ARMY RESEARCH LABORATORY

The Effects of Recoil on Shooter Performance

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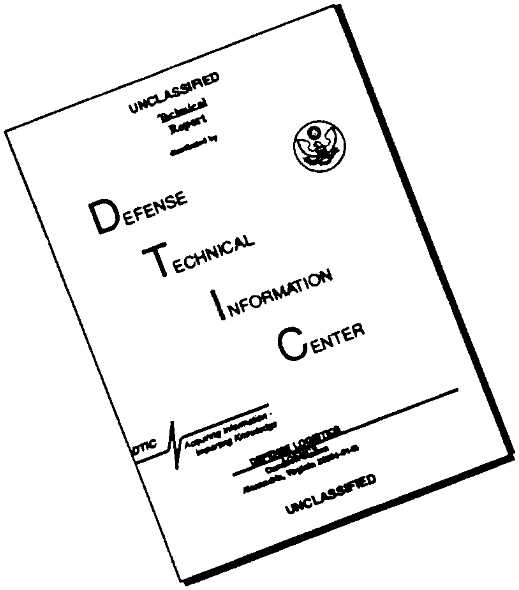

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This research was performed to investigate the effects that weapon recoil has on aiming accuracy and on the number of shots soldiers are willing to fire. The research also investigates the possible benefits of adding a recoil-mitigating device to high recoil weapons. One hundred five soldiers were assigned to one of seven test groups, with each group firing only one of the test weapons. Five of the test weapons were shotguns of various weights and cartridge impulse levels to provide different levels of recoil energy and recoil velocity. The remaining two groups fired one of the two weapons with a recoil-mitigating device. Each test group fired five shots with a baseline weapon, followed by as many shots as they were willing to fire with the test weapon; shots were temporally spaced by approximately 30 seconds. The aiming accuracy was recorded via a small video camera mounted on the forestock of the weapon. Results showed that although significantly more shots could be fired with weapons with a recoil-mitigating device, the aiming accuracy was no better than that of weapons without the device. The higher recoil test weapons had significantly poorer aiming accuracy than the weapon with the lightest recoil, and the aiming error with the high recoil weapons was consistently above the target.

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EXECUTIVE SUMMARY

The Human Research and Engineering Directorate (HRED) of the U.S. Army Research Laboratory (ARL) conducted a study to determine the effects of firing high recoil weapons on human performance. This study was funded by the Joint Services Small Arms Program (JSSAP) office in support of the bursting munitions program. The goal of the bursting munitions program is to develop a weapon that will fire a bursting munition, rifle grenade, or other muzzle-launched ordnance. The infantry community is extremely interested in delivering relatively large payloads to targets several hundred meters away with sufficient precision that the target is within the effective radius of the warhead. Recoil is the dominant component of firing trauma in this class of weapons because the recoil energies associated with firing these types of devices are usually high.

This research was designed to investigate the effects that weapon recoil has on aiming accuracy and on the number of shots soldiers are willing to fire. The testing was designed around modified, commercially available, 12-gauge shotguns and ammunition. A small video camera was mounted on the forestock of each weapon to capture aiming performance data. Incremental magnitudes of recoil velocity and recoil energy were produced by varying the cartridge impulse levels (4.32 lb-sec and 3.30 lb-sec) and modifying the weight of the shotguns (5, 7, 9, and 12 lb). The recoil levels chosen for this study were 43 ft-lb of energy with 20 ft/s velocity, 34 ft-lb of energy with 20 ft/s velocity, 34 ft-lb of energy with 15 ft/s velocity, 25 ft-lb of energy with 15 ft/s velocity, and 25 ft-lb of energy with 11 ft/s velocity. In addition, the 43 ft-lb of energy with 20 ft/s velocity recoil and 34 ft-lb of energy with 15 ft/s velocity were examined with and without a recoil-mitigating device, for a total of seven recoil energy-velocity test conditions. These combinations of recoil velocity and recoil energy were chosen because they seemed to encompass almost all those anticipated by the development community for various future bursting munitions.

One hundred five male soldiers and marines participated in the study. Fifteen subjects were placed in each of the seven test groups, each of which fired one test weapon. Subjects were required to first fire five rounds in a baseline condition with a recoil energy of 18 ft-lb and a recoil velocity of 11 ft/s and then fire five rounds in one of the seven test conditions if they could. After firing five shots in the test condition, subjects completed a rating scale comparing the recoil of the test condition with that of the baseline condition. The subjects then fired as many shots as possible (as many as 50) in the same test condition.

The aiming performance results showed that two of the highest recoil conditions and one of the conditions with the recoil-mitigating device had significantly worse aiming performance than one of the lower recoil conditions without the recoil-mitigating device. These differences can be mostly attributed to differences in the aiming performance in the vertical direction since these same recoil test conditions were significantly different from each other in vertical aiming performance but not in horizontal aiming performance. This significantly poorer aiming performance in the vertical direction for these higher recoil conditions would seem to indicate that some test subjects were flinching when they fired weapons in these conditions.

The aiming error associated with all the recoil conditions tested was poor. One of the lowest recoil conditions tested (recoil approximately equal to the M79 grenade launcher) had significantly better aiming performance than several of the higher recoil conditions, yet a mean aiming error radius of 3.05 mils was recorded. A weapon that produces this magnitude of aiming error will require a very effective (large lethal radius and precisely timed airburst) fragmenting round to compensate. To obtain such a lethal radius from a bursting munition with a 3- to 4-lb-s impulse will be difficult.

The shot quantity data showed that the number of shots that could be fired in the conditions without a recoil-mitigating device was so few that the practical use of a weapon with recoil characteristics such as those used in this study would be very limited. The highest mean number of shots fired in any of the conditions without a recoil-mitigating device was only 17.27. The mean number of shots fired in the highest recoil condition was a mere 6.73. However, the number of shots that subjects were willing to fire in the conditions with the recoil-mitigating device was 47.73 in the lower recoil condition and 38.80 in the higher recoil condition. The subjects were willing to fire many more shots in the conditions using recoil-mitigating devices than in those conditions without recoil-mitigating devices.

The subjective rating data showed that most differences in subjective ratings were found between conditions with the recoil-mitigating devices and those without. The lower recoil condition of the two conditions with recoil-mitigating devices was given a lower (milder) subjective recoil rating than any of the conditions without recoil-mitigating devices except the lowest recoil condition. The higher recoil condition of the two conditions using recoil-mitigating devices was given a milder recoil rating than two of the higher recoil conditions without recoil-mitigating devices. Some differences in subjective recoil ratings were also found between weapons without recoil-mitigating devices. The lowest recoil condition without a recoil-mitigating device was given a lower subjective recoil rating than the two highest recoil conditions.

THE EFFECTS OF RECOIL ON SHOOTER PERFORMANCE

INTRODUCTION

Program History

Recent interest in bursting munitions, rifle grenades, and other muzzle-launched ordnance has sparked inquiries to the Human Research and Engineering Directorate (HRED) of the U.S. Army Research Laboratory (ARL) about human tolerance of recoil and the effects of recoil on the delivery error of such systems. Research into the effects of recoil on shooter performance has clearly been neglected. Data are almost nonexistent; the last known study was done in the 1950s.

In the interest of filling the data void in this area, ARL submitted a recoil research proposal to the Joint Services Small Arms Program (JSSAP) Office in the latter part of 1991 and subsequently received funding to conduct the research during a 2-year period.

Recoil Characteristics and Their Effects

Three factors of the physics of recoil contribute to a shooter's sensation of firing a weapon: recoil impulse, recoil velocity, and recoil energy. The equations that describe these involve projectile, propellant, weapon, body mass of the shooter, accelerations, and velocities. These components are interrelated by basic laws of physics and are well understood. What is not well understood is the role each plays in the perception of recoil and what steps can be taken to make a weapon recoil more tolerable.

Flinch, or the unwanted movement of the weapon away from the desired point of aim in anticipation of the trauma of firing, can reasonably be expected to be directly related to the magnitude of the trauma. Recoil is the dominant component of firing trauma in this class of weapons because the recoil energies associated with grenade firing are usually high.

The infantry community is extremely interested in delivering relatively large payloads to targets several hundred meters away with sufficient precision that they land within the effective radius of the warhead from the target. When fighting occurs in cities, the concern often becomes firing these munitions through windows or doorways and at other narrowly defined targets. These types of munitions typically have high trajectories because of their relatively large masses and low velocities. As the height of the trajectory of a ballistic system increases, small errors in superelevation rapidly produce intolerable delivery errors--errors that exceed by a large degree the effective radius of the munition.

Since the trajectory is largely a function of the velocity of the projectile, increasing the velocity by increasing the propellant or decreasing the mass launched will flatten the trajectory and result in less delivery error. Unfortunately, the recoil characteristics are also dictated by mass and propellant. If the trajectory is flattened by increasing velocity through increasing the propellant, the recoil characteristics can become intolerable to the shooter before the delivery error becomes small enough for the effective radius of the payload. If the flat trajectory is achieved by reducing the projectile mass, the effective radius of the payload may become unacceptably small before the delivery error becomes reasonable.

OBJECTIVES

The overall objectives of this research were to

1. Isolate and quantify recoil characteristics that affect aiming error.

2. Investigate and measure how those factors affect a soldier's perception and tolerance of recoil.

3. Evaluate the effectiveness of a recoil-mitigating device.

4. Establish a data base, methodology, and criteria with which future shoulder-fired kinetic energy (KE) weapons can be designed and evaluated.

METHODOLOGY

Test Hardware and Ammunition

The testing was designed around standard, commercially available 12-gauge shotgun ammunition and instrumented 12-gauge shotguns. This commercial ammunition is manufactured in a wide range of loads, with light 2-3/4-inch trap and skeet loads at one end of the spectrum and 3-inch magnum loads at the other. Incremental magnitudes of recoil impulse can be achieved by selecting specific loads. Incremental magnitudes of recoil velocity and recoil energy can be produced by modifying the weight of the shotguns. A 3-inch magnum load with a recoil impulse of 4.32 pound-seconds (lb-s) and a 2-3/4-inch load with a recoil impulse of 3.30 lb-s were chosen for this study. The resultant range of recoil characteristics (calculated) (see Table 1) encompasses almost all those anticipated by the development community for various future bursting munitions. (See Appendix A for some current and proposed weapon system recoil characteristics.) The values that appear underlined represent the recoil velocity and recoil energy combinations of the weapons chosen for this study. As can be seen in Table 1, not all combinations of recoil energy and velocity levels could be used in this study. This was because of practical considerations such as the number of test weapons and participants that would be required to test all combinations. The value that is shown in bold type inside the parentheses represents the baseline weapon (recoil velocity of 10.6 ft/s and recoil energy of 17.5 ft-lb) fired by all test participants to serve as a basis of comparison, against which, all weapons were subjectively compared.

Table 1

Calculated Recoil Impulses (Ir), Recoil Velocities (Vr), and Energies (Er) for Selected 12-Gauge Shotgun Loads and System Weights

System weight (lb)	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
Ir = 4.32 lb-s (1)										
Vr (ft/s)	27.8	23.2	19.9	17.4	15.4	13.9	12.6	11.6	10.7	9.9
Er (ft-lb)	60.0	50.0	42.9	37.5	33.4	30.0	27.3	25.0	23.1	21.4
Ir = 3.30 lb-s (2)										
Vr (ft/s)	21.2	17.7	15.2	13.3	11.8	**(10.6)**	9.7	8.9	8.2	7.6
Er (ft-lb)	35.0	29.2	25.0	21.9	19.5	**(17.5)**	15.9	14.6	13.5	12.5

___ Conditions tested

( ) Baseline

(1) Remington SP duplex. Order Number: MRP12XH Mag.
3-inch Magnum shell. #4x6 2 oz @ 1175 ft/s
Recoil impulse = 4.32 lb-s Measured by Tim Brosseau, Weapons Technology Directorate (WTD)

(2) Remington Express extra long range. Order Number: SP12.
2-3/4-inch shell. 1-1/4 oz @ 1330 ft/s
Recoil impulse = 3.30 lb-s Measured by Tim Brosseau, WTD

Test Weapons

Browning Citori over-and-under 12-gauge shotguns were used in this test. These weapons were modified by making them lighter or heavier. The shotguns were modified to weigh 5.0, 7.0, 9.0, 10.0, and 12.0 lb. The weapons weighed within 0.1 lb of the specified weights except in the case of the 5-lb weapon, which weighed approximately 5.15 lb. The weight modifications were done by either removing material from or adding weights to the lower barrel and butt stock. In all cases, the lower barrel was rendered incapable of being fired. Because of limitations as to where weight could be safely added or subtracted, the center of gravity (CG) of each of the weapons varied. The CG measurements taken from the front edge of the barrel were measured in inches aft of that point. The 5-lb weapon had a CG of 20 inches; the 7-lb weapon, 18-7/8 inches; the 9-lb weapon, 20-5/8 inches; the 10-lb weapon, 21-1/16 inches; the 12-lb weapon, 21-3/8 inches; the 7-lb weapon with recoil-mitigating device, 23-1/4 inches; and the 9-lb weapon with the recoil-mitigating device, 21-1/4 inches.

These weapons had the rubber butt stock pad removed and the rear-most edge around the periphery of the butt stock rounded with an 1/8-inch radius. The pads were removed to eliminate the high degree of variability inherent in rubber compounds and to provide a basic condition that can be built upon systematically. There were two versions of the 7- and 9-lb shotguns. One of each had no butt stock pad as described previously, and one of each had a hydraulic shock absorber built into the butt stock. The shock absorber was a model 67DP-14146 manufactured by the Taylor Corporation and installed by the Shooter's Emporium, Inc. This shock absorber had a 1-inch stroke and was used with a 7/8-inch-outside-diameter x 2-inch-long return spring made of 0.085-inch-diameter wire. In addition to the Taylor shock absorbers, the 7-lb weapon had an energy-absorbing recoil pad made by the KickEZZ Corporation, and the 9-lb weapon had an energy-absorbing pad made by Pachmayr Incorporated. The test weapons and the recoil mechanism components are shown in Appendix B.

Each test weapon was equipped with "post and peep" iron sights similar to the sights on the M16A2 rifle except that they were not adjustable. The sight was exactly the same on every test weapon, and therefore, the sight radius for each test weapon was constant. The butt stocks for each of the test weapons without the recoil-mitigating devices were exactly the same in shape and length so that they did not cause the subjects to "cheek" the weapons differently. The weapons with the recoil-mitigating devices were designed with a sliding cheek plate so that although the butt stock moved with the weapon recoil, the cheek plate remained relatively still to allow subjects to cheek these weapons in the same manner as the other test weapons.

Each shotgun had a charge coupled device (CCD) micro TV camera mounted on it for data-gathering purposes. The cameras were boresighted with sufficient precision that the entire target panel was well within the field of view (FOV) of the camera. Zeroing the weapons for each shooter was accomplished by recording a section of calibration tape for each shooter and weapon from the sandbag-supported position (see the Procedures section of this report).

Weapon and Ammunition Calibration

Before the present study was conducted, the Weapons Technology Directorate (WTD) of ARL conducted a test by firing samples of the test ammunition from one of the test shotguns to obtain the recoil impulse values used to perform the calculations that were the basis of Table 1. To do this, they used a test fixture that includes a mass representative of the human shoulder. Optical trackers sensed the displacement over time for the weapon during firing and plotted the data as curves on a graph. Appendix C contains the graphs of the acceleration and displacement of each of the test weapons and the baseline weapon.

WTD also fired the two types of ammunition used in this test plus a lighter target load from a shotgun equipped with various recoil-mitigating devices and mounted in the fixture described previously. Appendix D shows the reduction in acceleration that could be acquired through the use of various recoil-mitigating devices on three different weight weapons. This was done before the shotgun weights that were used in this study had been determined, so the weights are not exactly the same. Also, the shotguns used in the WTD test had a slightly longer barrel, so the recoil impulses, although from the same cartridges, are slightly higher than for the shotguns used in this study.

Instrumentation

Gun Cameras

Each weapon used in this study was equipped with a Panasonic WV-CD1BW CCD micro-miniature (52.9-mm x 17.5-mm diameter), lightweight (25.0 g) TV camera. The lens used had a 24-mm focal length to give it a sufficient FOV (13^{o} wide x 10^{o} high) to capture the aiming error and give good resolution of the target. The camera was mounted on the sight bracket so that the camera axis closely coincided with the axis of the sight. The camera was connected to a video data recorder and processor via a small cable. Each trial was recorded on a video cassette for later playback and data reduction with MotionAnalysis Corporation equipment.

Data-Reduction Equipment

The data cassettes were processed and the data reduced via equipment and software made by MotionAnalysis Corporation of Santa Rosa, California. This system calculated the x and y coordinates every 0.017 second for selected trials.

