Forensic Science International 370 (2025) 112430

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

The effect of wrist angle and finger grip on maximum trigger pull force

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ARTICLE INFO

Keywords:
Trigger
Force
Finger
Strength
Biomechanics
Firearm

ABSTRACT

A forensic investigation into a shot fired by a handgun may require analysis of the body posture of the shooter or an opinion of whether the shot was deliberate or inadvertent. Determining the amount of force which can be applied to the trigger or the direction in which the handgun was pointing could be critical to the investigation. Studies investigating the effect of arm posture on whole hand maximum grip force suggest that maximum index finger force will be highly dependent on wrist angle and finger grip. The present study was designed to quantify the effect of these factors on maximum index finger trigger pull force. We found that even under almost optimal conditions, trigger pull force is substantially reduced with wrist flexion and is significantly lower with a finger pad grip compared to a finger hook grip. Our results indicate that for wrist flexion angles greater than 60°, maximum trigger pull force dropped by 50 % for male subjects and by 38 % for female subjects compared to the neutral or extended wrist. Other studies have shown that when a firm grip cannot be established, maximum index finger force can be less than 30 % of what we measured. Thus, maximum trigger pull forces could be below 22.9 N (5.1 lb) for male subjects and 19.0 N (4.5 lb) for female subjects in certain scenarios. If a subject is unable to get a firm grip on a handgun and the arm is in an awkward posture, it is possible that the subject would not be able to exert sufficient index finger force to overcome the trigger weight of many handguns.

1. Introduction

A question that might arise in a forensic investigation of a shooting, is the amount of force required to pull a trigger, i.e. trigger pull weight, and whether an individual was capable of exerting sufficient force to pull the trigger, based on grip strength and/or upper limb posture. There is abundant evidence that a number of factors affect grip strength, including wrist, elbow and shoulder angles [1,10,11,15,17,20,22,23,27,28,6-9] and grip span, i.e. distance between the thumb and fingers [26].

Arm or hand postures near joint range of motion limits may occur during struggles in which a firearm is handled. If the struggle involves a shot being fired, a forensic investigation may require determining the body posture of the individual firing the shot or determining whether the shot was fired deliberately or inadvertently. An informed opinion in the investigation may require an analysis of whether the individual was capable of pulling the trigger or the direction in which the handgun was likely pointing based on specific body postures. Wrist angle, in particular, has been found to have a profound effect on maximum whole hand grip force [10,11,15,27,6,8], particularly because grip force depends on the strength of the wrist extensor muscles [29], which vary with wrist angle [13,16,5].

The results of whole hand grip force studies cannot be applied directly to determining maximum index finger trigger force for several reasons. The grip span for a handgun is not the same as the grip span that has been used in whole hand grip force studies. In addition, it has been shown that the maximal flexion force which individual fingers can produce in isolation is greater than the maximum force which they can produce in a coordinated whole hand grip [21]. Furthermore, finger force varies with finger joint angles (Milner and Franklin 1998; [31]; [32]. The length of the extrinsic index finger flexor muscles, located in the forearm, also varies with wrist angle which affects the force that they can produce [3].

For example, the results of such studies could be applied in a case such as the following, where it was not known whether a shooter and the victim of a gunshot wound were face to face or whether the shooter was behind the victim. The trajectory of the bullet was determined from evidence at the scene, which established the orientation of the muzzle of the firearm. Entrance and exit wounds on the victim's right leg were used to constrain the position and orientation of his body. If the two men had been facing one another, it would not have been possible for the

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https://doi.org/10.1016/j.forsciint.2025.112430
Received 30 October 2024; Received in revised form 21 January 2025; Accepted 24 February 2025
Available online 6 March 2025

shooter to reach the firearm with his right (dominant) hand. However, if he held the firearm in his left hand, his wrist would have been in extreme flexion which would have reduced the maximum index finger grip force. Given the significant effect that wrist angle has on maximum whole hand grip force and the fact that maximum index finger force has been shown to vary with finger joint angles, the present study was designed to quantify the effect of wrist angle and finger grip on maximum index finger grip force to provide data which could be used to address cases such as that described above

