Workflow for accurate injury reconstruction in forensic investigations

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Abstract: We present a workflow developed for injury reconstruction in forensic investigations. The workflow comprises four steps: defining the injury, planning the analysis, conducting the analysis and discussing the results of the analysis. The critical step is the discussion of the analysis in which all data are assessed for consistency. In particular, the discussion includes comparison of the data derived from the case material with independent objective data acquired through analysis. Any inconsistency becomes grounds for reassessment of the original assumptions and possible additional analysis to bring all data into harmony. Only after all inconsistencies have been resolved can conclusions be drawn.

Keywords: workflow; injury; reconstruction; forensic; investigation.

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Biographical notes: Geoffrey T. Desmoulin is the Principal of GTD Scientific Inc. (www.gtdscientific.com). He offers biomechanical consulting services on behalf of clients throughout North America. His focused practice areas include injury biomechanics, incident reconstruction and physical testing with a sub-specialty in the science of violence®. He has been retained in significant complex injury litigation cases involving municipal police department use of force, violent encounters and TASER International to name just a few examples. Furthermore, he developed landmark testing and shooting reconstruction methodology was recently upheld as reliable and admissible by the US Federal District Court for the 9th District of California.

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1 Introduction

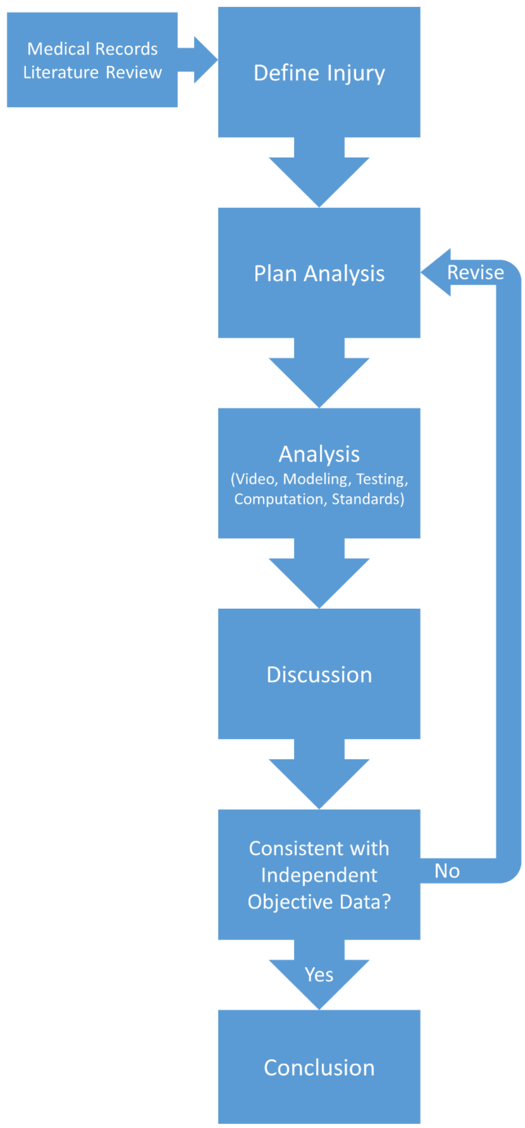
Forensic analysis that attempts to determine the cause of injury must frequently be performed with incomplete data. Consequently, a well-defined process for determining the approach, including methodology and workflow is essential to achieve the best results. Nahum and Gomez (1994) described the process of injury reconstruction as "a method of analysing an accident and resulting injuries to produce a comprehensive description of the injuries in both medical and engineering terms which reflect the injury and associated causative factors." Once the injury has been defined, there are frequently many possibilities as to the mechanism which caused the injury. The challenge is to determine which mechanism is consistent with available data. Nahum and Gomez (1994) presented a workflow for injury reconstruction in the case of vehicle accidents. Their iterative process consists of adjusting body and vehicle motions within parameters established by the available data until a result is achieved that provides a plausible explanation for the injuries. Their focus is primarily on the location of injury and the force that would be necessary to produce a given type of injury. Evidence from the vehicle can establish points of contact with the body and analysis of vehicle motion can be used to estimate the forces applied to the body.