Target

The target was an 8-foot-high x 12-foot-wide plywood panel painted flat white with three 8-inch-diameter black circular targets painted on it. One black target was in the exact center of the panel, and the two others were 42 inches (center to center) on either side (see Figure 1). The target panel was 80 yards from the firing point so that pellets bounced off the panel rather than destroying it. The shooter was instructed to aim at the center circle; the other two circles were for the calibration of the data-reduction equipment (see Figure 2). The video data processor (MotionAnalysis Corporation) is a contrast seeker and is designed to calculate the precise location of these targets with respect to the exact center of the video image.

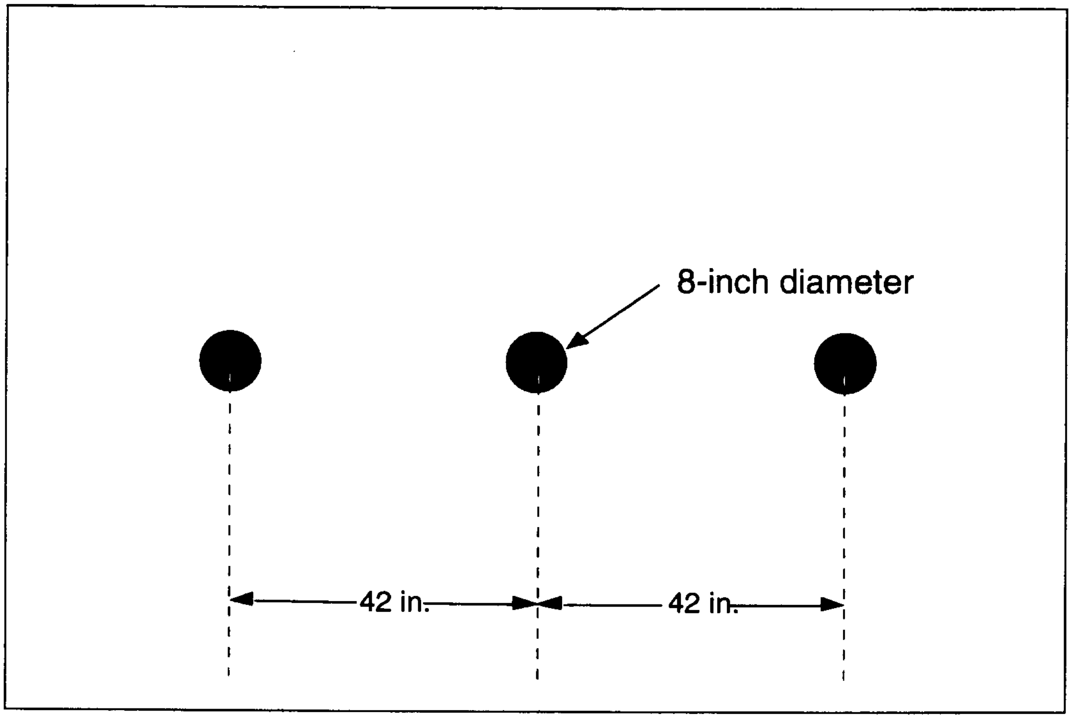

Figure 1. Illustration of target panel. (The target panel was 12 feet wide x 8 feet high, constructed of plywood, and painted white with black targets. The target panel was situated 80 yards down range from the firing position.)

Test Subjects

The subjects were 105 male soldiers and marines stationed at Aberdeen Proving Ground or on temporary duty (TDY) to Aberdeen Proving Ground for the HRED JAVELIN portability study. The subjects were all volunteers and were required to sign a volunteer agreement affidavit (see Appendix E) before participating.

Figure 2. Test setup. (The test subject aimed at the center target of the target board and fired the weapon. Gun-mounted camera and video recording equipment recorded the aiming performance.)

Anthropometric Data

The height and weight of each subject were recorded at the time of testing. Subjects were randomly assigned to test groups. However, there was some deviation from the randomization scheme if a disproportionate number of tall, short, heavy, or light people were being assigned to a particular group. This practice resulted in seven test groups that were relatively homogeneous in terms of subject height and subject weight.

Test Facilities

The testing was conducted at the HRED small arms test facility at M range.

EXPERIMENTAL DESIGN

Independent Variables

The independent variables were

1. Recoil velocity (11, 15, and 20 ft/s)
2. Recoil energy (25, 34, and 43 ft-lb)

Practical considerations, such as the number of cartridge impulse levels available and weapon weight constraints, resulted in a fractionated factorial design of this experiment. As can be seen in Table 2, six combinations of recoil energy and recoil velocity (including the baseline condition) were chosen for this study from the combinations shown in Table 1. These variables were achieved by using weapon weights of 5.0, 7.0, 9.0, and 12.0 lb and cartridge impulse levels of 4.32 and 3.30 lb-s. The recoil levels chosen for this study were 43 ft-lb of energy with 20 ft/s velocity, 34 ft-lb of energy with 20 ft/s velocity, 34 ft-lb of energy with 15 ft/s velocity, 25 ft-lb of energy with 15 ft/s velocity, and 25 ft-lb of energy with 11 ft/s velocity. In addition, the 43 ft-lb of energy with 20 ft/s velocity recoil and 34 ft-lb of energy with 15 ft/s velocity were examined with and without a recoil-mitigating device, for a total of seven recoil energy-velocity test conditions. A recoil level of 18 ft-lb of energy with 11 ft/s velocity was chosen as the baseline. These combinations of recoil velocity and recoil energy were chosen because they seemed to encompass almost all those anticipated by the development community for various future bursting munitions.

Fifteen subjects were randomly assigned to each of the five recoil energy-velocity conditions without the recoil-mitigating devices. Because of scheduling problems, the two conditions with recoil-mitigating devices were added toward the end of the study. When the weapons with the recoil-mitigating devices became available, 15 subjects were randomly assigned to each of these recoil energy-velocity conditions.

Table 2

Matrix of Test Groups

Recoil velocity (ft/s)	Recoil energy (ft-lb)			
	43.0	34.0	25.0	18.0
20	7 lb H	5 lb L		
15		9 lb H	7 lb L	
11			12 lb H	10 lb L (b)

(b) = baseline

(L) Remington Express extra long range. Order Number: SP12.
2-3/4-inch shell. 1-1/4 oz @ 1330 ft/s
Recoil impulse = 3.30 lb-s Measured by Tim Brosseau, WTD

(H) Remington SP Duplex. Order Number: MRP12XH Mag.
3-inch Magnum shell. #4x6 2 oz @ 1175 ft/s
Recoil impulse = 4.32 lb-s Measured by Tim Brosseau, WTD

To simplify the reference to a specific recoil energy-velocity level, naming conventions are applied to the different combinations of recoil energy and recoil velocity. The naming convention begins with the recoil energy of the condition followed by a dash and the recoil velocity of the condition. If the letters "RM" follow the designation, this condition used a recoil-mitigating device. Table 3 shows the different recoil characteristics used in this study and the name used to describe each one.

Table 3

Recoil Energy-Velocity Naming Convention

43 ft-lb of energy with 20 ft/s velocity	43 ft-lb - 20 ft/s
34 ft-lb of energy with 20 ft/s velocity	34 ft-lb - 20 ft/s
34 ft-lb of energy with 15 ft/s velocity	34 ft-lb - 15 ft/s
25 ft-lb of energy with 15 ft/s velocity	25 ft-lb - 15 ft/s
25 ft-lb of energy with 11 ft/s velocity	25 ft-lb - 11 ft/s
43 ft-lb of energy with 20 ft/s velocity and a recoil-mitigating device	43 ft-lb - 20 ft/s RM
34 ft-lb of energy with 15 ft/s velocity and a recoil-mitigating device	34 ft-lb - 15 ft/s RM

Dependent Variables

1. Aiming error.

2. The number of rounds fired until the shooter terminated the trial because of discomfort.

3. The subjective rating of the magnitude of the recoil.

Each dependent variable was analyzed separately.

Sample Size

Fifteen subjects were assigned to each of the seven recoil energy-velocity groups. A subject was placed in one test group and fired in one recoil energy-velocity condition.

PROCEDURE

Firing Position

All weapon firing in this test was done from the standing off-hand position. The superelevation was approximately zero.

Firing Instructions

The subjects were told how to properly shoulder, hold, aim, and fire weapons of these levels of recoil. The subjects were told to stop firing and terminate the trial if they reached a point when they felt they were no longer willing to tolerate the recoil effects of the weapon they were firing. They were instructed in the firing commands they would receive while shooting: "Shoulder the weapon. Take the weapon off 'safe.' Fire when you are ready."

Weapon Familiarization

Weapon familiarization consisted of having the subjects handle, aim, and then fire five rounds with the weapon used in the baseline condition. Then they followed the same handling procedure with the weapon assigned for their recoil energy-velocity condition.

Zeroing the Weapons

Rather than zero each weapon for each shooter by adjusting the sights so that the point of aim was coincidental with the center of the camera image, a 5- to 10-second section of videotape was taken of the shooter holding as precise an aim as he could at the target from the sandbag-supported position. This was later used as the basis for calculating each shooter's aiming error. A zero was obtained in this manner before firing in the baseline condition and before and after firing in the assigned recoil energy-velocity condition.

Firing Procedure

An experimenter at the firing point was responsible for safety, instruction, loading the weapon, timing the 30-second between-shot interval, and issuing the fire commands.

When the subject came to the firing point for his trial, he was given the firing instructions described earlier. A data sheet displaying the subject number, the test condition, and the date was then filmed through the gun camera so that the data to follow could later be identified. The subject was then given time to handle and become familiar with the weapon. After this, the shooter established his zero with the weapon used for the recoil energy-velocity baseline. The subject next fired five rounds with the baseline weapon at a rate of one round every 30 seconds. He then switched to the weapon for his assigned recoil energy-velocity condition and performed the zeroing exercise with it. The subject then fired five rounds with this weapon at the same rate of fire. Then the subject was asked to rate the recoil of the recoil energy-velocity condition using a 12-point scale (see Figure 3). On the scale, the recoil of the baseline condition was considered to be a 6, and the subject was required to circle the number that best represented the recoil of his recoil energy-velocity condition. Once this rating had been completed, the subject was told to continue firing until he had fired 50 rounds or had reached such a point of discomfort that he was unwilling to continue.

MILD	1	2	3	4	5	6	7	8	9	10	11	12	SEVERE
						^							

Figure 3. Recoil rating scale. (This was provided for subjects to complete immediately after they fired their fifth test round or after firing their last test round if they fired fewer than five rounds.)

Data Collection

Continuous aiming error data for each trial were collected via the weapon-mounted TV camera and recorded with a Panasonic AG-7350 videotape recorder for later review and analysis.

DATA REDUCTION

The aiming error data were processed for analysis by means of equipment and software made by MotionAnalysis Corporation. This initial processing was done under contract by Innovative Technical Consulting, Inc., 485 Leafy Lane, Sebastopol, California 95472.

The MotionAnalysis system uses the raw data videotapes from the weapon-mounted camera and calculates x,y position data of the targets at a sampling rate of 60 hertz. It performs this by looking for areas of the video image that have a high contrast ratio. The system operator can aid the computer in determining which areas of high contrast are of interest and which areas of the image to ignore. The system then calculates the centroids of the targets and outputs the location of the target, in both the x and y axes, in pixel units. The accuracy of the system in determining the location of the centroid of the target is approximately 1/10 of a pixel. This resolution reflects an approximate resolution of 1/4 inch and no worse than 1/2 inch in determining the location of the target.

The aiming error data were collected by analyzing the videotape from the cameras mounted on the various weapons. The videotape was analyzed using the MotionAnalysis system. This system basically determined areas of high contrast ratio and determined these areas to be the targets on the target board.

The appropriate aim point for each of the soldiers was determined by reducing the calibration data. As discussed in the Procedures section, the calibration data were collected by having the soldiers aim the weapon at the target for about 10 seconds before and after the test trials. The calibration data were reduced by determining the average horizontal (x) and vertical (y) location of the target. The data were then examined to determine if any large differences in aim point location existed between the two calibration trials. If large differences did occur, the aim point data were then examined to determine if either of the calibration trials was in obvious error. It was determined through this method that four of the calibration files were not correct, and the data for those calibration trials were discarded. For every subject who had two calibration trials remaining, the average of the two x,y locations of the target was used as the appropriate aim point.

The next step in analyzing the aiming error data was to determine the correct scale of the video images. The MotionAnalysis system does its computation and provides its output in pixel units. To determine what the aiming error is in inches or mils, a scaling factor, which can be obtained by determining the number of pixels between two known distances in the video image, must be employed. The distance between the center point of the middle target and the center point of the two other targets was exactly 42 inches. The average distance in pixel units was determined for each of the calibration files using this known measurement. It was discovered that the average number of pixels was not uniform across all the subjects but fell into two distinct groups. The distance between the center and either of the outside targets was about 17.7 pixels for 96 of the subjects and about 19.5 pixels for the remaining 9 subjects. It was subsequently determined that these two groups fired from different firing points. The group of 9 subjects with an average distance of 19.5 pixels fired from Firing Point 1 while the other group all fired from Firing Point 2. These differences were determined to be caused by a slight variance in the distance from the shooter to the target.

The scaling factors were then computed by dividing the number of inches between the targets on the board (42 inches) by the number of pixels in distance between the targets (either 17.7 or 19.5). Therefore, two scaling factors used for this study were 2.2 for the 9 subjects who fired from Firing Point 1 and 2.4 for the remaining 96 subjects who fired from Firing Point 2.

The aiming location for each shot was defined as the video frame that preceded significant target image movement attributable to weapon recoil. This definition ensured that the recoil had not yet started and would not be included as aiming error. The scaling factor for each subject was applied to the aiming data. Finally, the data were converted to mils so that they would not be range dependent.

RESULTS

Analyses of Shot Quantity Data

Means and standard deviations (SDs) for the number of rounds fired from each recoil energy-velocity condition were computed and are presented in Table 4. The means are also presented in graphical form in Figure 4.

Table 4

Mean Number of Shots Fired for Each Recoil Energy-Velocity Condition

Recoil energy-velocity	Mean number of shots fired (standard deviation)
43 ft-lb - 20 ft/s	6.73 (2.74)
34 ft-lb - 20 ft/s	7.40 (4.91)
34 ft-lb - 15 ft/s	13.07 (13.74)
25 ft-lb - 15 ft/s	17.27 (16.06)
25 ft-lb - 11 ft/s	13.00 (8.15)
43 ft-lb - 20 ft/s RM	38.80 (16.57)
34 ft-lb - 15 ft/s RM	47.73 (8.78)

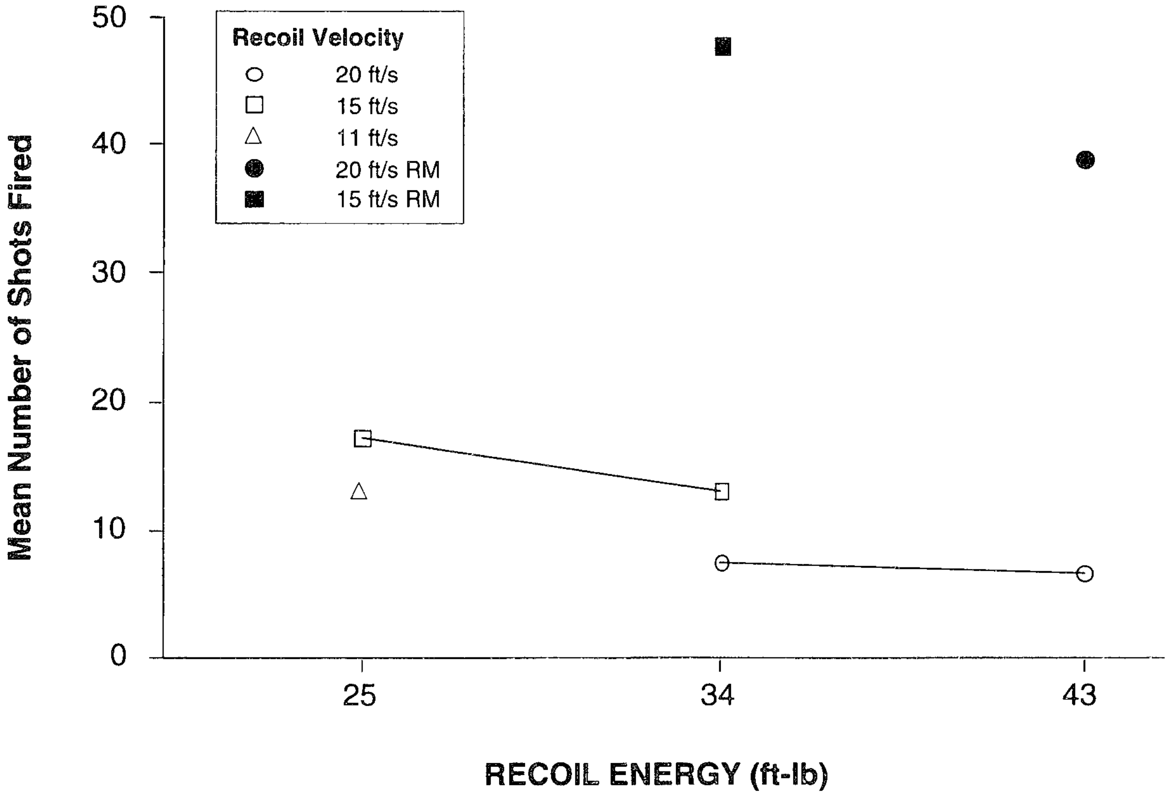

Figure 4. The mean number of shots fired as a function of recoil energy (ft-lb) and recoil velocity (ft/s). (Significantly more shots were fired in each of the conditions using the recoil-mitigating devices than in the comparable energy-velocity conditions without the devices. See text for further results.)