2. Methods

2.1. Subjects

Thirteen female (21–45 years old) and ten male (21–67 years old) subjects participated in the study. Two female subjects were left-hand dominant and one male subject was left-hand dominant. All other subjects were right-hand dominant. Subjects were provided with a written and verbal description of the study protocol and signed an informed consent form. All procedures were carried out in accordance with the Declaration of Helsinki.

2.2. Apparatus

A red training gun (H&K USP.45 Compact) was adapted for measuring maximum trigger pull force. The trigger and trigger guard were cut away and the red gun was securely mounted on T-slot rails as shown in Fig. 1. A tension gauge (MK-10) was mounted on the same rail and linked to a chain which ended in a shackle. The tension gauge was positioned such that the distance to the inside of the shackle reproduced the grip span to the original red gun trigger when the chain was taut, which was equal to 73.5 mm. A second T-slot rail with a pivot and two arm rests was connected to the rail on which the gun was mounted. The pivot arm served to support the forearm and control the wrist angle. The entire assembly was placed on a counter at elbow height. An angle guide was aligned with the center of rotation of the pivot. The location of the pivoting rail was adjusted for each subject such that the zero angle of the angle guide represented the subject's relaxed wrist position. Thus, flexion and extension angles of the wrist were measured relative to the relaxed (neutral) position of the wrist indicated in Fig. 2A.

2.3. Protocol

Subjects sat in a chair with their forearm resting on the pivot arm of the apparatus. Subjects were permitted to moved the chair in order to adjust their shoulder abduction angle so that the position of the forearm felt comfortable. The chair was then maintained in the same position for the duration of the experiment. They were told that they could grip the shackle either with the pad of the distal phalanx of the index finger of their dominant hand (pad grip) or with a hook grip between the distal and proximal phalanges of the index finger as illustrated in Fig. 2B,C. Five of the subjects performed the complete protocol twice, once using the pad grip and once using the hook grip. The remaining subjects performed the complete protocol once, but were allowed to choose whichever grip they felt was more comfortable for producing the maximum grip force and were permitted to change the type of grip from one trial to another if they preferred.

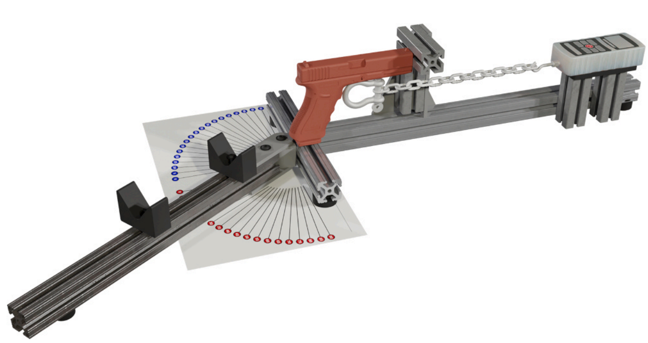

Fig. 1. Apparatus layout illustrating (from left to right) pivoting forearm support, wrist angle indicator, red gun, shackle, chain and tension gauge.

The experimental session began with a maximum whole hand grip force test using a handheld dynamometer (CAMRY Digital Hand Dynamometer EH101). Subjects first exerted their maximum grip force with their right hand and then repeated the test with their left hand. Following whole hand grip force testing, subjects placed the forearm of their dominant hand on the arm support rail, grasped the red gun and pulled on the shackle with the index finger of their dominant hand. For each trial, subjects were instructed to smoothly increase the grip force applied to the shackle with the index finger (trigger force) to their maximum after which they were told to relax for one minute. The wrist angle was then changed and the procedure repeated. Maximum trigger force was tested for 7 wrist angles, -60°, -40°, -20°, 0°, 20°, 40° and 60°. Negative angles denote wrist extension, positive angles denote wrist flexion and 0° denotes the neutral angle. The wrist angle was set by moving the pivot rail so that it was aligned over the corresponding line on the angle guide. The order of wrist angles was randomized.