A framework for injury reconstruction, which can be applied to any injury, has been developed by GTD Scientific, Inc. (GTD). A distinguishing feature of this framework is the requirement that conclusions are consistent with independent objective data (Figure 1). Lawsuits frequently involve disputes centered on conflicting accounts of an incident. Accounts of witnesses and involved parties provide a narrative that can set the scene. However, these accounts cannot be accepted as reliable without supporting evidence. Therefore, it is necessary to determine the consistency of testimony with independent objective data. The analysis can begin with a set of presumptions based on testimony, but ultimately it must be supported by independent objective data.

The process developed by GTD consists of first defining the injury based on medical records and then accounting for the injury based on plausible mechanisms consistent with a review of relevant published literature on the injury biomechanics. Issues that need to be considered when defining the injury include physical tolerance, timing of the injury and the mechanism of the injury. Physical tolerance is a determination of the magnitude of the force necessary to cause the injury, which is frequently expressed as a range about a mean value from which probability of injury can be calculated. Timing of the injury is important for determining when the injury occurred in the sequence of events and may be established through analysis. The mechanism of injury may be known, e.g., from video evidence or by agreement. In some situations, there may not be proof of the mechanism but its aetiology may have been established in published research, i.e., the mechanism can be inferred from prior knowledge. However, it is also possible that the mechanism of injury is unknown, in which case analysis is likely required to determine the mechanism of injury.

The initial injury reconstruction is based on accounts of witnesses, medical records or autopsy reports and knowledge of the mechanism of injury obtained from a review of relevant literature. Videos and photos of the location of bodies, objects, damage, blood stains, etc. relevant to the incident can provide independent objective data to corroborate witness accounts as well as input for quantitative analysis. The analysis is planned based on the investigative questions and available or missing information required to address these questions. Analysis is necessary to establish causal relationships between the injuries and the dynamics of the incident. This analysis may involve methods such as photogrammetry, impact tests, computer models and mechanical calculations. In some cases, ergonomic analysis may be necessary to determine the cause of the injury.

Figure 1 Workflow diagram for injury reconstruction (see online version for colours)



In general, a single line of reasoning does not conclusively answer all of the questions addressed by the investigation. Therefore, a discussion of the evidence, results of the analysis and independent objective data is required to draw conclusions. The discussion includes elements such as a review of standards relevant to the incident and whether the standards were observed, results of tests which were performed as part of the analysis and the probability of risk of injury under the conditions which existed at the time of incident, as determined by the analysis. However, before any conclusions can be drawn, agreement must be established between the different lines of reasoning. Critically, any conclusions drawn from witness accounts or evidence recovered from the scene must be consistent with independent objective data. Generally, the independent objective data are derived from the analysis, although they may also come from outside sources such as published validated studies.

If the results from different lines of investigation are inconsistent or there is inconsistency with the independent objective data, the analysis must be revisited as there may be an error or assumptions may be invalid. In addition to repeating the analysis, it may also be necessary to review the injury literature again to ensure that the referenced studies are appropriate for the specific mechanism of injury and demographics of the case. The final conclusions should represent a harmony of the data gathered from the case material and independent objective data derived from the analysis and referenced literature.

In this paper, two case studies are presented to illustrate the workflow developed by GTD with a particular focus on how consistency with the independent objective data was incorporated in determining the final conclusions.

2 Case 1

The first case involved a shooting in which a suspect was shot twice and killed during an altercation with the apprehending police officer. The only eyewitness account of the shooting was that of the officer, although several witnesses testified to hearing the two shots and stated they were in relatively quick succession, without any significant pauses in between. GTD was retained to biomechanically determine the relative motion between the officer and the suspect during the incident, including analysis of the shooting.

The first step in GTD's investigative process is to define the injury. The autopsy report indicated one gunshot wound to the abdomen just left of and superior to the navel. The bullet was recovered from the left buttock, having perforated the sacrum. The entry point of the second gunshot wound was located on the neck near the posterior midline just below the hair line. The bullet was recovered midline in the diaphragm. Posterior cervical spinous processes were fractured at levels C5-C7, the left transverse processes of C6-C7 were fractured and the left lateral aspect of the vertebral body of C7 was fractured. The spinal cord was nearly transacted at levels corresponding to C6-C7. In addition, 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 autopsy also revealed multiple forehead abrasions.