An initial test for homogeneity of variance of the raw data showed that the shot quantity data were not homogeneous. The data were therefore transformed using a natural logarithm transformation. A one-way analysis of variance (ANOVA) with recoil energy-velocity as the single independent variable was performed using the transformed number of rounds fired data. This analysis showed that there was a significant difference in the number of rounds fired for the different recoil energy-velocity conditions F(6, 98) = 18.021, $p < .001$.

Post hoc comparisons using Tukey's Honestly Significant Difference (HSD) Test were performed on the transformed data to determine if any conditions that had either recoil energy or recoil velocity in common or were the same except for the recoil-mitigating device, were significantly different in terms of the number of shots fired. These results showed that both conditions with the recoil-mitigating devices were able to be fired significantly more times than the same recoil energy-velocity conditions without the recoil-mitigating devices. Significantly more shots were fired in the 43 ft-lb - 20 ft/s RM condition than in the 43 ft-lb - 20 ft/s condition ($p < .001$) and significantly more shots were fired in the 34 ft-lb - 15 ft/s RM condition than in the 34 ft-lb - 15 ft/s condition ($p < .001$). All other comparisons made with either recoil energy or recoil velocity held constant failed to show any significant differences in the number of shots that soldiers were willing to fire.

The Tukey Test, which was used to examine all remaining pairwise comparisons, showed that no significant differences in the number of shots fired were found among any of the recoil energy-velocity conditions that did not have a recoil-mitigating device. Also, there was no difference in the number of shots fired between the two recoil energy-velocity conditions that had recoil-mitigating devices. However, all remaining comparisons between those recoil energy-velocity conditions that had a recoil-mitigating device and those conditions that did not have a device were significant. Significantly more shots were fired in the 43 ft-lb - 20 ft/s RM condition than in the 34 ft-lb - 15 ft/s condition ($p < .001$), the 25 ft-lb - 11 ft/s condition ($p < .01$), the 34 ft-lb - 20 ft/s condition ($p < .001$), and the 25 ft-lb - 15 ft/s condition ($p < .01$). Also, significantly more shots were fired in the 34 ft-lb - 15 ft/s RM condition than in the 43 ft-lb - 20 ft/s condition ($p < .001$), the 25 ft-lb - 11 ft/s condition ($p < .001$), the 34 ft-lb - 20 ft/s condition ($p < .001$), and the 25 ft-lb - 15 ft/s condition ($p < .001$).

Analyses of Aiming Error Data

An examination of the raw data revealed that some trials had very high aiming error values, which means that either these shots were aimed very far from the calibrated aim point or equipment problems caused erroneous readings. Between-measures designs are not robust to outliers and therefore should be removed (Daniel, 1960). Outliers were identified and removed from each of the experimental cells using a criterion of 2.5 SDs greater than the cell mean. This conservative approach only eliminated observations that fell outside the 99th percentile.

With the outliers removed from the data set, the remaining aiming error data were used to calculate average horizontal, vertical, and radial distances from the target for Shots 2 through 10 (or fewer if 10 shots were not fired). The means and SDs for these data are presented in Table 5. For these data, the assumptions of normality and homogeneity of variance were violated. Since the root mean square (RMS) of the observations follows a chi-square distribution, a natural log transformation was used to transform the data to adhere to the assumptions of normality before the ANOVA was performed.

Table 5

Mean Horizontal, Vertical, and Radial Aiming Error for Each Recoil Energy-Velocity Condition After Outliers Were Removed

Recoil energy-velocity	Mean horizontal error in mils (SD)	Mean vertical error in mils (SD)	Mean radial error in mils (SD)
43 ft-lb - 20 ft/s	2.18 (1.38)	3.50 (1.97)	4.99 (2.30)
34 ft-lb - 20 ft/s	1.87 (0.78)	2.83 (0.97)	3.89 (1.16)
34 ft-lb - 15 ft/s	1.57 (1.05)	4.57 (3.40)	5.54 (3.37)
25 ft-lb - 15 ft/s	1.51 (0.64)	1.78 (0.92)	3.05 (1.28)
25 ft-lb - 11 ft/s	1.67 (0.57)	2.82 (1.34)	3.90 (1.15)
43 ft-lb - 20 ft/s RM	1.94 (1.12)	2.82 (1.32)	4.22 (1.81)
34 ft-lb - 15 ft/s RM	1.75 (0.41)	3.55 (1.00)	4.67 (1.37)

The ANOVA performed on the radial distance data showed that there was a significant difference in the mean radial distance from the target for the different recoil energy-velocity conditions F(6, 95) = 18.021, $p < .05$.

Post hoc comparisons using the Tukey Test were performed on the transformed data to determine if any conditions that had either recoil energy or recoil velocity in common or were the same except for the recoil-mitigating device, had significantly different radial aiming error. The Tukey Test revealed that with a 15-ft/s velocity, there was a significantly larger aiming error in the 34-ft-lb energy condition than in the 25-ft-lb condition ($p = .05$). All other comparisons made with either recoil energy or recoil velocity held constant or that were the same except for a recoil-mitigating device, failed to show any significant differences in radial aiming performance.

The Tukey Test, which was used to examine all remaining pairwise comparisons, showed that two other conditions also had significantly larger aiming error than the 25 ft-lb - 15 ft/s condition. The 25 ft-lb - 15 ft/s condition had a significantly smaller mean radial distance in aiming error than did the 43 ft-lb - 20 ft/s condition ($p = .05$) and the 34 ft-lb - 15 ft/s RM condition ($p = .05$). All other comparisons among recoil energy-velocity conditions failed to show significant differences. Figure 5 shows the mean radial aiming error in mils for each of the recoil energy-velocity conditions.

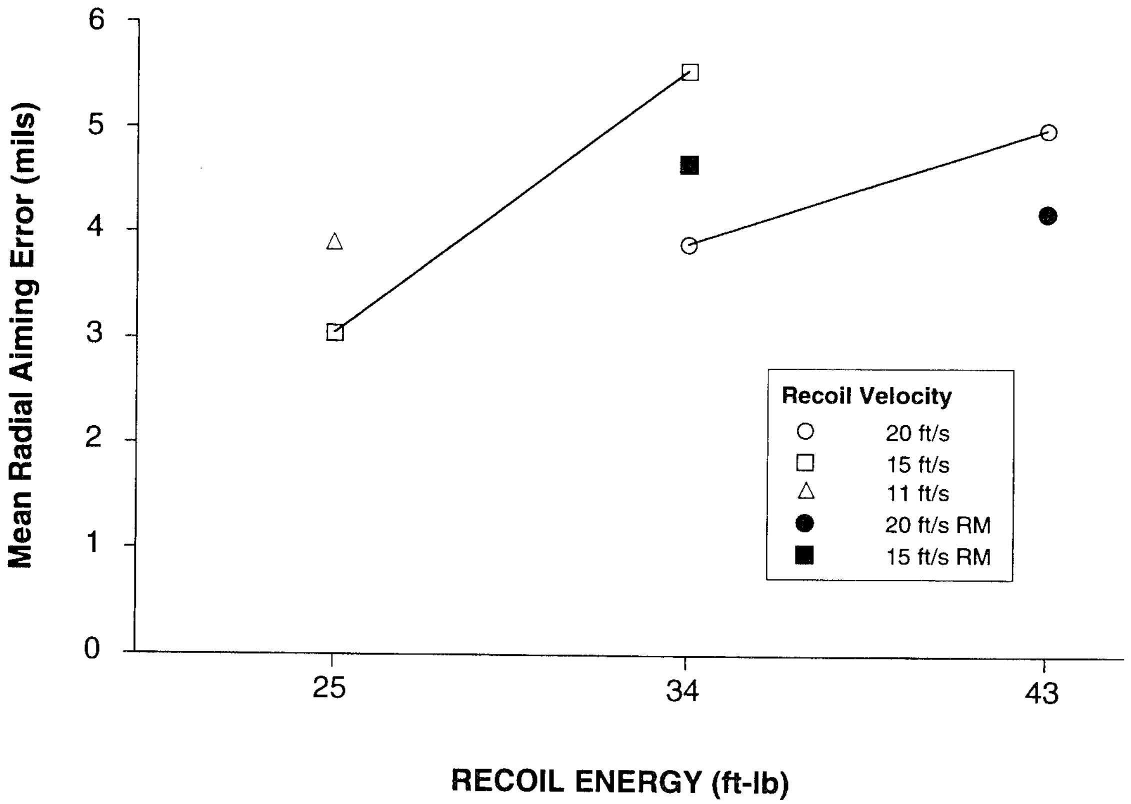

Figure 5. The mean radial aiming error as a function of recoil energy (ft-lb) and recoil velocity (ft/s). (At a recoil velocity of 15 ft/sec, the 25-ft-lb recoil energy condition had a significantly smaller mean radial distance in aiming error than did the 34-ft-lb condition. See text for further results.)

The aiming error data were then analyzed by their vertical (y) and horizontal (x) components to determine if the differences found among recoil energy-velocity conditions were occurring in the horizontal or vertical direction or both. Again, the data points greater than 2.5 SDs away from the mean in the "off target" direction were removed, and a log transformation was performed to correct for homogeneity of variance problems. Means and SDs were computed for the x and y data before the log transformation was performed and are shown in Table 6.

Table 6

Mean Subjective Recoil Rating for Each Recoil Energy-Velocity Condition

Recoil energy-velocity	Mean subject recoil rating (standard deviation)
43 ft-lb - 20 ft/s	9.93 (0.70)
34 ft-lb - 20 ft/s	9.87 (1.06)
34 ft-lb - 15 ft/s	9.33 (1.45)
25 ft-lb - 15 ft/s	8.73 (1.10)
25 ft-lb - 11 ft/s	8.40 (1.50)
43 ft-lb - 20 ft/s RM	6.00 (2.67)
34 ft-lb - 15 ft/s RM	5.80 (2.27)

The horizontal aiming error data show that overall the mean horizontal aiming error for each of the recoil energy-velocity conditions tested was less than 2.2 mils, and the means are very similar. The ANOVA for the horizontal aiming error data supports this. No significant differences were found among test conditions in horizontal aiming error. Appendix F shows the dispersion of aim points around the target (0,0 on the graphs). As can be seen from Figures F-1 through F-7, the dispersion is approximately equal on either side of the target. When the means for these data (positive and negative values rather than purely distance values) were calculated for each of the recoil energy-velocity conditions, the largest mean offset from the target was less than 0.5 mil. This indicates that the aiming error associated with firing weapons at these recoil levels did not produce a consistent bias to the left or right of the target.

The mean vertical aiming error data (see Figure 6) are very different from the horizontal aiming error data. The mean vertical aiming error is much larger than the mean horizontal aiming error and much more varied among recoil energy-velocity conditions. The differences in vertical aiming error seem to closely resemble the differences in radial aiming error, which may indicate that differences occurring in the radial aiming error data are primarily attributable to differences in the vertical direction. These data were subjected to an ANOVA, which showed that significant differences among recoil energy-velocity conditions did exist F(6, 96) = 3.67, $p < .01$.

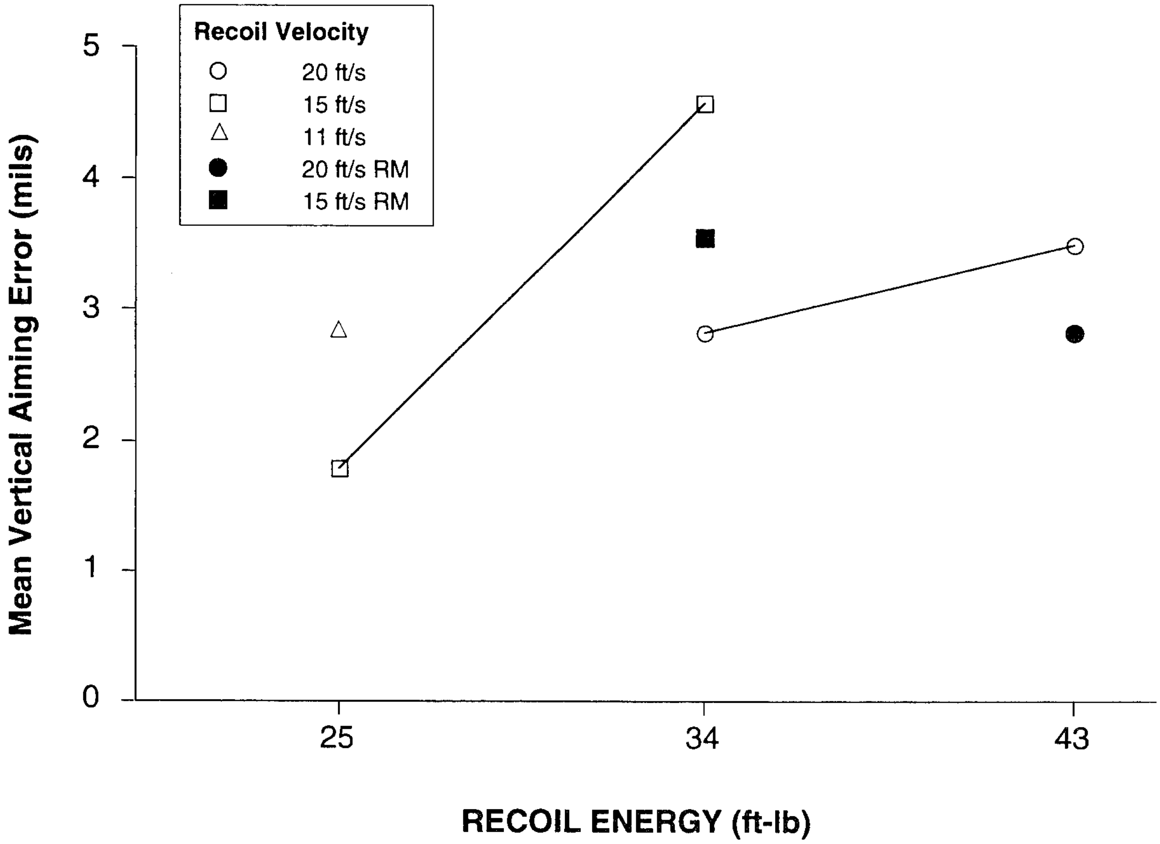

Figure 6. The mean vertical (y) aiming error as a function of recoil energy (ft-lb) and recoil velocity (ft/s). (At a recoil velocity of 15 ft/sec, the 25-ft-lb recoil energy condition had a significantly smaller mean vertical distance in aiming error than did the 34-ft-lb condition. See text for further results.)

Post hoc comparisons using the Tukey Test were performed on the transformed data to determine if any conditions that had either recoil energy or recoil velocity in common or were the same except for the recoil-mitigating device, had significantly different vertical aiming error. Consistent with the radial aiming error results, the Tukey Test revealed that with a velocity of 15 ft/s, there was significantly larger vertical aiming error in the 34-ft-lb energy condition than in the 25-ft-lb condition ($p < .01$). All other comparisons made with either recoil energy or recoil velocity held constant or that were the same except for a recoil-mitigating device, failed to show any significant differences in radial aiming performance.

The Tukey Test used to examine all remaining pairwise comparisons showed that two other conditions also had a significantly larger vertical aiming error than the 25 ft-lb - 15 ft/s condition. The 25 ft-lb - 15 ft/s condition had a significantly smaller mean vertical aiming error than did the 43 ft-lb - 20 ft/s condition ($p < .05$) and the 34 ft-lb - 15 ft/s RM condition ($p < .01$). All other comparisons among recoil energy-velocity conditions failed to show significant differences. These results are also consistent with the radial aiming error results.

As was done for the horizontal aiming error data, the positive and negative vertical aiming error data were analyzed to determine if any consistent aiming biases occurred in the firing of these high recoil weapons. Figures F-1 through F-7 in Appendix F show the dispersion of aim points around the target. Unlike the horizontal aiming error data in which no consistent bias to the right or the left was noticeable, the vertical aiming error appears to be consistently above the target. When the means for these data (positive and negative values rather than purely distance values) were calculated for each of the recoil energy-velocity conditions, every mean was above 0 (above the target), although some were only slightly above. The aiming error for the high impulse load (4.32 lb-s) was considerably above the calibrated aim point. More than 30% of all shots from each of the weapons firing the high impulse magnum load (4.32 lb-s) were aimed higher than 2 mils above the target.

Analyses of Subjective Rating Data

The means and SDs for the subjective rating of recoil were computed for each recoil energy-velocity condition and are presented in Table 6. The means are presented in graphical form in Figure 7.