Subjects who were given the option of applying the trigger force with a pad or hook grip were permitted to do so for all wrist angles except the neutral angle. At the neutral angle, maximum trigger force was recorded for both the pad grip and the hook grip. These two trials at the neutral angle were randomized among the other wrist angles. After performing the procedure for the complete set of wrist angles, subjects were given a 10-minute rest. They then repeated the procedure for the complete set of wrist angles but in a different random order. In all, three sets of trials were performed. The maximum trigger force was recorded for each trial.

2.4. Statistical analysis

A previous study by Li [15] found a significant effect of flexion/extension wrist angle on individual finger forces for a population of 9 male subjects. Consequently, we determined that a minimum of 10 subjects of each gender would be adequate to test the gender specific effect of wrist angle on maximum index finger grip force. As described in the Introduction, the primary effect of interest was the effect of wrist angle on maximum index finger grip force., i.e. trigger force. Of secondary interest, was the effect of finger grip on maximum trigger force at the neutral wrist angle. For each wrist angle, maximum trigger force was defined as the highest force from the three trigger force trials. Separate analyses were performed for the group of male subjects and female subjects. No gender comparisons were performed since it is already well known that male subjects can exert greater grip forces than female subjects [24]. The Kolmogorov-Smirnov goodness of fit test was first applied to the data to determine whether the data were normally distributed. A single factor ANOVA was then performed to determine whether the effect of wrist angle on maximum trigger force was statistically significant. Since the data did not pass the test for normality, the non-parametric Wilcoxon signed rank test was used to compare the difference in the maximum trigger force between selected wrist angles in post-hoc tests and to determine whether there was a significant difference in the maximum trigger force between the pad and hook grips at the neutral wrist angle. Where multiple comparisons were performed, the Benjamini-Hochberg adjustment [2] was used to reduce the possibility of Type 1 errors.

3. Results

The mean maximum whole hand grip force was 256 N (SD 52 N) for the left hand and 274 N (SD 47 N) for the right hand for female subjects compared to 455 N (SD 158 N) for the left hand and 474 N (SD 155 N)