By combining information about the bullet entry point, the location of the internal injuries and the location where the bullet was recovered, it was possible to accurately reconstruct the path of each bullet. The locations of the head abrasions indicated where contact was made with the ground following the shooting. However, these data by themselves are insufficient to determine the relative positions and movements of the suspect and the officer during the incident. Consequently, additional independent analysis was required.

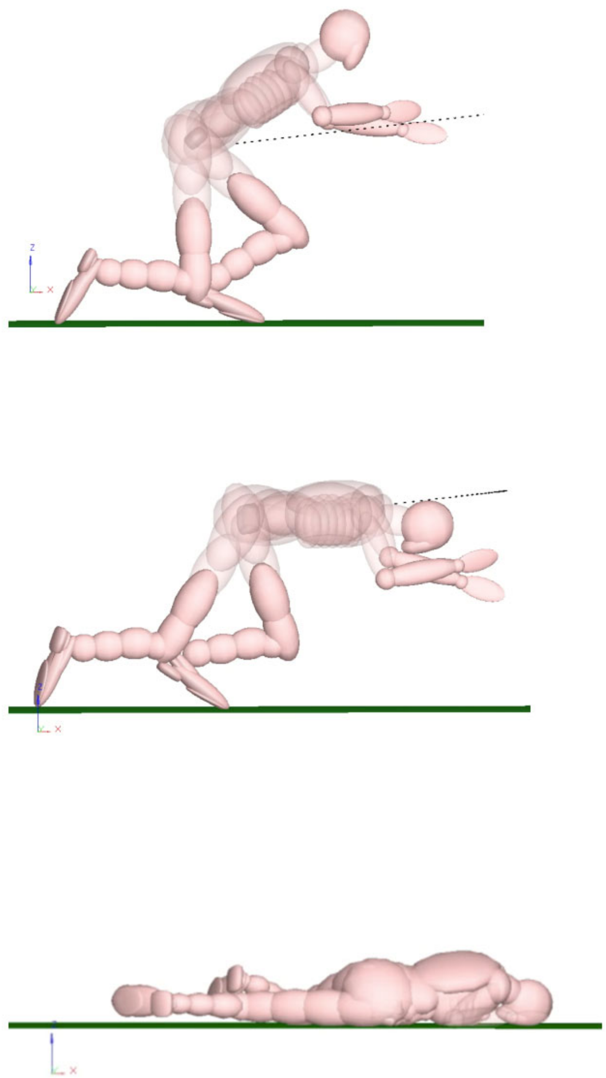
Although the bullet paths can be used to determine the orientation of the officer's firearm relative to the suspect and the orientation of the suspect's torso relative to the firearm at the time the shots were fired, the bullet paths do not constrain the position of the officer relative to the suspect. To better understand where the suspect and officer were situated, a reenactment of the incident was constructed based on the officer's account and recorded on video. In the reenactment, the suspect and the officer were facing each other and the suspect was in the process of rapidly getting up from the ground. The suspect reached for the officer's firearm as quickly as possible with both hands, as recounted by the officer. According to the account, the suspect's hand was approximately 30 cm from the muzzle of the firearm when the first shot was fired. The video of the suspect's movements in the reenactment was used to estimate the velocities and joint angles of specific body parts. In particular, it yielded values for the suspect's torso angle, shoulder angle, elbow angle and forward velocity of the torso. These served as initial conditions for a dynamic body model implemented in MADYMO.

Initially, it was thought that the momentum imparted by the bullets might have a significant impact on the motion of the suspect's body. Consequently, ballistics testing with a replica of the officer's firearm was performed to determine the bullet velocity, the penetration distance, the impact force impulse and firearm movement between successive firings. This involved shooting through a ballistic soap brick into a sheet of synthetic bone (SYNBONE). The travel distance of the bullets in the ballistic soap brick was compared to estimates of the travel distance in the suspect's body, based on the autopsy report and an anthropometric model of the suspect's body, and found to be in agreement. The dynamic ballistic test revealed that, on average, the second bullet hit the target above and to the left of the first bullet, which corresponded to the autopsy descriptions of the bullet wound entry points.