A chi-square analysis was performed to determine if there were significant differences between any of the recoil energy-velocity conditions regarding the rating of recoil. The subjective ratings scale was divided into three groups: 1 through 4 represented less severe recoil, 5 through 8 represented medium recoil, and 9 through 12 represented more severe recoil.

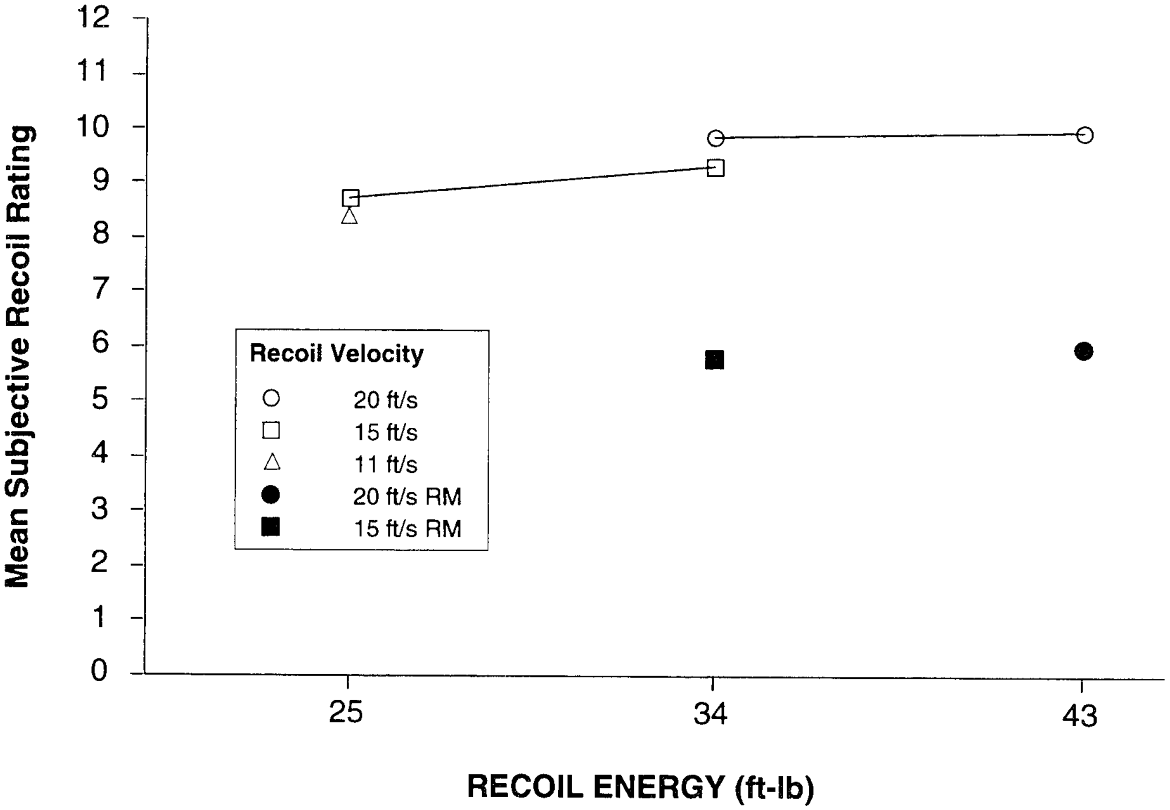

Figure 7. The mean subjective ratings of recoil severity based on a 12-point scale as a function of recoil energy (ft-lb) and recoil velocity (ft/s). (Each of the conditions using the recoil-mitigating devices had significantly lower (milder) subjective recoil ratings than in the comparable energy-velocity conditions without the devices. See text for further results.)

The frequencies of the scores in each one of these groups were determined for the subjects in each of the seven recoil energy-velocity conditions. Because the low (1 through 4) group had many cells with a frequency of zero and a very low expected frequency (which could cause the cell's contribution to the chi-square to be unduly large), the frequencies for the low (rating of 1 through 4) and medium (rating of 5 through 8) were combined (see Table 7). These frequency data were then subjected to a chi-square analysis to determine if significant differences among recoil energy-velocity conditions existed in terms of subjective recoil levels. The chi-square performed on the seven recoil energy-velocity conditions and two levels of rated recoil severity showed a significant difference in the rating of the recoil severity among the different recoil energy-velocity conditions with a chi-square of 38.182 and $p <.001$.

Table 7

Frequencies Used in Chi-Square Analyses to Evaluate Subjective Ratings for Each Recoil Energy-Velocity Condition

Recoil energy-velocity	Frequency of ratings 1 through 8[a]	Frequency of ratings 9 through 12[a]
43 ft-lb - 20 ft/s	0	15
34 ft-lb - 20 ft/s	1	14
34 ft-lb - 15 ft/s	4	11
25 ft-lb - 15 ft/s	4	11
25 ft-lb - 11 ft/s	7	8
43 ft-lb - 20 ft/s RM	10	5
34 ft-lb - 15 ft/s RM	13	2

[a] 1 = mild recoil, 6 = recoil of baseline condition, and 12 = severe recoil.

Individual chi-square analyses were subsequently performed to determine the exact locations of the difference found in the overall chi-square. These chi-square tests were performed using a continuity correction to adjust the statistic for a degree of freedom of 1. The 43 ft-lb - 20 ft/s condition had a significantly higher subjective recoil rating than the 25 ft-lb - 11 ft/s condition (chi-square with continuity correction of 6.708 and $p < .01$). The 34 ft-lb - 20 ft/s condition also had a significantly higher recoil rating than the 25 ft-lb - 11 ft/s condition (chi-square with continuity corrections = 4.261, $p < .05$).

The subjective rating of recoil for the 43 ft-lb - 20 ft/s RM condition was significantly lower than for the 43 ft-lb - 20 ft/s condition (chi-square with continuity correction = 12.15, $p < .001$) and for the 34 ft-lb - 20 ft/s condition (chi-square with continuity correction = 9.187, $p < .01$).

The subjective rating recoil for the 34 ft-lb - 15 ft/s RM condition was significantly lower than for the 43 ft-lb - 20 ft/s condition (chi-square with continuity corrections = 19.548, $p < .001$), as well as the 34 ft-lb - 15 ft/s condition (chi-square with continuity corrections = 8.688, p

$< .01$), the 34 ft-lb - 20 ft/s condition (chi-square with continuity corrections = 16.205, $p < .001$), and the 25 ft-lb - 15 ft/s condition (chi-square with continuity corrections = 8.688, $p < .01$).

In summary, the 43 ft-lb - 20 ft/s and 34 ft-lb - 20 ft/s conditions had significantly higher subjective recoil ratings than both of the conditions with the recoil-mitigating devices and the 25 ft-lb - 11 ft/s condition. Also, the 34 ft-lb - 15 ft/s and 25 ft-lb - 15 ft/s conditions were rated as having higher recoil than the 34 ft-lb - 15 ft/s RM condition.

DISCUSSION

Shot Quantity

The comparisons performed to determine if manipulations of either recoil energy or recoil velocity (while the other variable remained constant) failed to show any significant differences in the number of shots that could be fired. These analyses showed that for the combinations of recoil energy and recoil velocities examined, neither recoil energy nor recoil velocity significantly affected the number of shots that could be fired. However, comparisons between the 34 ft-lb - 15 ft/s and 34 ft-lb - 15 ft/s RM condition and between the 43 ft-lb - 20 ft/s and 43 ft-lb - 20 ft/s RM condition showed significant differences. In both these cases, significantly more shots were fired in the conditions with the recoil-mitigating devices than in the conditions without the devices. In fact, all significant differences in the shot quantity data were between the conditions that used recoil-mitigating devices and the conditions that did not, and every one of these comparisons was significant. This means that significantly more shots were fired in each of the conditions using the recoil-mitigating devices than in every condition that did not.

The number of shots fired in virtually all the recoil energy-velocity conditions tested that did not have recoil-mitigating devices was so small that the practical use of a weapon with these recoil characteristics would be very limited. The highest mean number of shots fired in any of the recoil energy-velocity conditions without a recoil-mitigating device was only 17.27 (in the 25 ft-lb - 15 ft/s condition). The mean number of shots fired in the 43 ft-lb - 20 ft/s condition was a mere 6.73. This is after firing only five shots with the baseline 18 ft-lb - 11 ft/s weapon. The reason most of the subjects gave when they stopped firing in the conditions that did not have the recoil-mitigating devices was that their shoulders hurt. Even the 25 ft-lb - 15 ft/s and 25 ft-lb - 11 ft/s conditions were bruising some of the test subjects. Figure 8 shows an example of bruising that occurred by firing five times in the baseline 18 ft-lb - 11 ft/s condition followed by firing in the 25 ft-lb - 15 ft/s condition 14 times. This photograph was taken less than an hour after the test subject completed firing. Many of the subjects showed signs of bruising shortly after completion of firing, and most probably showed some signs of bruising within 24 hours of firing any of the weapons that did not have the recoil-mitigating device.

The shot quantity data showed a large difference between the number of shots that subjects were willing to fire in the recoil energy-velocity conditions with the recoil-mitigating device compared with the conditions without these devices. Fourteen of the 15 subjects fired the maximum number of shots in the 34 ft-lb - 15 ft/s RM condition, and 9 of the 15 subjects fired 50 rounds in the 43 ft-lb - 20 ft/s RM condition.

Figure 8. An example of the bruising that many of the test subjects experienced. (This subject fired five shots in the baseline 18 ft-lb - 11 ft/s condition, followed by 14 shots in the 25 ft-lb - 15 ft/s condition.)

It was evident that the recoil-mitigating device helped dissipate much of the energy that would normally bruise and make the shoulder area sore, which was the reason most of the subjects stopped firing in the recoil energy-velocity conditions that did not have recoil-mitigating devices. The subjects who stopped firing in the conditions with the recoil-mitigating device seemed to stop for reasons other than the shoulder being hurt. One soldier was being hit in the hand with the trigger guard, and several test subjects were hitting themselves in the nose or face with their hands as the weapon recoiled. Several of the subjects firing in the recoil energy-velocity conditions with the recoil-mitigating devices received bloody noses, but often this did not stop them from firing. The physical pain caused by the recoil energy-velocity conditions with recoil-mitigating devices seemed to be significantly less than that caused by the conditions without the devices.

Aiming Performance

Comparisons were performed to separate the effects of recoil energy and recoil velocity (by comparing two conditions in which one of the variables changed and one remained constant). All paired comparisons, in which recoil energy was held constant and recoil velocity changed, failed to show a significant difference in radial aiming error. However, one paired comparison in which recoil velocity was held constant and recoil energy changed showed a significant effect on radial aiming performance. The 34 ft-lb - 15 ft/s condition had significantly larger radial aiming error than did the 25 ft-lb - 15 ft/s condition. This same effect was also significant in the vertical aiming error data. These results show that an increase in recoil energy from 25 ft-lb to 34 ft-lb at a recoil velocity of 15 ft/s results in poorer aiming performance and that the performance is primarily affected on the vertical axis. The other comparison in which recoil energy changed and recoil velocity remained constant failed to reach significance.

The aiming performance results examining all possible pairwise comparisons showed that in addition to the 34 ft-lb - 15 ft/s condition, the 43 ft-lb - 20 ft/s condition and the 34 ft-lb - 15 ft/s RM condition had a larger aiming error than did the 25 ft-lb - 15 ft/s condition. These differences can be mostly attributed to differences in the aiming performance in the vertical direction since these same recoil energy-velocity conditions were significantly different from each other in vertical aiming performance but not in horizontal aiming performance. This significant difference in the vertical direction for the higher recoil energy-velocity conditions (at least the 43 ft-lb - 20 ft/s and 34 ft-lb - 15 ft/s conditions) would seem to indicate that some test subjects were flinching when subjected to these levels of recoil.

It is interesting that in this study, the recoil-mitigating devices, while allowing the soldier to fire more shots, did not provide any significant degree of improved aiming accuracy in comparison to the conditions without the device. These results agree with a study by Ganem, Kramer, and Torre (1965). In the study, seven weapons, including several shotguns and an M-79 grenade launcher, were fired with and without recoil-mitigating devices. The results from the study failed to show any shooting performance differences between the weapons with and without the recoil-mitigating devices. This seems to indicate that the firing event when using the recoil-mitigating device was still a physically or psychologically traumatic event, and observation at the range during this test seems to support this idea.

The soldiers in this test had difficulty controlling the weapons in the conditions with the recoil-mitigating devices (especially 43 ft-lb - 20 ft/s RM). Often during the first few shots in the 43 ft-lb - 20 ft/s RM condition, the weapon jumped out of the subject's hand that held the forestock. The 43 ft-lb - 20 ft/s RM condition seemed to have a very light muzzle because much of the allotted weapon weight was used for the recoil-mitigating device in the butt stock. The subjects in the 34 ft-lb - 15 ft/s RM condition also had some trouble controlling the weapon. Several subjects complained that the trigger guard hit their hands, and some complained that their hands hit them in the face or nose during recoil. Several of the subjects got bloody noses from firing the weapons with the recoil-mitigating devices, while no subject in the other conditions did. This might be because the weapon traveled farther before the shoulder began to decelerate it, which allowed the hand to come back into the shooter's face and caused some loss of weapon control. An observation by experienced range personnel was that the subjects did not seem any more at ease firing the weapons with the recoil-mitigating devices than those without. Subjects in the conditions with the recoil-mitigating devices were often seen trying to grip the weapons differently to gain more control.

The inclusion of the mitigating devices did reduce one aspect of the trauma associated with firing high recoil weapons, namely, the forces of recoil that in shoulder-fired weapons are transmitted to the shoulder of the shooter, often causing pain, bruising, and a reluctance to fire. However, the taming of the recoil through the use of these devices did not seem to compensate for the degraded performance associated with other noxious events coincidental with firing high recoil weapons.

Subjective Rating

The subjective rating data may have been hindered by the fact that the baseline condition had the lowest recoil energy-velocity level of any of the conditions without the recoil-mitigating device. This level was chosen to avoid having the baseline condition substantially reduce the number of shots that could be fired in the test conditions. The fact that the recoil energy-velocity level was lower than all the other conditions without the recoil-mitigating devices pushed most recoil ratings for those conditions onto the same half of the scale (above six, which subjects were told represented the recoil of the baseline condition). Despite the probable effects of having the baseline recoil energy-velocity condition lower than all the others without the recoil-mitigating device, the 43 ft-lb - 20 ft/s condition and the 34 ft-lb - 20 ft/s condition both received significantly higher (more severe) ratings than the 25 ft-lb - 11 ft/s condition did.

To try to examine the effects of recoil velocity and recoil energy separately, all paired comparisons were examined in which either recoil energy or recoil velocity was constant while the other variable changed. However, all the comparisons between recoil energy-velocity conditions without recoil-mitigating devices that were significant varied in both recoil energy and recoil velocity. In these cases, it is impossible to tell if one of the variables or both played a part in significantly affecting the subjective rating.

Most of the significant differences in the subjective rating data were between recoil energy-velocity conditions with the recoil-mitigating devices and those without. It is theorized that the differences between the conditions with the recoil-mitigating devices and those without may have been exaggerated by the low baseline recoil energy-velocity since most of the energy-velocity conditions without the recoil-mitigating devices were rated above the baseline, and those with the devices were most often rated below the baseline. The 43 ft-lb - 20 ft/s RM condition was rated as having significantly milder recoil than both the 43 ft-lb - 20 ft/s condition and the 34 ft-lb - 20 ft/s condition. The 34 ft-lb - 15 ft/s RM condition was rated as having significantly milder recoil than every recoil energy-velocity condition without recoil mitigation except the 25 ft-lb - 11 ft/s condition. No significant difference in the subjective recoil ratings was found between the two conditions with the recoil-mitigating devices.

General Discussion

The recoil-mitigating devices did not improve aiming performance in comparison to the conditions without the devices. This is not totally unexpected since a study by Ganem, Kramer, and Torre (1965) failed to show an improvement in shooting performance when using a recoil-mitigating device on seven different high recoil weapon-ammunition combinations. However, the mechanical recoil-mitigating devices did allow the shooter to fire significantly more shots than in the conditions that did not have the devices.

One possible explanation for the failure of the recoil-mitigating devices to improve performance of the weapons is the startle reflex caused by the noise and tactile feedback of the weapon. Torre, Querido, and Conway (1990) reported that studies have been performed in which the noise intensity and tactile feedback of the weapon are positively correlated with the aiming error and time to recover to previous level of aiming accuracy. In the present study, the weapons used in the conditions with the recoil-mitigating devices were just as loud, and the tactile feedback to the hands was just as powerful as with the weapons used in the conditions that did not have recoil-mitigating devices. The startle reflex caused by these two factors might be as prominent for the weapons with the recoil-mitigating devices as it is for the weapons without the devices, and therefore, the aiming error is high for both.

The recoil-mitigating device used in this study was far from ideal mechanically in that it allowed the parts of the weapon held in the hands to recoil fully. Only the butt stock of the weapon was buffered. This lack of isolation of the recoiling parts may have prevented the shooter from feeling less threatened by the weapon and kept the aiming error high. A design in which the weapon barrel and chamber are allowed to travel independently within a one-piece stock, with a shock-absorbing system between the two, might be a better approach for a grenade-launching or high energy system.