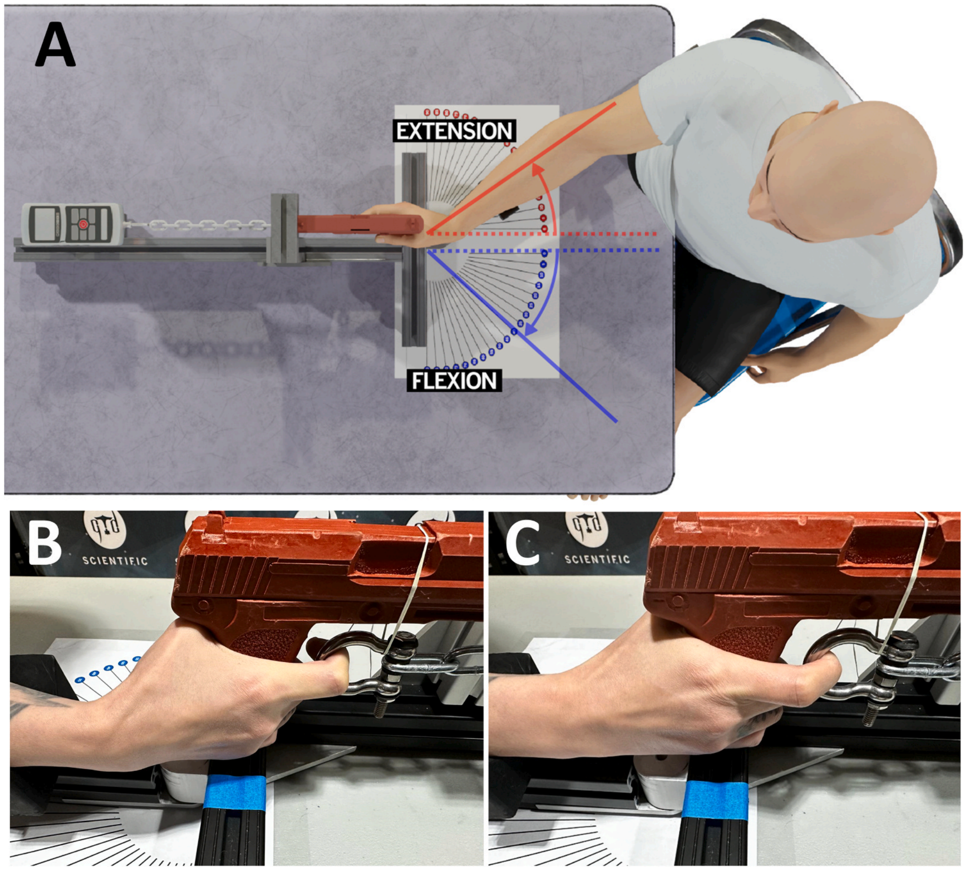

Fig. 2. A. Overhead view of the experimental setup, illustrating the subject's arm posture. B. Example of the index finger hook grip. C. Example of the index finger pad grip.

for the right hand for male subjects. The maximum trigger force for male and female subjects at each wrist angle is shown in Fig. 3. One male subject was unable to achieve the 60° wrist flexion angle. Therefore, this subject was excluded from statistical comparisons related to wrist angle but was included for the comparison related to grip type at the neutral angle. There was a significant effect of wrist angle on maximum trigger force for both male ($p = 0.00875$) and female subjects ($p < 0.00001$). The maximum trigger force was relatively constant for wrist extension angles but dropped significantly as the wrist was flexed. The maximum trigger force, beginning from the neutral position, was found to decline significantly as the wrist flexion angle progressively increased by 20° increments (Table 1).

Both male and female subjects were able to exert greater maximum trigger force when using a hook grip than a pad grip at the neutral wrist angle (Fig. 4). The mean maximum trigger force for male subjects, when using the hook grip, was 151.4 ± 51.1 N compared to 101.9 ± 20.6 N,

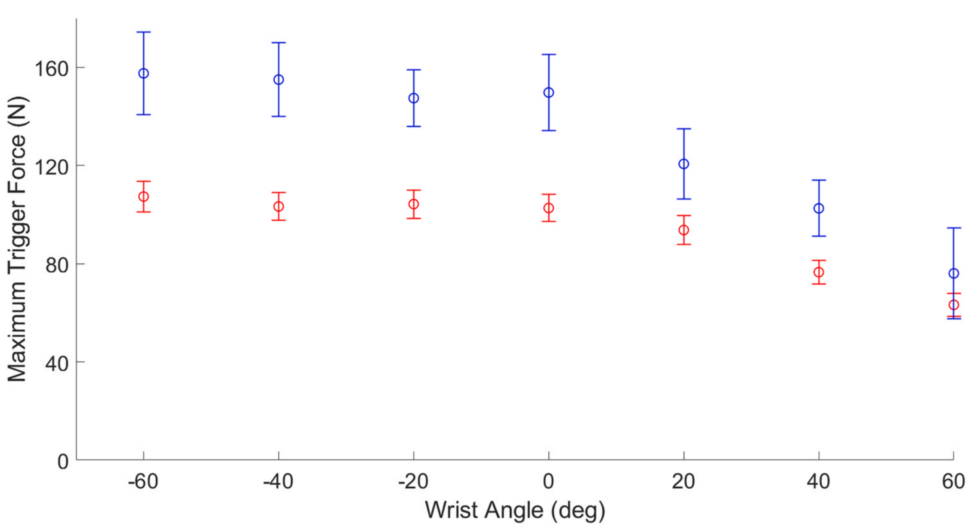

Fig. 3. Mean maximum index finger trigger force as a function of wrist angle for male subjects (blue symbols) and female subjects (red symbols) together with standard errors.