The model implemented by MADYMO was scaled to the height and weight of the suspect and the ground surface was given a coefficient of friction that matched skin on concrete, i.e., 0.5 (Fricke and Baker, 1990). With the initial conditions obtained from the video analysis of the reenactment, MADYMO produced an output which was inconsistent with certain aspects of the officer's account of the incident, with medical records and with independent research regarding bullet discharge times. In particular, it was determined that the model's torso rotated forward too soon with respect to the timing of the shots and that the neck was not sufficiently flexed between the first and second shots.

To harmonise the MADYMO modelling with the narrative of the account, the inputs to the model were modified. First, the suspect's left foot was moved rearward to reduce body rotation, firearm position was adjusted to more accurately correlate with the bullet path and patterns found in the dynamic ballistic tests and the suspect's right arm was adjusted outward to produce better agreement between the position of the head when it struck the ground and the location of the abrasions on the suspect's forehead. Although this produced better agreement with the injuries, there was still some discrepancy with the entry point of the second bullet. Therefore, the initial torso velocity was revised as determined from the reenactment video and additional neck flexion was implemented, which resulted in the second bullet striking the neck at the location described in the autopsy (Figure 2). Firearm position and orientation, body position and torso angle were adjusted to better match the officer's account and the bullet paths determined from the autopsy. These adjustments also resulted in greater consistency with the results of the dynamic shooting tests in which the second shot tended to be above and to the left of the first shot. The effect of bullet force on body motion was included in the model, although its effect turned out to be minimal. Therefore, motion produced by the model depended principally on the initial body position and velocities.

Figure 2 Suspect body positions corresponding to bullet wounds (top two panels) and head abrasions (bottom panel) as predicted by MADYMO (see online version for colours)



The discussion brings together the different lines of reasoning, notably the location of the injuries, the accounts of witnesses, the results of ballistics testing and the results of the MADYMO modelling. Initially, there were discrepancies between the modelling and data derived from the case material and ballistics testing. Consequently, it was necessary to adjust the inputs to the model, i.e., to revise some of the assumptions. In this way, consistency between the independent objective data and the case material was achieved. Specifically, the MADYMO modelling was able to match gross body kinematics to witness accounts, match four key injury locations to the autopsy report (two bullet wounds and two abrasions), match the timing between shots with data from independent sources and match the bullet pattern from dynamic shooting tests. MADYMO models are both calibrated and validated on a component level and a full system level. Component level calibration involves both static and dynamic properties, translated into model parameters such as stiffness, damping and hysteresis. Hoof et al. (2003), performed independent validation of the MADYMO models.

3 Case 2

The second case also involved a shooting in which a suspect was shot seven times and killed during an altercation with the apprehending police officer. The only eyewitness account of the shooting was that of the officer, although in this case the officer was wearing a body camera so video evidence of the incident was available. GTD was retained to determine whether the suspect posed a threat to the officer's life prior to the onset of the shooting.

The first step, again, is to define the injuries. The bullet entry and exit or recovery locations were determined from the autopsy report: a bullet entered the lower left quadrant of the abdomen and was recovered from the lower right chest cavity; two bullets entered the lateral left mid-ribcage and exited from the left chest and the posterolateral upper right chest wall; a bullet entered the superior parietal left scalp and was recovered from the right temple above the ear; a bullet entered near the lateral base of the left scapula and was recovered from the left mid-clavicle; a bullet entered the lateral right mid-thoracic back and exited from the lower anterior right shoulder; a bullet entered the posterior left mid-forearm and exited from the posterolateral left elbow.