Even though it was not evaluated in this study, a properly designed energy-absorbing recoil pad (nonmechanical) such as provided with many shotguns might increase the mean number of shots that could be fired on any one occasion. A recoil pad could also reduce the amount of bruising and soreness that probably affects the number of rounds that can be fired on subsequent occasions.

The aiming error associated with the recoil energy-velocity conditions tested was poor. The 25 ft-lb - 15 ft/s condition had the lowest recoil of any condition tested (recoil approximately equal to that of the M79 grenade launcher) and as expected, had the best aiming performance of any of the recoil energy-velocity conditions. However, the 25 ft-lb - 15 ft/s condition still had a mean aiming error radius of 3.05 mils after the 2.5 SD outliers were removed. A weapon that produced this magnitude of aiming error would require a very effective (large lethal radius and precisely timed airburst) grenade to compensate. To obtain such a lethal radius from a bursting munition with a 3- to 4-lb-s impulse will probably be difficult.

The authors expected that these results would provide the foundation for the development of a human performance data base that would correlate performance (in this case, aiming error) with the recoil of a shoulder-fired weapon. It was thought that the data would show an increase in aiming error as recoil energy increased and that there would be a functional relationship among aiming error, recoil energy, and number of rounds fired. However, the aiming error data did not support the development of these anticipated functional relationships.

The data in this study do not lend themselves to very discriminating analysis because of the large variability that exists in the aiming error data. Relationships that were thought to exist and were expected to be found in the data may have been masked by this variability, with only the most robust effects reaching significance. The results, although less different than expected, agree with previous grenade launcher studies employing the M79 grenade launcher (Ganem, Kramer, & Torre, 1965).

One detrimental factor to the aiming performance of the test subjects was that they were not provided with feedback regarding how well they were aiming. Despite being briefed about the importance of good aiming performance, the subjects were possibly not as interested in performing the aiming task well because they were not scored or provided any immediate feedback about their performance. On the other hand, the number of rounds fired became immediate knowledge and was often the subject of discussion among the subjects at the test site. The subjects were never given any information about how well they were shooting (thus aiming), so the number of shots fired was the only readily available basis for competition among the subjects.

One obvious reason for the level of variance in the aiming performance was the fact that all the recoil energy-velocity conditions in the study produced a high amount of recoil in comparison with the weapons that most of the subjects had fired previously. The recoil energy-velocity conditions without the mitigating devices caused pain and discomfort to most of the subjects, as can be seen by the small number of rounds fired in these conditions. The recoil energy-velocity conditions using the recoil-mitigating devices were not as uncomfortable to shoot; however, the shooters still had to fire high impulse systems that are difficult to control. The recoil-mitigating device in the stock and the change in the design as well as function of the stock required the subjects to grip the weapons in a way that did not interfere with the function of the device or cause injury. While the mitigating device may have dampened the energy that is normally transmitted to the shooter's shoulder, the unfamiliar grip and movement of the weapon might have offset any gains in aiming performance.

RECOMMENDATIONS

One important recommendation for this program is that a surrogate weapon be designed, built, and tested, which has the following features:

- a stock that combines the forestock and butt stock into a single unit and is relatively lightweight;

- a weapon mechanism that is mounted on the stock in such a way that it can move forward and backward independently of the stock;

- a recoil-mitigating mechanism between the weapon mechanism and the stock so that the forces and motion transmitted through the stock to the shooter are minimized.

Future testing to study the aiming error associated with firing high recoil weapons should be conducted independently from tests to determine the number of rounds that can be fired. To provide aiming accuracy feedback to the shooter and to simplify data reduction, one could test with high energy hunting cartridges of the appropriate impulse (rather than shotguns) and could use the bullet hole location as the data. Alternatively, the same 12-gauge cartridges could be used with the bottom barrel converted to .22-cal long rifle and fired simultaneously.

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Torre, J. P., Querido, D., & Conway, D. (1990). Small arms technology assessment: Individual's infantry weapon - grenade launchers. Working papers submitted to U.S. Army Materiel Command.

APPENDIX A

RECOIL VALUES FOR VARIOUS WEAPON SYSTEMS

RECOIL VALUES FOR VARIOUS WEAPON SYSTEMS

Weapon system	Weapon weight (lb)	Projectile weight (lb)	Muzzle velocity (ft/s)	Recoil impulse (lb-s)	Recoil velocity (ft/s)	Recoil energy (ft-lb/J)
M16A2	8.80	.008	3050	1.22	4.57	2.70/3.6
M14	9.30	.021	2750	2.60	9.00	11.69/15.8
40MM/M79	5.95	.37	250	3.00	16.25	24.18/32.6
M203/M16A2	11.80	.37	250	3.00	8.18	12.26/16.6
ARGM/M16A2[a]	8.80	.79	216	5.30	19.39	51.45/69.4
ARGM/M16A2[a]	8.80	.85	206	5.44	19.90	54.22/73.2
ARGM/M16A1[a]	7.80	.85	206	5.44	23.35	61.02/82.4
ARGM/M16A2[a]	8.80	1.15	170	6.09	22.28	67.92/91.7
ARGM/M16A2[a]	8.80	1.40	170	7.42	27.14	100.67/135.9
12-gauge mag.	8.25	.10	1315	4.84	18.89	45.70/61.7
10-gauge mag.	12.00	.125	1330	6.04	16.22	48.80/65.9
.375 H&H mag.	9.00	.043	2450	4.96	16.90	44.00/59.4
460 Wby. Mag.	10.00	.070	2550	7.57	24.40	92.30/124.6

[a] Rifle grenades

APPENDIX B

TEST WEAPONS

TEST WEAPONS

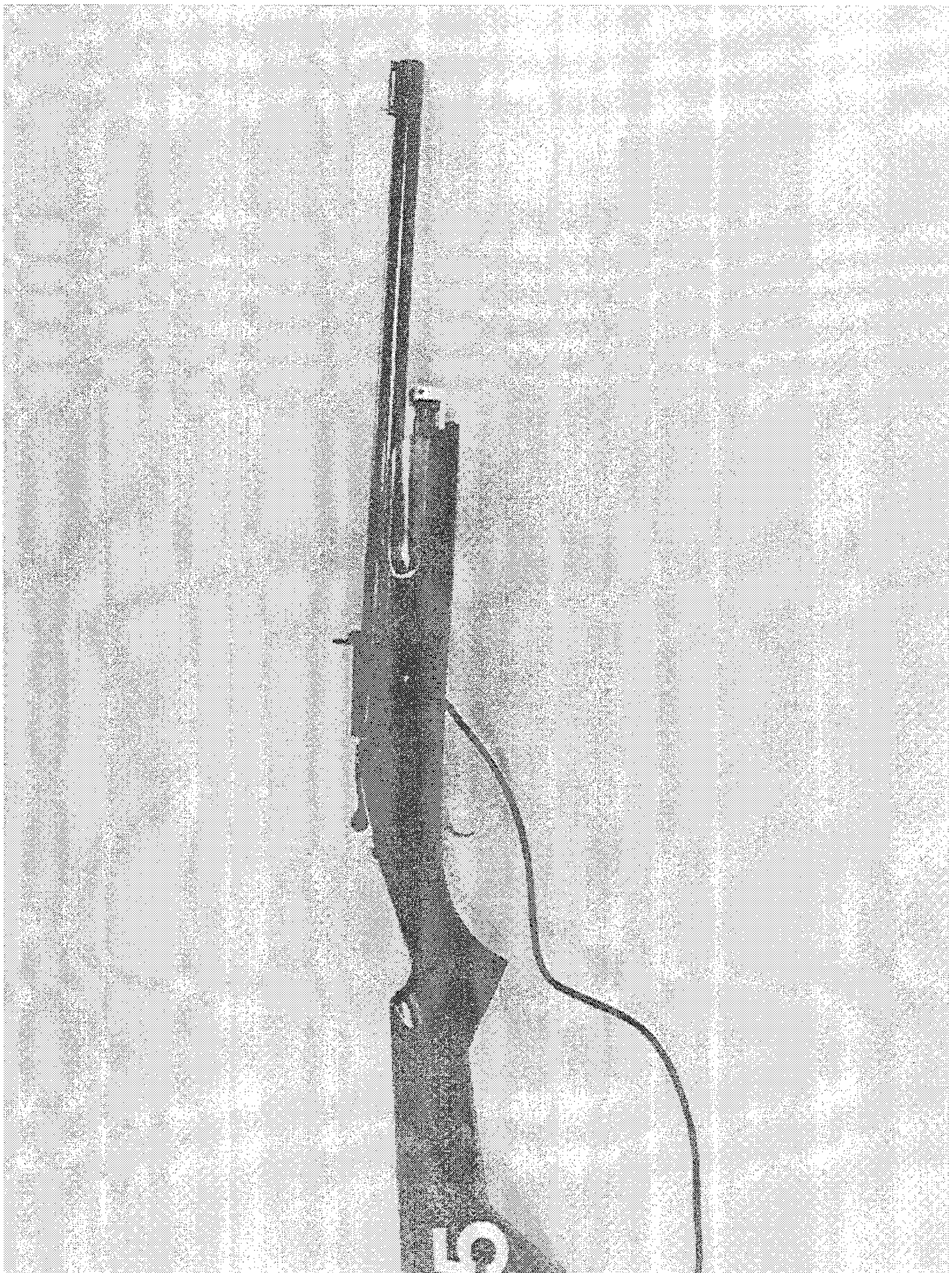

Figure B-1. The 5-lb weapon used in the 34 ft-lb - 20 ft/s condition was a Browning Citori over-and-under 12-gauge shotgun. This weapon was modified by cutting the barrel to 20-5/8 inches, removing the rubber butt stock pad, some of the butt stock, the lower barrel, the trigger guard, and the auto ejector.

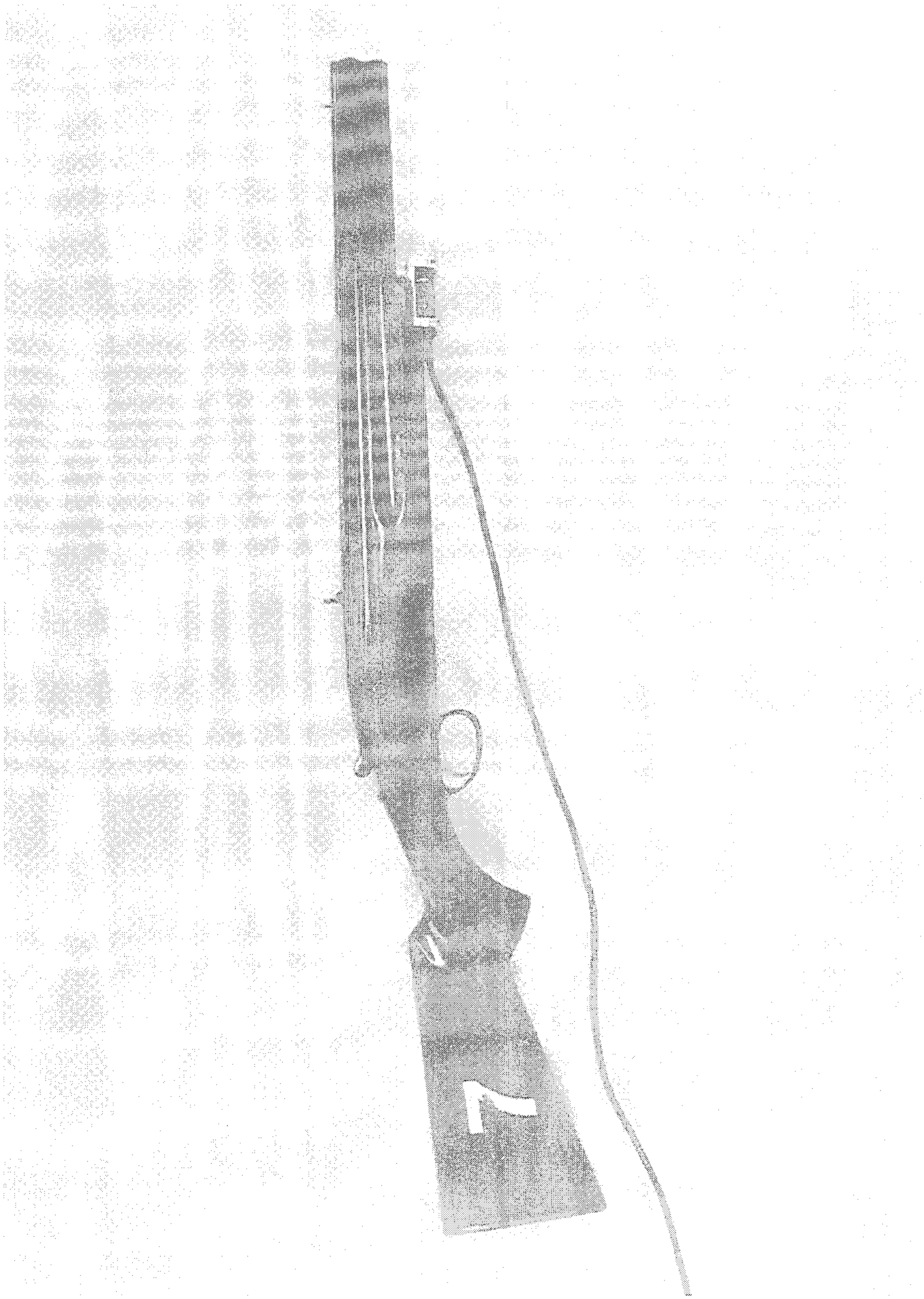

Figure B-2. The 7-lb weapon used in the 43 ft-lb - 20 ft/s condition and the 25 ft-lb - 15 ft/s condition was a Browning Citori over-and-under 12-gauge shotgun. This weapon was modified by cutting the barrel to 20-5/8 inches, removing the rubber butt stock pad, the lower chamber hammer, and firing pin.

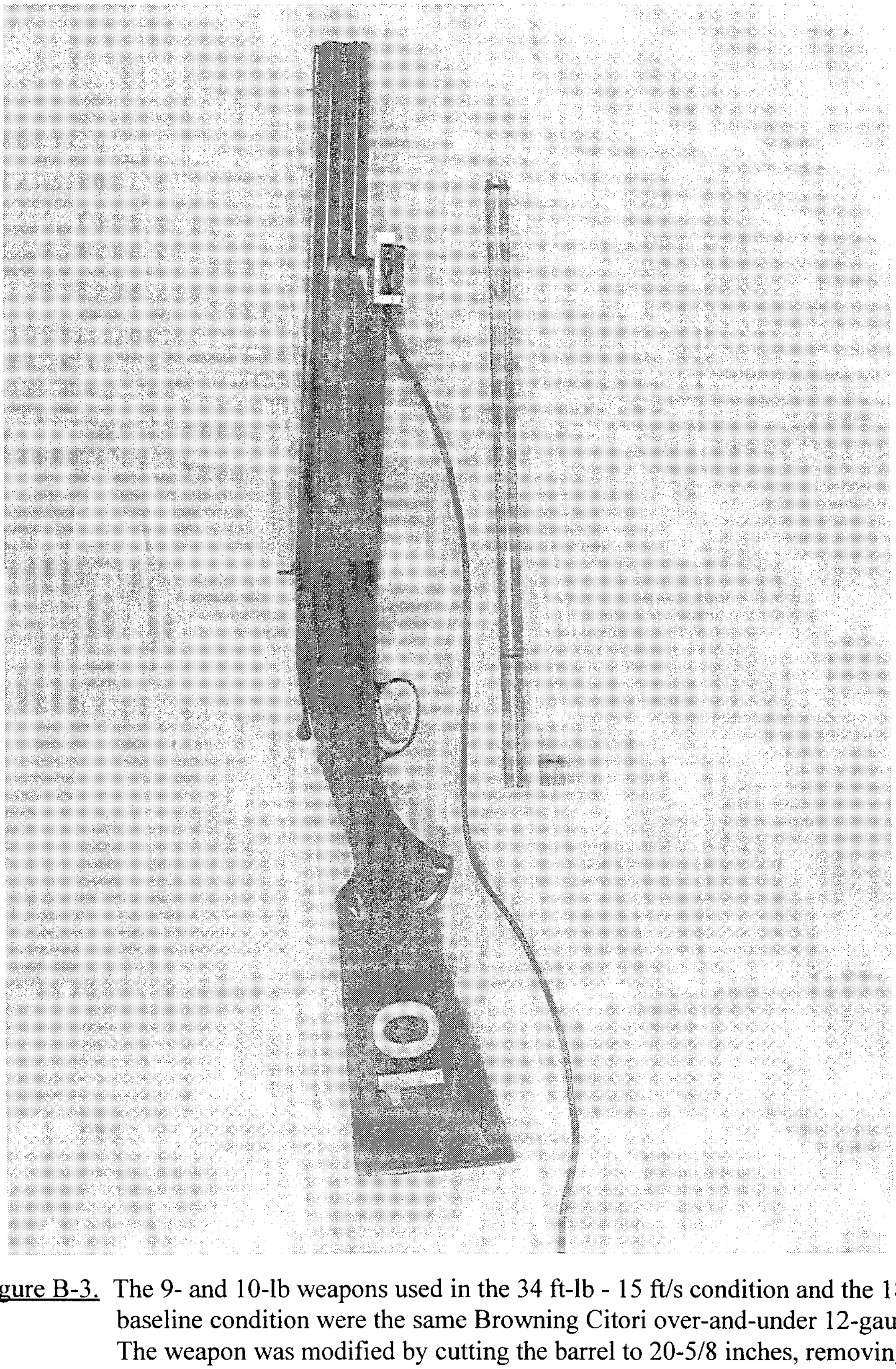

Figure B-3. The 9- and 10-lb weapons used in the 34 ft-lb - 15 ft/s condition and the 18 ft-lb - 11 ft/s baseline condition were the same Browning Citori over-and-under 12-gauge shotgun. The weapon was modified by cutting the barrel to 20-5/8 inches, removing the rubber butt stock pad, adding lead inside the butt stock, and adding either the 4.5-oz or the 1-lb 4.5-oz steel weight (shown) to the lower barrel.

