 286 ms, the second bullet is fired, hitting the suspect at 290 ms into the simulation. This timing between shots is necessary in order to achieve the impact location in the neck similar to that found in the autopsy and described previously. Notably, the 286 ms aligns with independent research on shot-to-shot time intervals. As an example, the Columbia International Forensics Laboratory (Warren, 2012) found that, on average, trained shooters have a 250 ms delay between shots when firing with a semi-automatic pistol. Others have also found similar time frames (Haag, 2000; Lewinski, 2002) with a range of approximately 200–333 ms. Our finding falls directly within this range.

After 290 ms, the model assumes that the suspect is unable to provide voluntary muscle input below the C6–C7 levels because of the damage to the spine produced by the second bullet impact. The remainder of the simulation, therefore, involves the body falling to the ground under the influence of gravity and inertia.

Figure 9 (a) Side view and (b) bottom view of the forehead and elbow impact with the ground (see online version for colours)

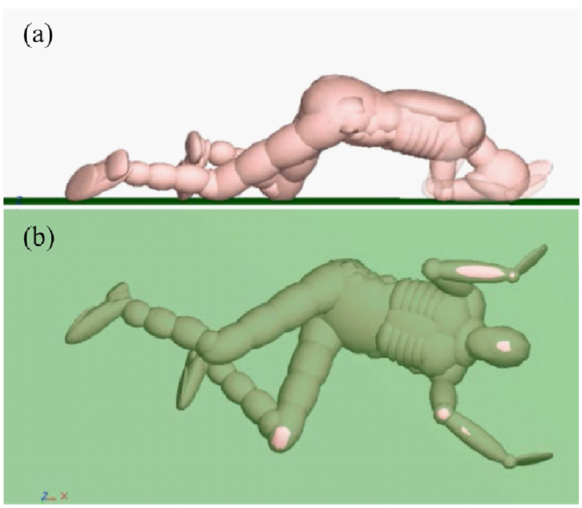
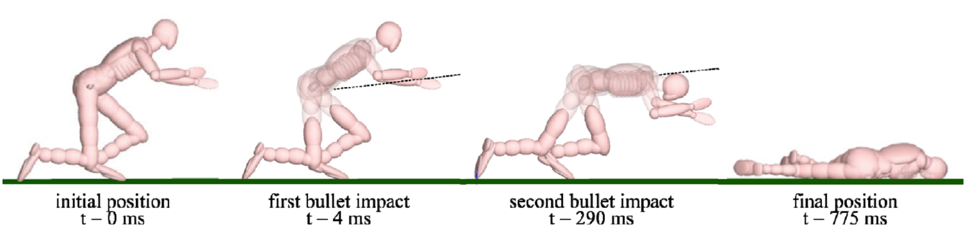


Figure 10 Key frames of model simulation showing human analogue scaled to suspect's dimension (see online version for colours)



From 540 to 775 ms into the simulation, the model's forehead and elbows impact the ground as shown in Figure 9. The simulation then shows the head and elbows slide along the ground for approximately 60 ms and the head comes to rest in a partially lateral position.

6 Discussion

The forensic biomechanical investigation sought to accept or reject the officers statements by testing against those same statements. Nothing in testing or the models outcome was in conflict with the officer's statements. Meaning that the officer's description of the altercation that lead to the suspect's death is probable and could not be rejected using scientific method. Multiple independent data elements confirmed this statement.

First, the bullet wound locations could be produced from the same movement patterns despite their significantly different entry points on the suspect's body. Despite the abdominal wound and neck wound being on two different sides of the body, the model was able to show how it is probable for two shots originating from a similar position to generate such injuries and be consistent with the officer's statements. The wound path trajectories showed in the model also matched the ones described by the medical examiner in the autopsy report. Therefore, the officer would not have had to relocate between shots in order to produce these gunshot wounds.

Second, both entrance wounds were produced when a 286 ms delay between each shot was introduced in the model. This finding is in agreement with independent literature that suggests that officers discharging their weapon take approximately 200–333 ms between shots when firing a semi-automatic pistol (Haag, 2000; Lewinski, 2002; Palmer, 2009; Warren, 2012). This suggests that the two shots were taken without the officer having time to perceive the outcome of the first bullet before firing the second one, which is consistent with research on the time necessary for an officer to recognise a change in threat and stop shooting (Lewinski and Redmann, 2009).

Third, both the forehead and elbow impacts seen in the model simulation after the bullets' impact can be correlated with the abrasions sustained by the suspect. As was reported by the medical examiner, the suspect's forehead and elbows showed signs of abrasion in a similar area as the contact areas seen in the simulation. These kinds of abrasions can be attributed to the impact and subsequent sliding against the pavement suggested by the model. This lends even further credence to the possibility that the model's simulated kinematic response corresponds to the narrative offered by the officer.

7 Conclusion

Within a reasonable degree of professional certainty, the movement patterns seen in the model simulation agree with the events described by the officer involved. Simultaneously, it refutes the narrative where the suspect had been handcuffed prior to discharge and subsequently fired upon while posing no threat. This was presented in the court of law and the jury was unanimous in finding the officer 'not guilty' on all counts.

This case exemplifies the usefulness of shooting reconstruction methods and biomechanical analyses when dealing with police officer-involved shootings.

Acknowledgements

The authors would like to thank the entity who requested to remain anonymous for funding this important research and for providing the authors with unfettered discretion in designing their methodology, conducting their investigation, and reaching their conclusions. Furthermore, the authors extend their gratitude to the following GTD Scientific Associates: Mr. Mark Nolette and Mr. Nachiket Pendse for their invaluable technical assistance and Ms. Christina Stevens (Operations Lead), for her continued support of R&D activities within our company.

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