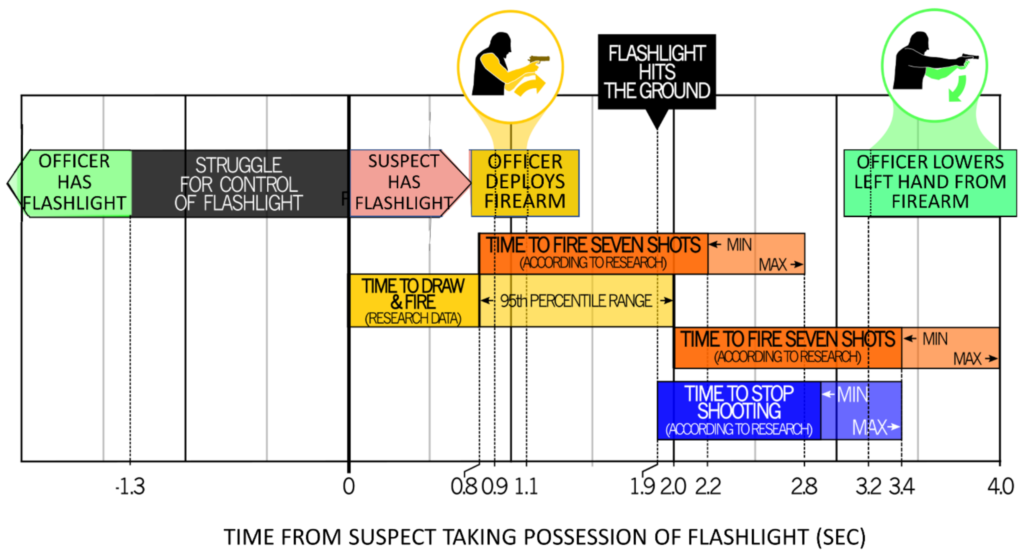
The analysis did not require modelling because there was sufficient video evidence to enable reconstruction of the movements of the officer and the suspect. However, the video images lacked clarity because the incident occurred at night. Furthermore, the suspect was not always entirely visible. Therefore, interpretation of the video images alone could not conclusively establish what transpired without additional independent objective data which, in this case, was provided by reenactment as described later. The initial interpretation of the video images is given in the following paragraphs.

The video record begins with an image of the suspect lying on the ground next to the officer as the officer attempts to stun the suspect using his Taser. Despite the Taser appearing to be functional (arcing visible in the video image), its action did not appear to produce a physical effect on the suspect. Following the failure to subdue the suspect with the Taser, the officer appears to manipulate the Taser with both hands while holding a flashlight in his right hand. At this time, the suspect attempts to get up and the officer responds by pushing the suspect and subsequently attempting to use the Taser again. For the next 4 s, there appears to be a physical struggle while the Taser is pressed against the suspect's torso and shoulder. Immediately thereafter video images lack sufficient clarity to determine the actions of the suspect and officer.

When sufficient image clarity is restored, the suspect appears to be kneeling after which it appears that the officer delivers several blows with his flashlight. The suspect is next seen lying on his left side with his head turned towards the officer. From the officer's shadow it appears that the officer is reaching for his left hip, possibly to holster his Taser. The suspect then rises from the ground and appears to reach toward the officer's right side and wrest the flashlight from the officer's right hand. The sequence and timing of events, as determined from the video taken by the officer's body worn camera, from this point on is depicted in Figure 3.

The officer then turns towards the suspect and moves his arms into a shooting posture with a firearm visible in his hands. The suspect appears to be crouched facing away from the officer, with part of his weight supported by his left hand. The officer's right arm appears to straighten fully as both hands can be seen supporting his firearm. Shortly after this the flashlight can be seen pointing in an upward direction at the suspect's thighs with the butt of the flashlight on or near the ground to the left of the suspect's right foot. The position of the flashlight suggests that it had recently been dropped and had just hit the ground. The suspect's left side is facing the officer with his left leg extended. Immediately, after this the suspect can be seen collapsing and approximately 2 s later the officer lowers his left hand from the firearm, although his right arm appears to remain extended as he points his firearm in the general direction of the suspect.