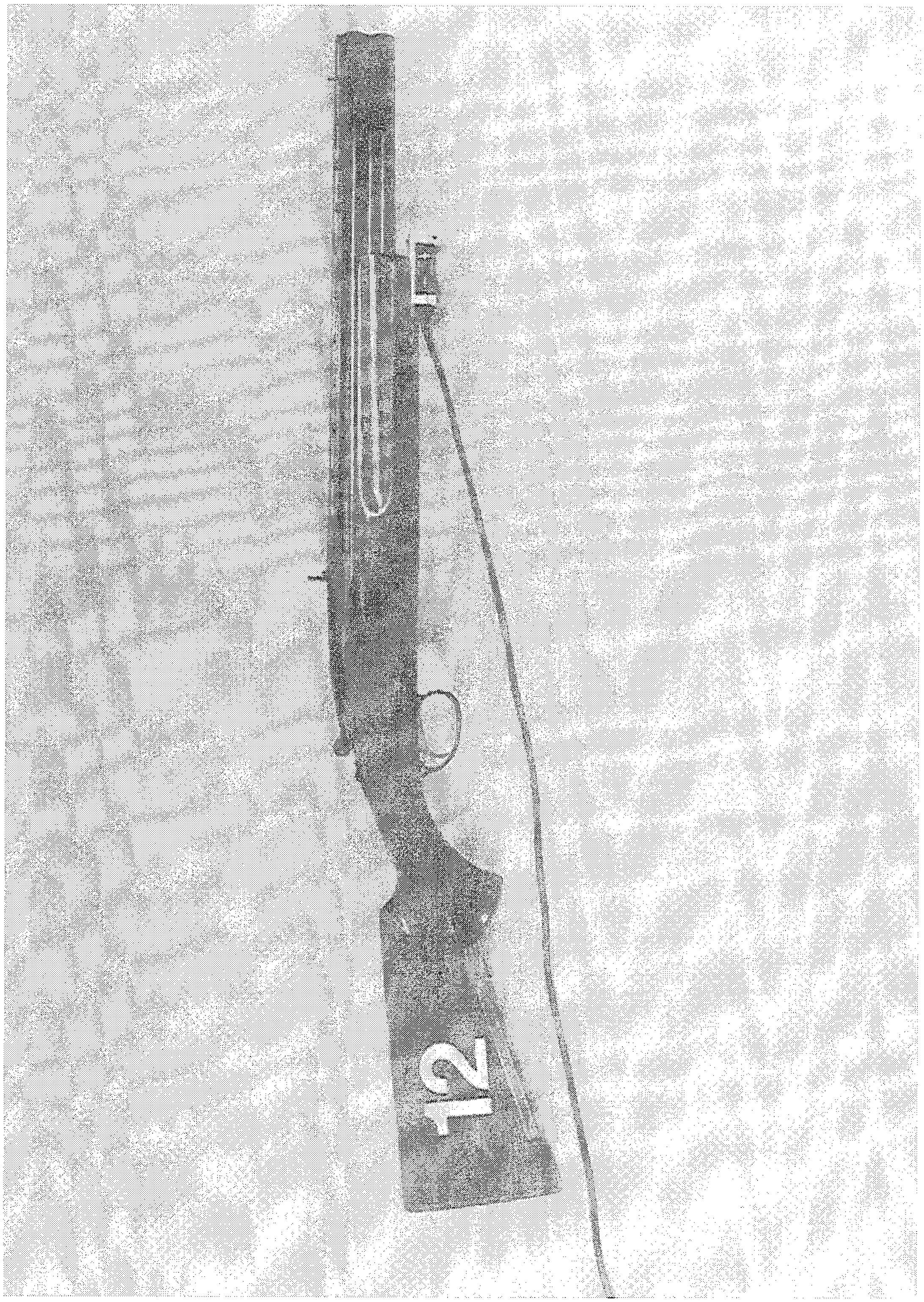

Figure B-4. The 12-lb weapon used in the 25 ft-lb - 11 ft/s condition was a Browning Citori over-and-under 12-gauge shotgun. This weapon was modified by cutting the barrel to 20-5/8 inches, removing the rubber butt stock pad, adding lead inside and outside the butt stock, and adding lead weight to the lower barrel.

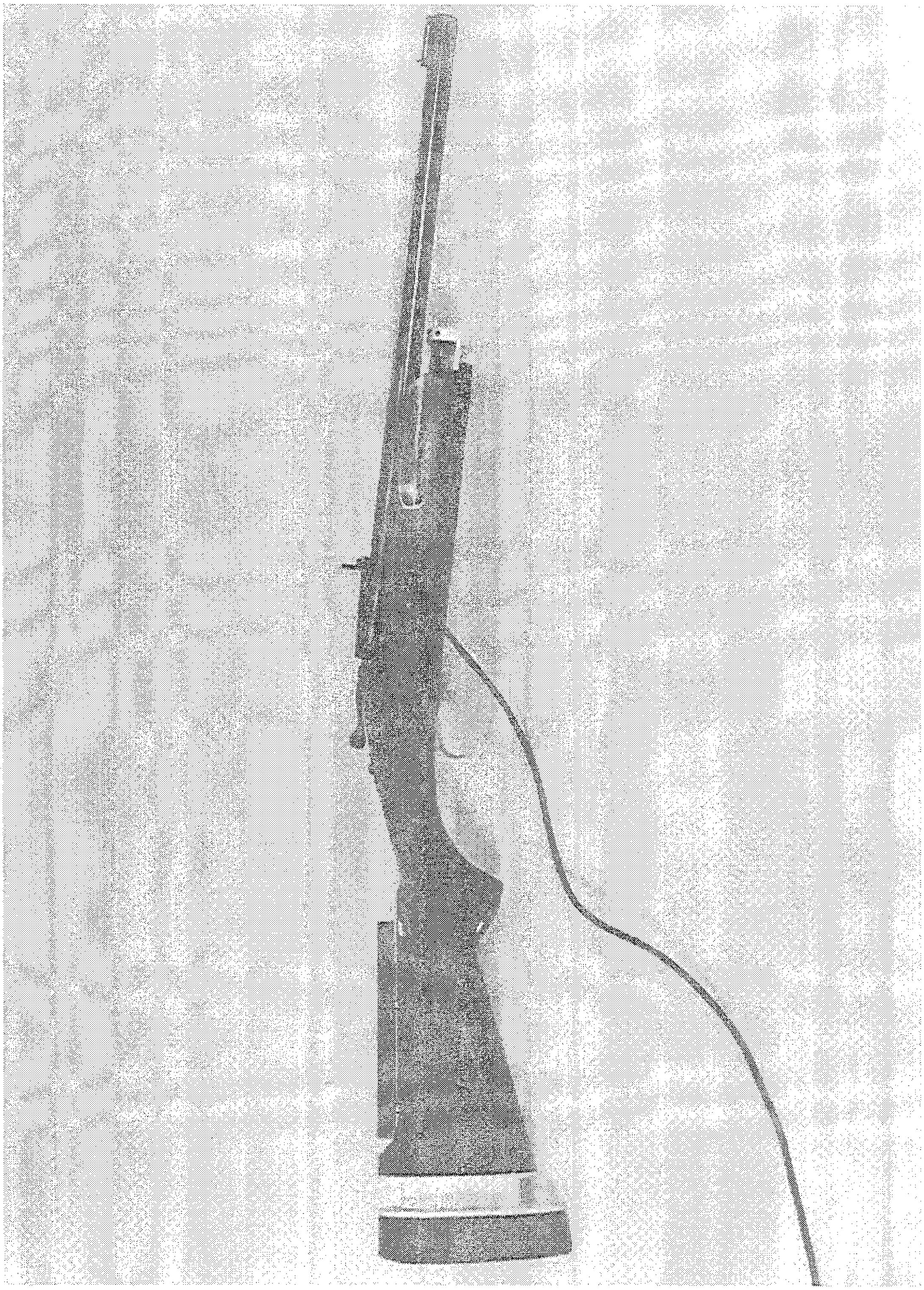

Figure B-5. The 7-lb weapon with recoil-mitigating device used in the 43 ft-lb - 20 ft/s RM condition was a Browning Citori over-and-under 12-gauge shotgun. This weapon was modified by cutting the barrel to 20-5/8 inches, removing the lower barrel and trigger guard, and adding the Taylor 1-inch recoil-mitigating device with the KickEZZ pad.

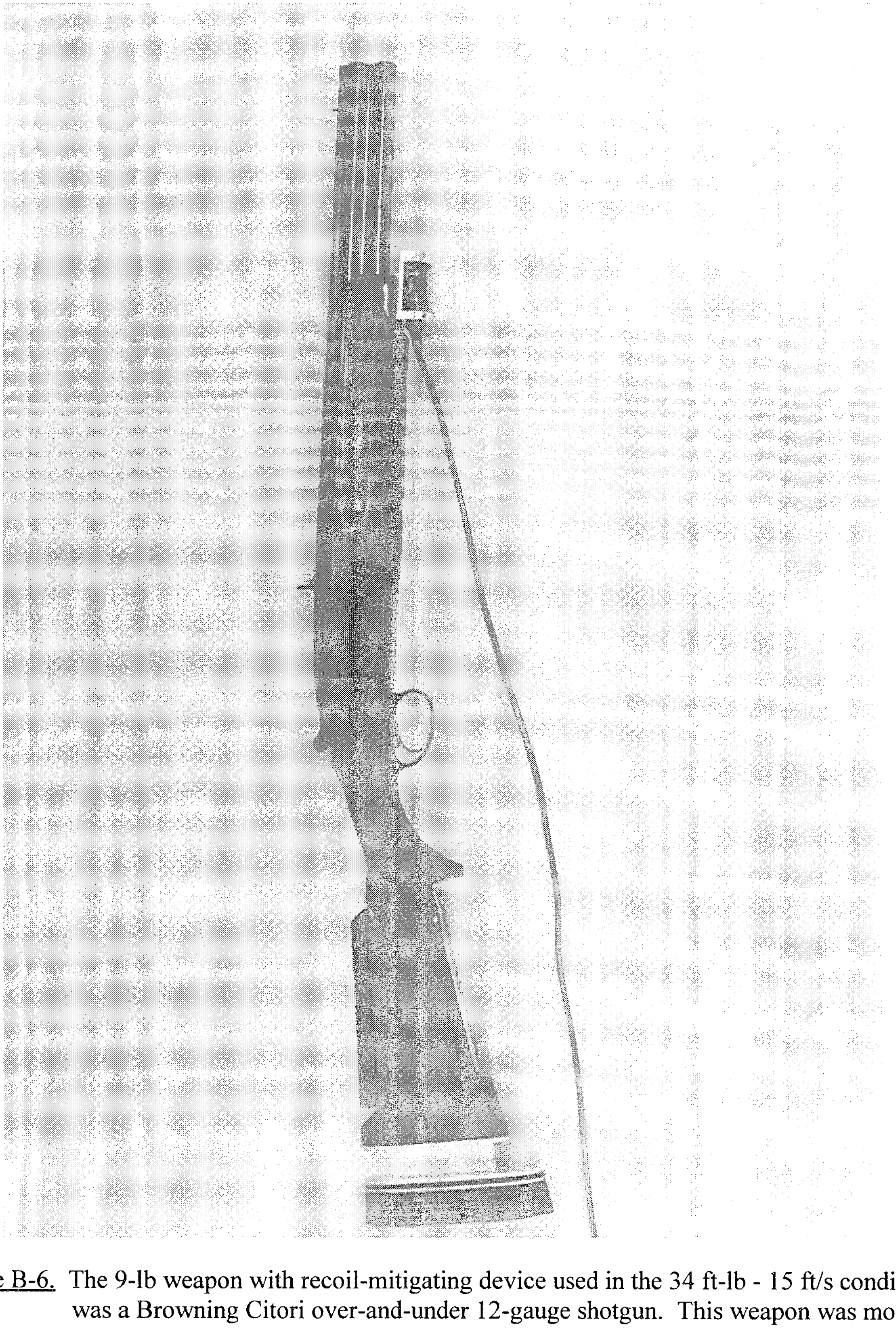

Figure B-6. The 9-lb weapon with recoil-mitigating device used in the 34 ft-lb - 15 ft/s condition was a Browning Citori over-and-under 12-gauge shotgun. This weapon was modified by cutting the barrel to 20-5/8 inches, adding a lead weight to the butt stock, and adding the Taylor 1-inch recoil-mitigating device and the Pachmayr pad.

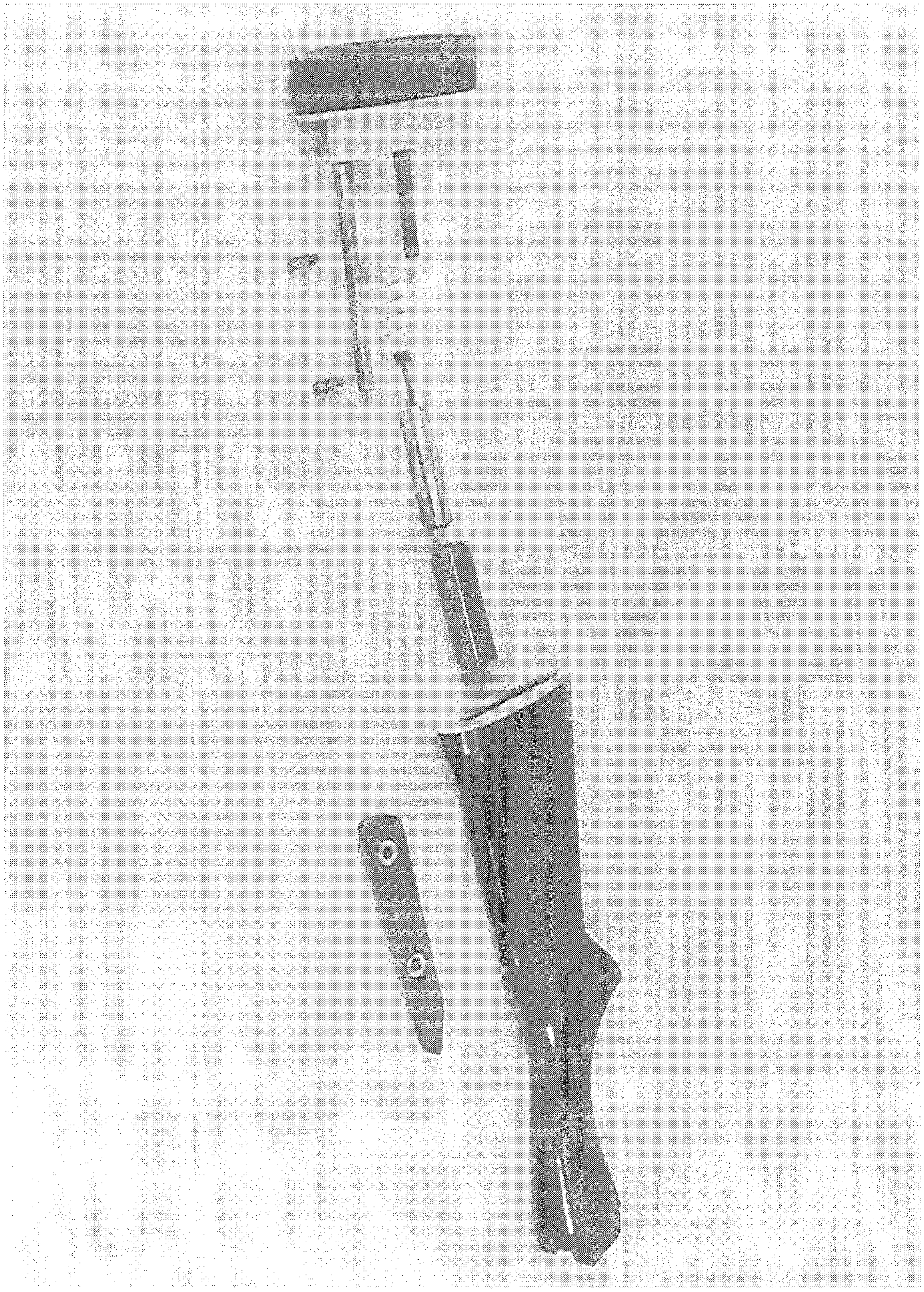

Figure B-7. The Taylor 1-inch recoil-mitigating device that was installed on two of the test weapons. The device consists of a hydraulic shock-absorbing piston. The butt stock of the weapon was modified to allow the cheek plate to move with the shock absorber. A pad was used with the recoil-mitigating devices. The pad pictured here is the KickEZZ pad.