Table 1
Maximum trigger force in wrist flexion.

Wrist Angle	0°	20°	40°	60°
Female N = 13	102.7 (19.9)	93.7 (21.1) p = 0.0056 (0 v 20)	76.3 (17.7) p = 0.00012 (20 v 40)	63.2 (17.1) p = 0.0017 (40 v 60)
Male N = 9	155.3 (53.3)	122.1 (47.3) p = 0.0020 (0 v 20)	104.6 (37.8) p = 0.0372 (20 v 40)	76.3 (28.6) p = 0.0039 (40 v 60)

when using the pad grip (p = 0.00098). The mean maximum trigger force for female subjects, when using the hook grip, was 86.8 ± 22.5 N compared to 68.2 ± 20.0 N, when using the pad grip. Two female subjects used only the hook grip type for all trials. All other subjects, male and female, changed the type of grip which they used among both trials and wrist angles. Although no systematic pattern was observed for the change in grip type, there was a strong preference for the hook grip. Subjects used the hook grip in 75 % of the trials for which they had the option of using either grip.

4. Discussion

The results of the present study indicate that the maximum force which can be exerted to pull the trigger of a handgun is relatively constant as the wrist extends from its neutral position, but progressively declines as the wrist is flexed. Furthermore, in the neutral wrist position, subjects are able to exert greater maximum trigger force with a hook grip than a pad grip, which is likely why the hook grip was predominantly used for other wrist angles. The mean maximum hand grip forces for our male and female subjects fall in the upper half of the range compiled by Roman-Liu [24], which is based on the results of fifty-eight studies. Given that the forces are still well below the upper limit of Roman-Liu's range, it can be inferred that our study sampled a representative population.

Although maximum whole hand grip force is commonly measured and has been documented in a number of published studies, there are fewer studies that have focused on maximum index finger force. Studies differ in the way in which the index finger is isolated from the rest of the hand. Ohtsuki (1984) measured the maximum index finger force while pulling against a leather loop using a hook grip, with the forearm supported and completely supinated and the wrist immobilized in a plaster cast. The mean maximum index finger force for 10 subjects was 149 N. Lee and Cheng (1994) measured the maximum force that the index finger could exert on a simulated power tool trigger with grip spans ranging from 40 mm to 60 mm. The mean maximum index trigger force for 15 male subjects was 138 N (14.1 kgf). The maximum index finger forces in the Ohtsuki (1984) and Lee and Cheng (1994) studies are similar to the maximum trigger force which we measured at the neutral wrist angle for male subjects.