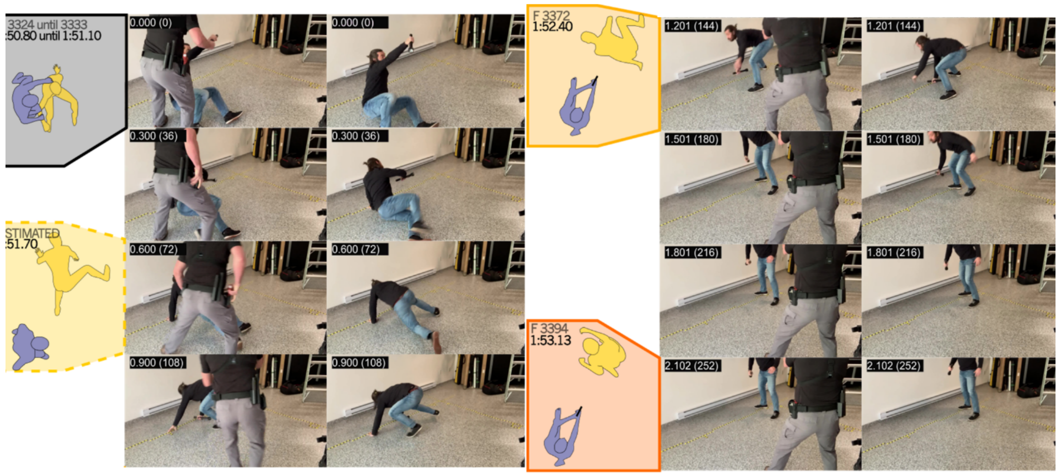
Figure 3 Sequence of events from onset to termination of the threat as determined from analysis of body camera video and incident reenactment (see online version for colours)



Because the exact time at which the firearm was discharged and the sequence of movements of the officer and suspect prior to the shooting could not be completely determined from the video images, it was necessary to conduct additional research and analysis to determine the actions of the officer and suspect with more certainty. This involved reviewing relevant research on reaction times and reenactment of key portions of the incident.

Because the suspect's movements during the struggle for the flashlight cannot be seen in the video images, the postulated scenario was reenacted to interpolate the suspect's movements between the last video frame in which he was visible before coming into possession of the flashlight and the next video frame in which he appears, which is 1.6 s later (Figure 4). The position of the officer in the reenactment was based on the video frames which suggest that his camera and, hence, his torso is facing toward the corner of a nearby building. In the reenactment, it is assumed that the officer reaches back with his right arm to draw his firearm. When the suspect reappears in the video, he is in a crouched position and appears to be primarily supporting his weight on his left arm. In the reenactment, the suspect pivots about his left hand and left foot as he attempts to stand. The officer can be seen with his arms outstretched, in a shooting position. In the next video frames, the suspect stands up and appears to have the officer's flashlight in his right hand. After standing, the suspect falls to his right side, presumably having been shot. The actor's movements in the reenactment were performed as quickly as possible. The actor's posture when 1.6 s had elapsed matched the suspect's posture in the corresponding video frame, suggesting that the reenactment accurately reflected the suspect's movements during the interval when he was not visible (Figure 4).

Figure 4 Reenactment of the incident from the onset of the threat to termination of the threat with actors portraying the officer and suspect (see online version for colours)



The timing of the officer's shots cannot be determined from the video. Therefore, wound path analysis was performed in which the suspect's position relative to the officer was determined from video evidence or from the reenactment when video evidence was lacking. If the officer drew his firearm quickly, the suspect's back would have been briefly exposed based on the reenactment. This is consistent with the gunshot wound which the suspect sustained in the upper right back area. Since the suspect's right mid-back is never similarly exposed later in the encounter, it suggests the officer's first shot occurred approximately 0.8 s after the suspect gained possession of the flashlight. As the suspect begins to rise, he rotates such that his left side becomes exposed. The relative positions of the suspect and officer, based on the reenactment, is consistent with the angle of the left side wound tracts, where the diagonal path of the first three shots would be followed by the more perpendicular tract of the next shot. When the suspect stands he appears to be turning away from the officer, such that his head faced in a direction consistent with the wound sustained to the left parietal scalp. Had the suspect been shot in the head while rising, it is unlikely that he would have been able to achieve a standing posture, given the path of the bullet through the brain. The timing of the wound to the forearm could not be determined since the arm was likely in a position to sustain such a wound at multiple times during the incident.