APPENDIX C

RECOIL CHARACTERISTICS

RECOIL CHARACTERISTICS

18 ft-lb - 11 ft/s Baseline Condition

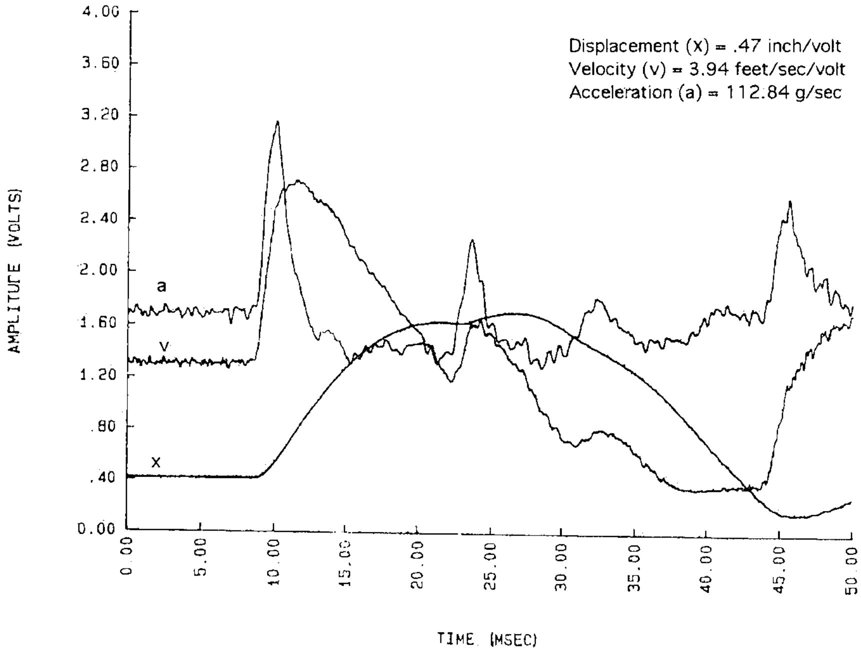

Figure C-1. The recoil characteristics of the 18 ft-lb - 11 ft/s baseline.

43 ft-lb - 20 ft/s Condition

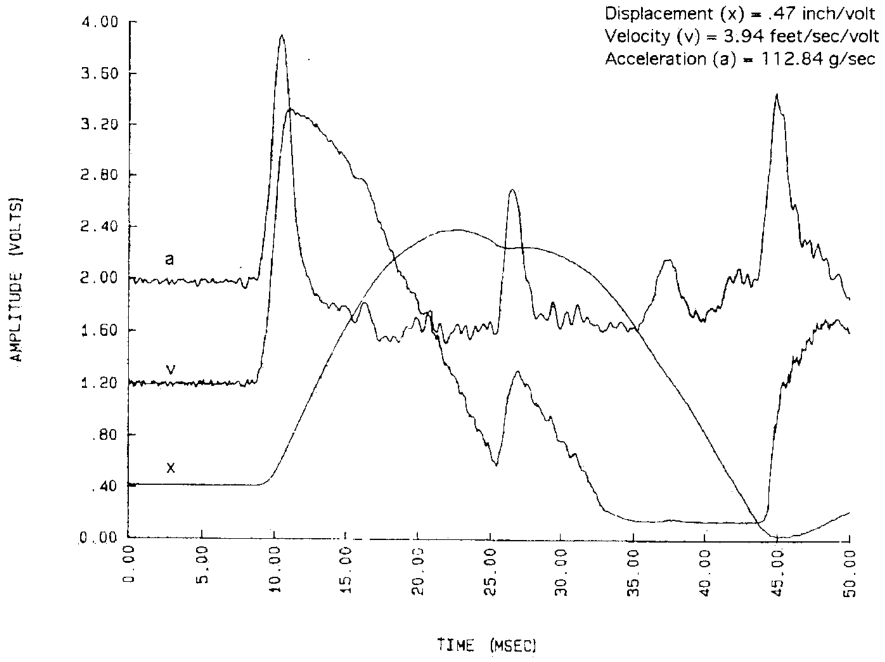

Figure C-2. The recoil characteristics of the 43 ft-lb - 20 ft/s condition.

34 ft-lb - 15 ft/s Condition

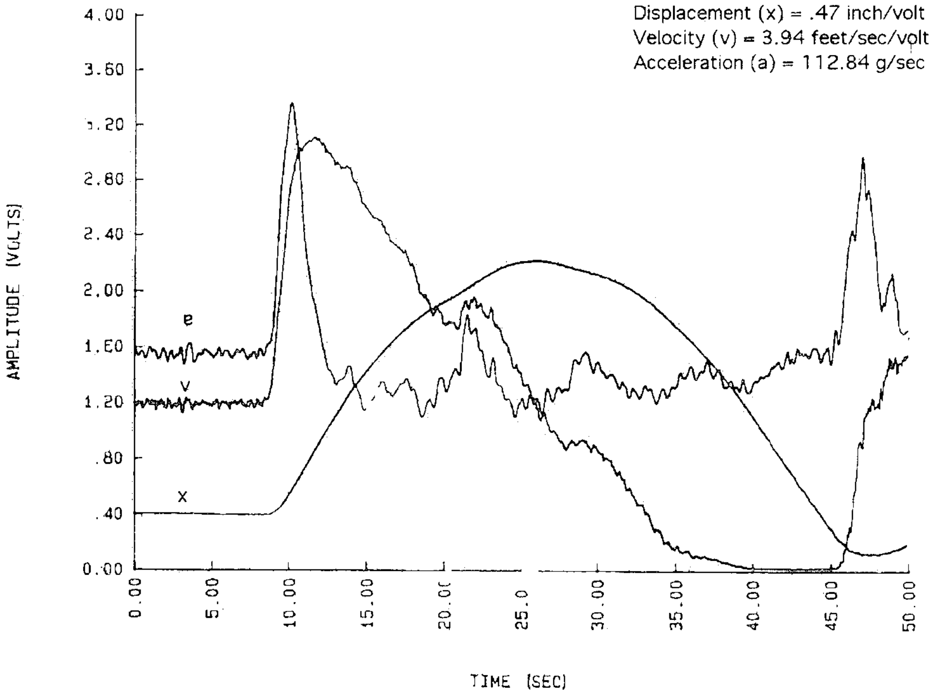

Figure C-3. The recoil characteristics of the 34 ft-lb - 15 ft/s condition.

25 ft-lb - 11 ft/s Condition

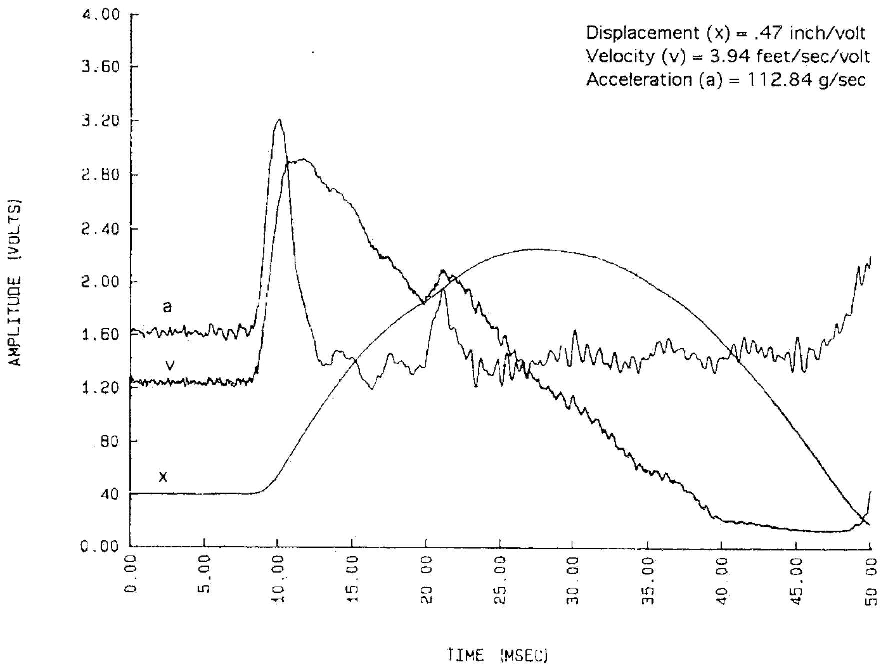

Figure C-4. The recoil characteristics of the 43 ft-lb - 20 ft/s condition.

34 ft-lb - 20 ft/s Condition

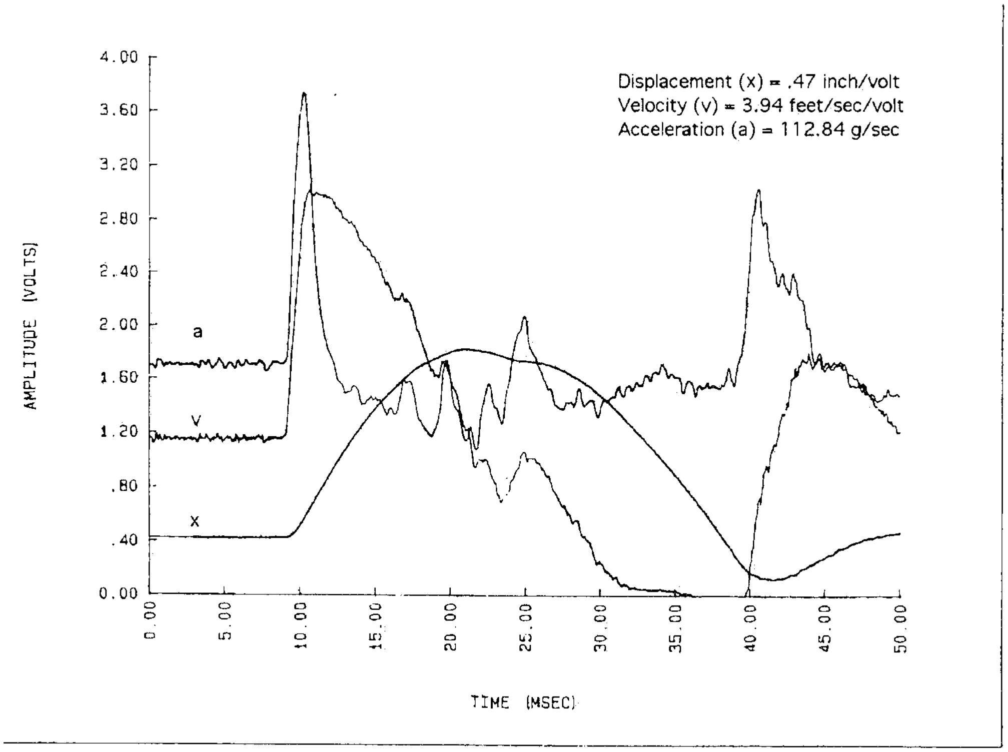

Figure C-5. The recoil characteristics of the 34 ft-lb - 20 ft/s condition.

25 ft-lb - 15 ft/s Condition

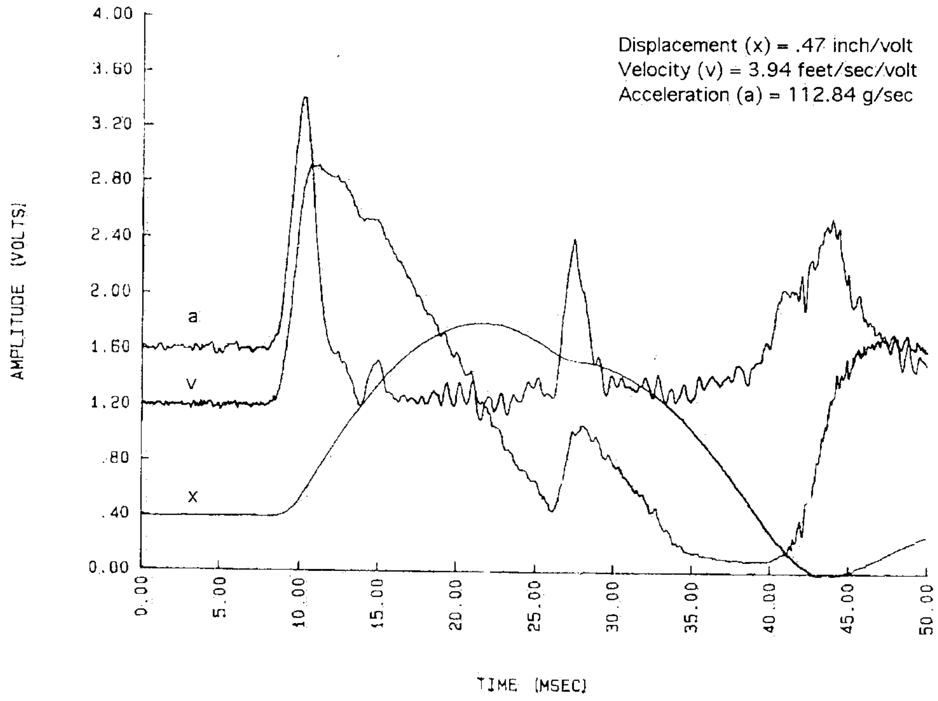

Figure C-6. The recoil characteristics of the 25 ft-lb - 15 ft/s condition.

43 ft-lb - 20 ft/s RM Condition

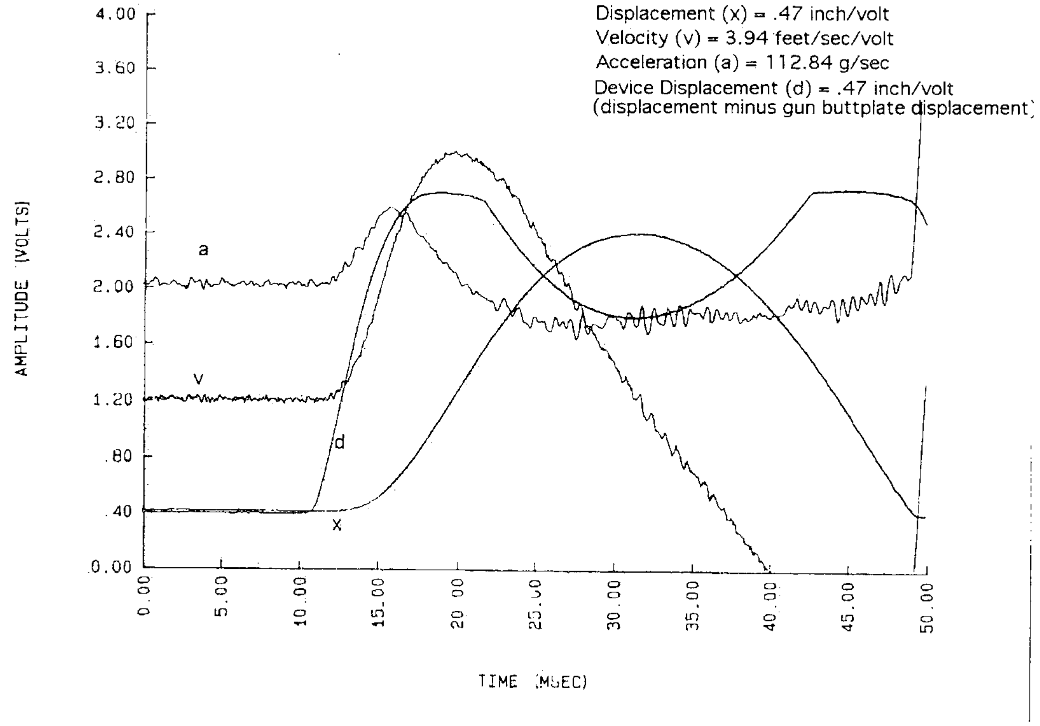

Figure C-7. The recoil characteristics of the 43 ft-lb - 20 ft/s RM condition.