Other studies have completely isolated the index finger, such that the rest of the hand could not exert an opposing force. This situation would be similar to an individual having their finger on the trigger without being able to grasp the pistol grip, e.g. pushing on the trigger without holding the gun. In this case, the maximum index finger force could be much lower than the forces which we measured. Milner and Franklin (1998) clamped the distal phalanx of the index finger with a hose clamp and stabilized the wrist in a splint with the forearm semi-pronated. The thumb and remaining fingers were left free so that they could not exert an opposing force. The mean maximum index finger force which Milner and Franklin (1998) measured for a group of 5 male subjects was 45.2 N for a similar finger posture and force direction to a trigger pull. Valeros-Cuevas et al. (1998) placed the index finger in a thimble which required precise control of the force direction to prevent slipping. The rest of the hand was stabilized by gripping a rod with the wrist is full extension and the forearm semi-pronated. The index finger precision required to prevent the thimble from slipping prevented subjects from using a power grip with the rest of the hand. Consequently, the mean maximum index finger force which Valero-Cuevas et al. [31] measured for a group of 8 subjects, was 27.9 N, for a similar finger posture and force direction to a trigger pull. Yokagawa and Hara [32] measured maximum index finger force in a manner similar to that of Valero-Cuevas et al. [31], except that the wrist was in its neutral position and the forearm was completely supinated. Although their results were only presented in graphical form, it was clear that the mean maximum index finger force, which they measured for a group of 5 male subjects, was less than 10 N for a similar finger posture and force direction to a trigger pull. Valero-Cuevas (1998) and Milner and Dhaliwal [18] found that co-contraction of index finger extensor muscles is frequently observed for flexed finger postures when producing flexion force at the fingertip. This could contribute to reduced maximum flexion force would be consistent with our finding that the maximum trigger force was significantly lower with a finger pad grip than a hook grip. However, not being able to use a power grip, where the palm and thumb can exert a force which opposes index finger flexion, is likely the primary reason for the reduced maximum index finger flexion force in the studies cited above.

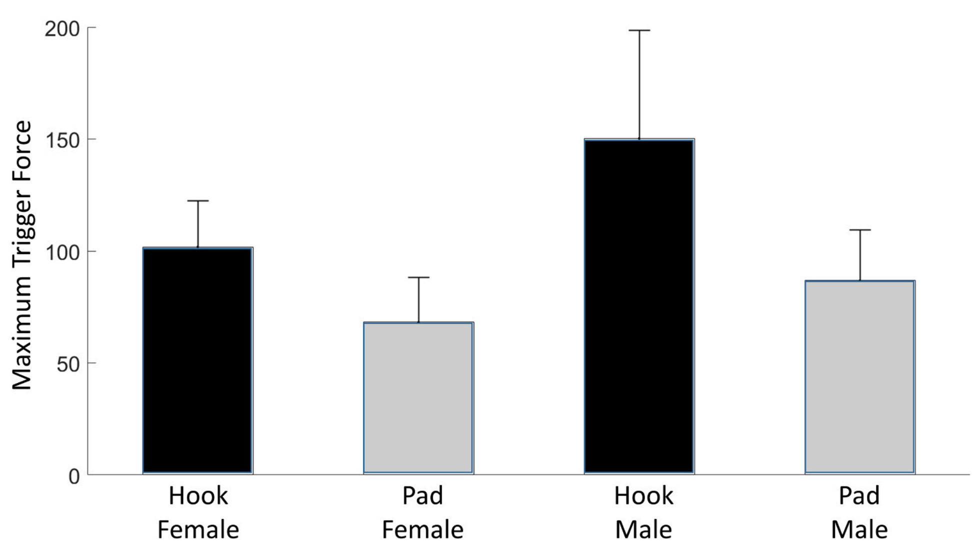

Fig. 4. Mean maximum index finger trigger force using the hook grip and pad grip for female subjects (left) and male subjects (right) together with standard deviation.

Our study, investigated only one grip span, i.e. 75.5 mm. Grip span has been studied in the context of power tool use [12] and in a cadaver model of the trigger grip [4]. Both studies found that index trigger force was optimal for a grip span of 50 mm. Lee and Cheng [12] found that maximum index trigger force was reduced by approximately 5 % for grip spans of 40 mm and 60 mm compared to 50 mm. Chang et al. [4] also investigated the effect of finger location on the trigger. Using the cadaver model, they maintained a constant tension in finger flexor tendons and varied the location of the index finger on the simulated trigger. They found that index trigger force was lowest with the distal pad of the finger on the trigger and highest when the trigger made contact with the finger between the distal and proximal interphalangeal joints, similar to a hook grip. This is consistent with our findings of a lower maximum index finger trigger force with a pad grip than with a hook grip. Therefore, it is important to take into account the grip span required to pull the trigger of a specific handgun and the finger joint angles necessary to achieve the required grip span in determining the maximum index trigger force.