Research suggests that drawing a pistol and firing a single shot in a close contact position takes, on average, 1.44 ± 0.31 s (mean and standard deviation, Lewinski et al., 2015). Based on a two standard deviation range (95% probability), the action of drawing and shooting the firearm could take from 0.8 s to 2.0 s. In the reenactment, there was an interval of approximately 0.9 s between the suspect's coming into possession of the flashlight and the likely timing of the first shot. Although this would require a relatively fast action by the officer, it is realistically possible. The time required to fire 7 shots at a target with a semi-automatic pistol similar to that carried by the officer has been shown to lie between 1.4 s to 2.0 s (Jason, 2010; Lewinski et al., 2014), although other research suggests 1.0 s to draw and 1.1 s to fire 7 rounds (Haag and Greenberg, 2000). The reenactment suggested that the firing of 7 shots was carried out in approximately 1.2 s. This agrees well with both the individual times and the total time to draw and shoot.

One issue arising from the investigation was whether the officer could have stopped firing sooner. Assuming that the officer fired the shots because he felt threatened, the onset and termination of the shooting would depend on the timing of the onset and termination of the threat. The threat onset is presumed to occur when the suspect comes into possession of the officer's flashlight and threat termination is presumed to occur when the suspect drops the flashlight approximately 1.9 s later (Figure 3). The first evidence that the officer no longer considers himself threatened appears to be when he releases his left hand from the firearm and drops it to his chest 1.3 s after the flashlight appears on the ground. Assuming that the officer began firing as soon as his firearm was in position, based on the reenactment, he could have been firing for approximately 2.2 s, i.e., until just before his left arm is lowered in the video. The assumption being that the officer kept both hands on his pistol while he was firing. However, firing may have ended at least 0.5 s earlier when the suspect had fallen to the ground since none of the wound paths are consistent with the suspect's posture on the ground. Assuming that the officer made the assessment that he was no longer threatened once the flashlight had fallen to the ground, the time to stop shooting would then have been between 0.8 s and 1.3 s (Figure 4). A number of studies (reviewed by Lewinski and Redmann, 2009) suggest that a latency of this magnitude is expected based on the amount of time required for the brain to process the threat assessment and inhibit the ongoing motor commands involved in pulling the trigger.

Although there was body camera video of the entire incident, the quality of the images was poor because of the low lighting, motion blur and proximity of the suspect. Consequently, information was missing from the video, particularly with regard to the timing of the shooting. The location of the bullet wounds and the bullet paths were well-documented but the video provided no information about the sequence in which they occurred. By extracting video frames where the suspect's position and posture were clear and by inferring the officer's position and body orientation from the camera images, it was possible to recreate the movements of the officer and the suspect. This was achieved through a reenactment to provide a plausible movement sequence from which the missing intermediate positions and postures could be determined and assigned specific times. The re-enactment revealed a likely order for which each gunshot wound hence validating the movement patterns. The independent objective data acquired through the reenactment was supplemented by other data from research conducted on firearm performance, perception response time and human factors psychology of threat assessment. By combining these data, it was possible to reconstruct the injuries in the context of a continuously unfolding scenario.

4 Discussion

The two cases which have been presented illustrate the workflow in injury reconstruction advocated by GTD and demonstrate how it can provide information about the events that transpired leading to and producing the injury. The goal of the methodology is to determine the most probable sequence of events consistent with the defined injuries and the mechanism of injury, taking into account all available evidence, as well as independent objective data relevant to the case. If there is a lack of corroboration, the initial assumptions must be revisited and revised. This was illustrated in Case 1, where the initial conditions for MADYMO were iteratively revised to match the details of the injuries. There were two independent objective sources of data, the location of the injuries and the body positions predicted by MADYMO. Given that the body positions predicted by MADYMO were not initially consistent with the injury locations, it was necessary to adjust the initial body position and velocity of the suspect's torso. This entailed reconciling values for these parameters obtained from a reenactment of the incident. By examining different possibilities in the reenactment and adjusting the initial conditions for MADYMO accordingly, it was possible to produce a plausible sequence of events consistent with the injuries.

The workflow shown in Figure 1 is applicable to injury reconstruction regardless of the type of incident. In addition to shootings, GTD has applied this methodology to different types of vehicle accidents, workplace accidents, accidents occurring during recreational activities, explosions, etc. Although the specific methodology may differ from case to case, the workflow does not change. The injury is defined followed by development of an analysis plan, always involving independent objective data against which the initial evidence must be tested for consistency.

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