Li [15] investigated the effect of wrist angle of maximum grip force. Individual fingertip forces were measured while the subject exerted maximum grip force between the fingers and palm. The wrist angle was varied in flexion/extension, as well as adduction/abduction with the forearm supported and stabilized in a semi-pronated posture. Li [15] found that finger forces were lower when the wrist was flexed than when it was extended and that finger forces varied more with wrist flexion angles than extension angles. This variation in maximum index finger force with wrist angle is similar to our findings. The finding that maximum trigger force varied little with wrist extension angle is likely due to a tradeoff between the increasing force generating capacity of extrinsic finger flexor muscles at longer muscle lengths [3] and the increasing opposing force of the extensor digitorum communis muscle contributing to holding the wrist in extension, which also increases with the wrist extension angle [25]. These two effects may counterbalance one another such that maximum trigger force remains relatively constant as the wrist is extended from the neutral position.

The maximum index finger forces measured by Li [15] ranged from a mean of 19.0 N in flexion to 34.7 N in extension for a group of 9 male subjects. These forces are much lower than the maximum trigger forces which we measured. This is likely due to a combination of individual finger forces being lower when measured during whole hand grip than during isolated finger grip (Ohtsuki 1994; [14], force being applied at the fingertip and subjects using a palm grip, which involved a relatively small grip span and reduced the contribution of the thumb compared to a power grip.

Although we were able to demonstrate the effect of wrist flexion in reducing the maximum trigger force, there are certain limitations in applying the results of our study to real world shooting scenarios. In particular, our subjects were not required to support the weight of the gun and arm, whereas a shooter will generally have to support both the weight of the gun and arm during real world shooting. In a group of 50 male and 50 female subjects, Swanson et al. [30] found that maximum grip force was reduced by approximately 6 % for male subjects and 9 % for female subjects when the arm was supported than when it was unsupported. However, interpretation of their results with respect to arm support are somewhat equivocal because they considered that holding the arm close to the body was similar to supporting the arm on a table. Furthermore, the wrist angle was not controlled. Taking these factors into consideration, it is likely that arm support has a relatively small effect on maximum grip force.

In addition to having the arm supported, our subjects adopted a relatively standard posture in which the forearm was semi-pronated (neutral), with the shoulder and elbow comfortably flexed. Although we did not specify the amount of shoulder and elbow flexion, subjects generally sat with the shoulder and elbow flexed by approximately 45°. Studies in which forearm orientation or elbow and shoulder angles have been varied have shown that proximal upper limb joint angles have an effect on maximum whole hand grip force. Presumably, the effect on maximum index finger trigger force would be similar to the effect on whole hand grip force, although this has not been investigated.

In the case of forearm orientation, Mogk and Keir [19] found that maximum whole hand grip force was approximately 20 % greater in the neutral posture than when fully pronated or fully supinated. Therefore, it would be expected that maximum index finger force could be reduced by up to 20 % when pulling the trigger of a handgun held horizontally as opposed to the normal vertical orientation.

In the case of elbow and shoulder angles, studies by Su et al. [28], involving 80 male and 80 female subjects, and by Parvatikar and Mukkannavar [22], involving 25 male and 25 female subjects, found that whole hand grip force was highest for 180° shoulder flexion with the elbow in complete extension (hand raised vertically overhead). A study by Karthikeyan et al. [7], involving 15 male and 15 female subjects, investigated maximum whole hand grip force for a range of elbow and shoulder angles, but only up to 90° of shoulder flexion. They found that whole hand grip force was highest for 0° shoulder flexion with the elbow in complete extension (hand pointing vertically downward). In a study involving 15 male subjects, Kattel et al. [8] varied the elbow angle and shoulder abduction angle. They found that maximum whole hand grip force was approximately 5 % greater when the shoulder was neutral compared to an abduction angle of 20° or when the elbow was at 135° (45° flexion) than when it was fully extended.

Su et al. [28] found that maximum whole hand grip force varied by approximately 6 % over the range of shoulder and elbow angles tested whereas Parvatikar and Mukkannavar [22] found a variation in maximum whole hand grip force of approximately 14 % over the same range of shoulder and elbow angles. However, Parvatikar and Mukkannavar [22] also tested an awkward posture, which was not included in the study of Su et al. [28]. They found that maximum whole hand grip force was reduced by approximately 30 % with the arm at 180° of shoulder flexion if the elbow as flexed at 90° (upper arm raised and hand pointing behind the body) compared to when the elbow was fully extended. Overall, it can be assumed that maximum trigger force will vary with shoulder and elbow angles, but that this variation will be relatively small, likely in the range of 10 %, unless the arm is in a very awkward posture.

In summary, the results of our study and other studies investigating the effect of wrist angle on maximum grip force, suggest that maximum trigger force is significantly reduced when the wrist is flexed by 20° or more. Although we examined a relatively small number of subjects, our results were statistically significant and, in terms of hand strength, our subjects appeared to be representative of populations investigated in other similar studies [24]. Based on previous studies, arm support, forearm orientation, as well as elbow and shoulder angles appear to have a relatively smaller effect (< 10 %) on maximum trigger force than wrist angle unless the arm is in a very awkward posture such as pointing behind the body. However, wrist angle, grip span and arm posture likely have a compound effect on maximum trigger force, as suggested by the results of Kattel et al. [8]. Therefore, maximum trigger forces, significantly lower than the 76.3 N and 63.2 N, which we measured for male and female subjects, respectively, could be expected in real world scenarios, particularly if the shooter cannot establish a firm grip on the firearm. Future studies could build on our study by examining the effects of elbow and shoulder angles, arm support and hand position on the firearm.

Given that maximum trigger force decreased continuously as wrist flexion angle increased, it can be inferred from our results that for male subjects, maximum trigger force for wrist flexion angles greater than 60° would be less than 50 % of its optimal value when the wrist is neutral or extended. Furthermore, other studies (Milner and Franklin 1998; [31]; [32] have found that maximum index forces can drop to less than 30 % of the values which we measured for neutral wrist angles. Thus, the combined effect of an extremely flexed wrist and not having a firm grip on the handgun, could reduce the maximum trigger force below 30 % of the values which we found for 60° wrist flexion, i.e. below 22.9 N (5.1 lb) for male subject and 19.0 N (4.3 lb) for female subjects. Considering that handgun trigger weights can vary from 4 lb (17.8 N) to 15 lb (66.8 N) (National Institute of Justice), the effects of wrist angle and trigger grip can have significant implications in forensic investigations. Consider again the scenario of the shooter and gunshot victim described in the Introduction. The outcome of the forensic investigation indicated that it was unlikely that the shooter would have been able to exert the force necessary to overcome the trigger pull weight of the firearm, which was determined to be greater than 10 lb (45 N) under the postural constraints of the face to face positioning. Thus, the investigation concluded that the shooter must have been behind the victim at the time of the shooting since this position would have allowed the shooter to hold the firearm in his right hand with a natural grip and straight wrist, optimal for generating trigger force. Our results, combined with those of other studies, indicate that scenarios in which a handgun is held awkwardly, such as with the wrist extremely flexed and with only the fingertip on the trigger, could reduce the amount of force which the index finger can apply to the trigger to a value less than the trigger weight, making it unlikely that the subject could fire a shot.

CRediT authorship contribution statement

Desmoulin Geoffrey Thor: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Nolette Marc-André:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Milner Theodore E.:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Gilmore Kevin:** Writing – review & editing, Visualization, Formal analysis, Data curation.

Declaration of Competing Interest

The authors have no conflict of interest as a result of being involved in this study and the entire study was funded internally by GTD Scientific Inc.

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