34 ft-lb - 15 ft/s RM Condition

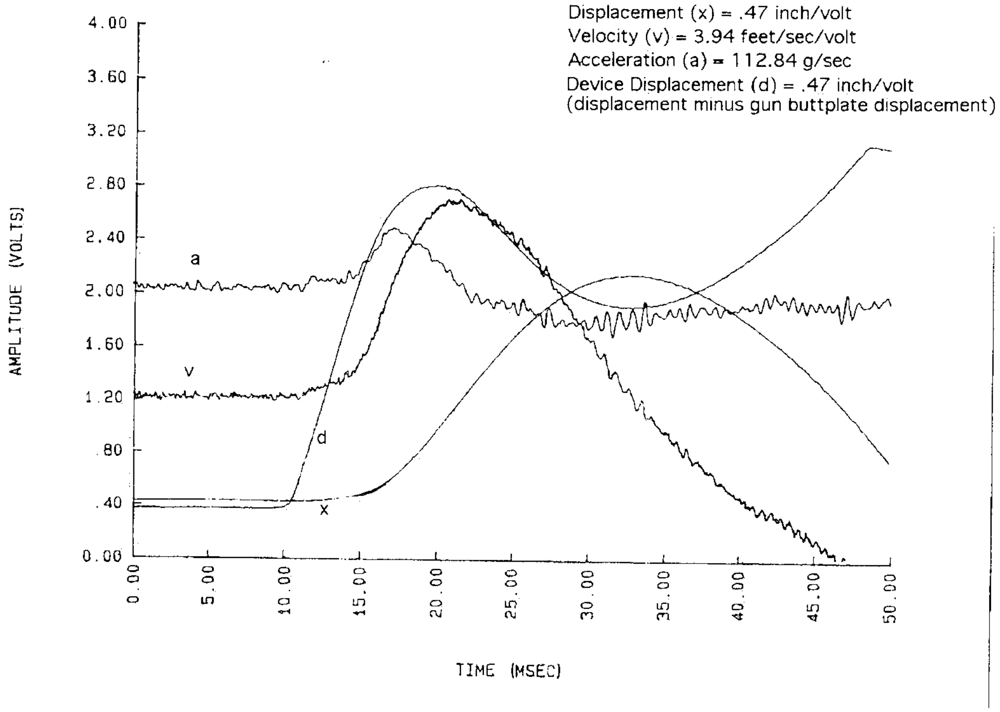

Figure C-8. The recoil characteristics of the 34 ft-lb - 15 ft/s RM condition.

APPENDIX D

ACCELERATION REDUCTION BY RECOIL-MITIGATING DEVICES

ACCELERATION REDUCTION BY RECOIL-MITIGATING DEVICES

Table D-1

Acceleration Reduction by Recoil-mitigating Devices for the 7-lb Weapon

	7-lb shotgun			
	3.60 lb-s		4.68 lb-s	
Device	Device displacement (inches)	Acceleration reduction (percent)	Device displacement (inches)	Acceleration reduction (percent)
Ace	.87	63	.87	55
Endine	.97	53	.99	46
Taylor (1 inch)	.68	79	.80	72
Pachmayr	.67	39	.77	2
KickEZZ	.30	38	.35	34
Kick killer	.31	39	.36	28
PAST	.36	40	.40	13
Taylor 1 inch and Pachmayr	.99	68	1.15	54
Taylor and KickEZZ	.65	77	.76	73
Acceleration without a recoil pad or device.	187.4 Gs		202.3 Gs	

Table D-2

Acceleration Reduction by Recoil-mitigating Devices for the 10-lb Weapon

	10-lb shotgun			
	3.60 lb-s		4.68 lb-s	
Device	Device displacement (inches)	Acceleration reduction (percent)	Device displacement (inches)	Acceleration reduction (percent)
Ace	.83	61	.79	62
Endine	.79	65	.77	56
Taylor (1 inch)	.68	79	.75	72
Pachmayr	.62	58	.71	29
KickEZZ	.25	46	.31	37
Kick killer	.30	52	.36	39
PAST	.32	47	.37	26
Taylor 1 inch and Pachmayr	.85	77	1.03	73
Taylor and KickEZZ	.71	78	.73	73
Acceleration without a recoil pad or device	157.4 Gs		182.0 Gs	

Table D-3

Acceleration Reduction by Recoil-mitigating Devices for the 14-lb Weapon

	14-lb shotgun			
	3.60 lb-s		4.68 lb-s	
Device	Device displacement (inches)	Acceleration reduction (percent)	Device displacement (inches)	Acceleration reduction (percent)
Ace	.85	72	.80	71
Endine	.85	77	.81	71
Taylor (1 inch)	.65	80	.75	78
Pachmayr	.56	66	.63	55
KickEZZ	.22	50	.27	43
Kick killer	.26	53	.30	44
PAST	.28	54	.34	28
Taylor 1 inch and Pachmayr	.72	82	.96	81
Taylor and KickEZZ	.72	80	.70	79
Acceleration without a recoil pad or device	135.8 Gs		156.0 Gs	

APPENDIX E

AIM POINT DATA

AIM POINT DATA

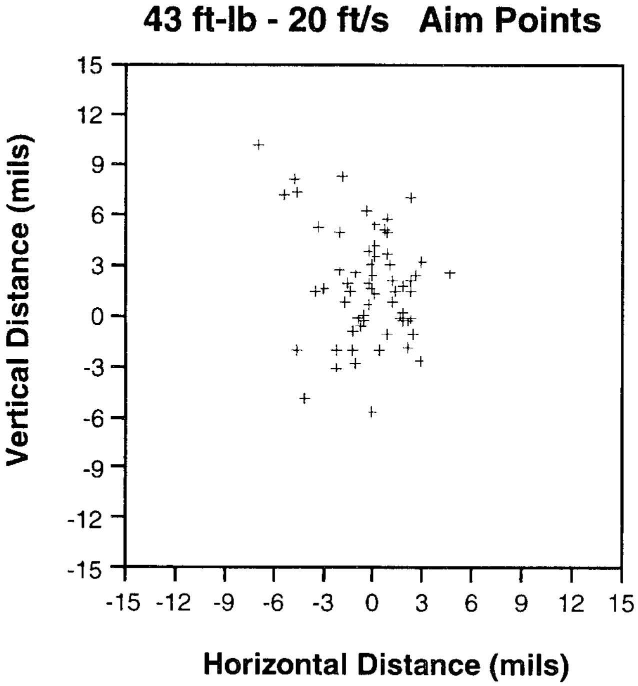

Figure E-1. The aim point data for the 43 ft-lb - 20 ft/s condition after horizontal or vertical distances greater than 2.5 SDs were removed.

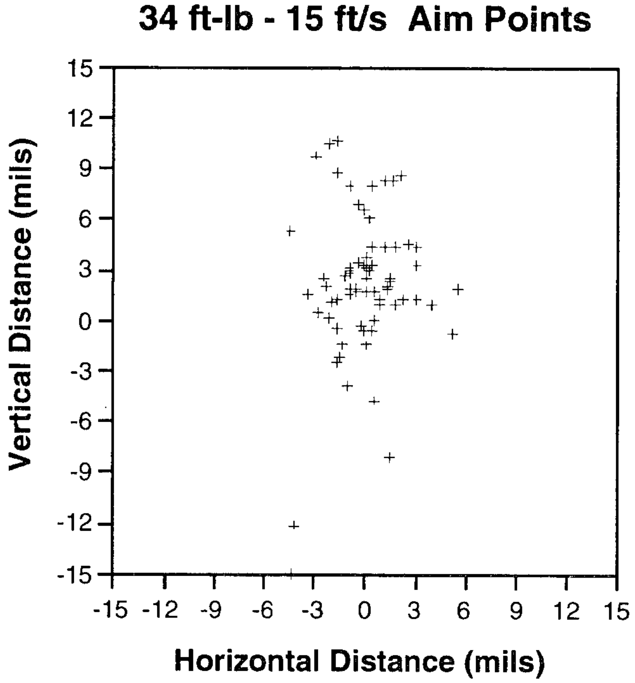

Figure E-2. The aim point data for the 34 ft-lb - 15 ft/s condition after data points with horizontal or vertical distances greater than 2.5 SDs were removed.

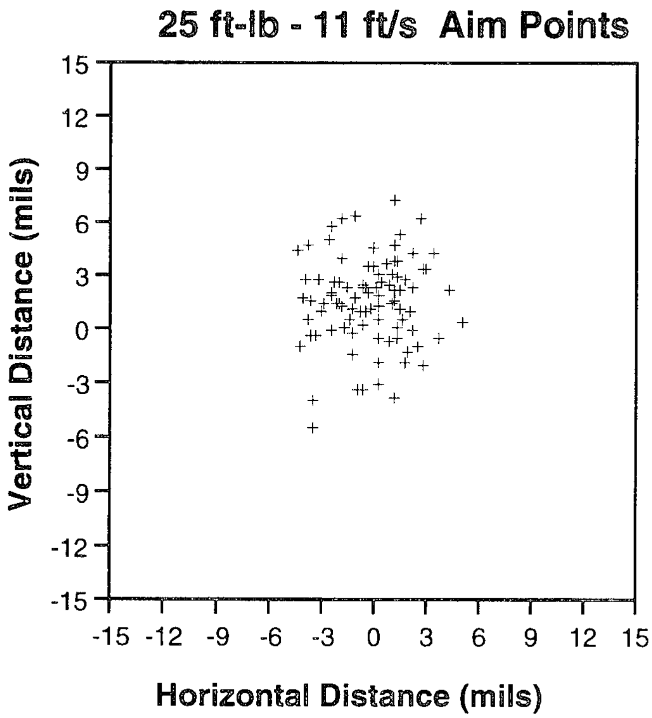

Figure E-3. The aim point data for the 25 ft-lb - 11 ft/s condition after data points with horizontal or vertical distances greater than 2.5 SDs were removed.

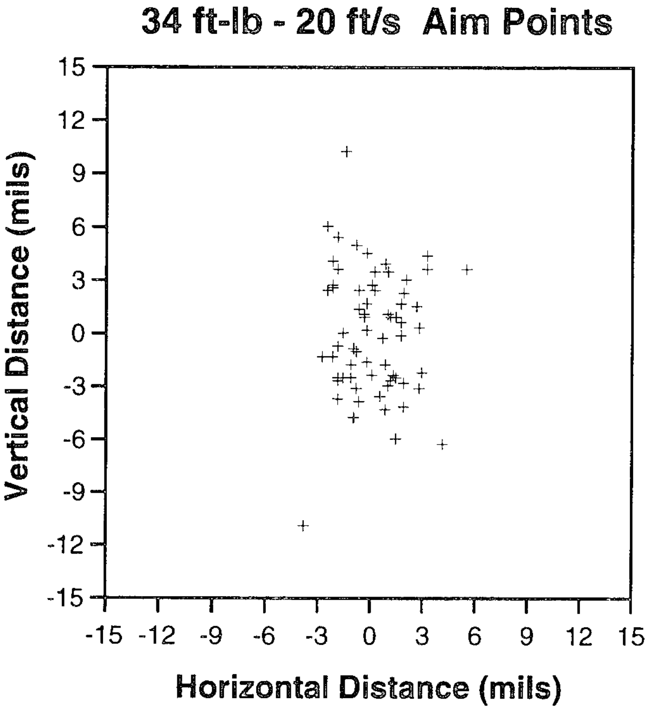

Figure E-4. The aim point data for the 34 ft-lb - 20 ft/s condition after data points with horizontal or vertical distances greater than 2.5 SDs were removed.

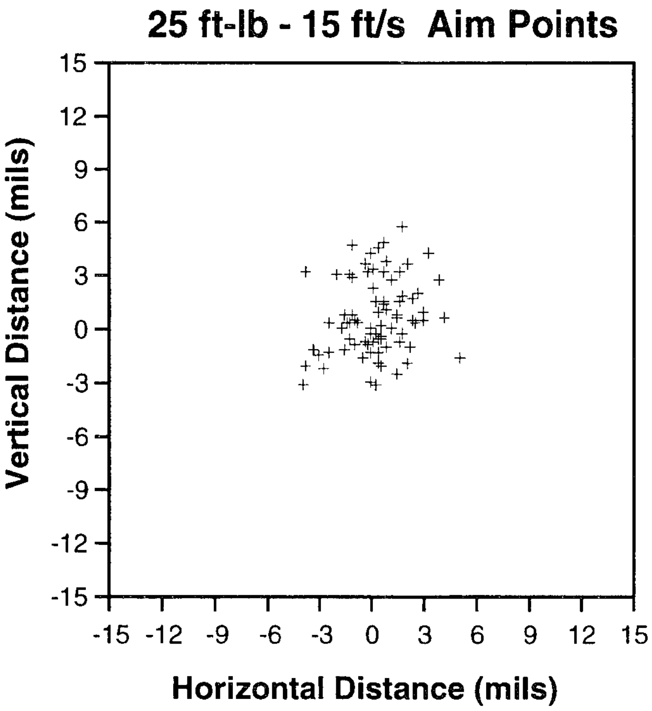

Figure E-5. The aim point data for the 25 ft-lb - 15 ft/s condition after data points with horizontal or vertical distances greater than 2.5 SDs were removed.

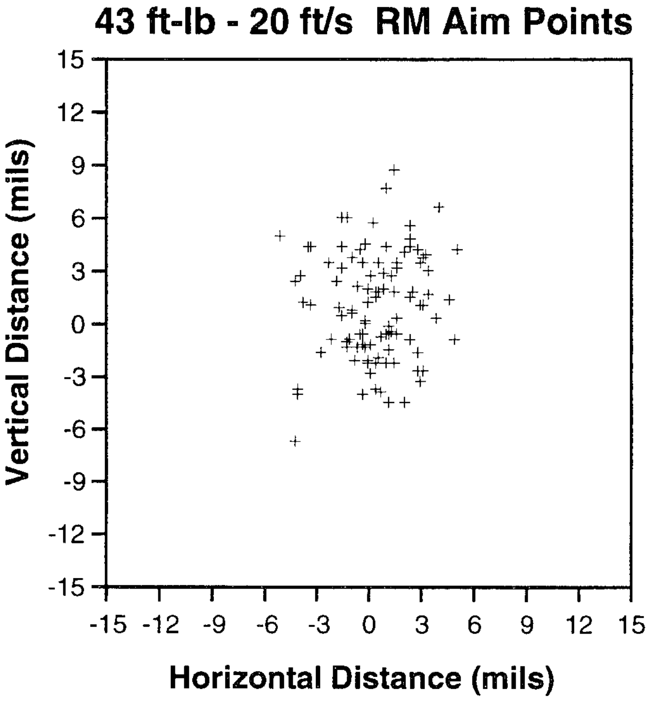

Figure E-6. The aim point data for the 43 ft-lb - 20 ft/s RM condition after data points with horizontal or vertical distances greater than 2.5 SDs were removed.

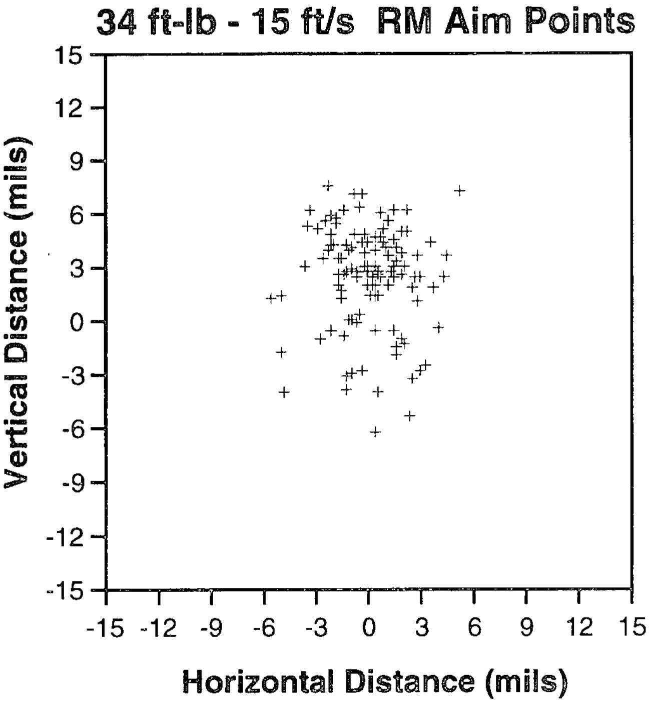

Figure E-7. The aim point data for the 34 ft-lb - 15 ft/s RM condition after data points with horizontal or vertical distances greater than 2.5 SDs were removed.

APPENDIX F

VOLUNTEER AGREEMENT AFFIDAVIT

VOLUNTEER AGREEMENT AFFIDAVIT

You have been given a pretest briefing in which the objectives of this research into the effects of recoil on human performance were explained to you. In addition, the nature of your participation in this test was also explained to you. Afterwards, you were given an opportunity to ask questions relating to your participation in this test. These questions were answered to your satisfaction before you volunteered to be a participant.

To reiterate, this research is being conducted

A. To isolate and quantify recoil characteristics that affect aiming error.

B. To investigate and measure how those factors affect a soldier's perception and tolerance of recoil.

C. To test the effectiveness of a recoil-mitigating device under these same circumstances and with the same basic weapon.

D. To establish a data base, methodology, and criteria with which future hand-held kinetic energy weapons can be designed and evaluated.

The testing will be designed around standard commercially available 12-gauge shotgun ammunition and instrumented 12-gauge shotguns chambered for firing the standard 3-inch magnum cartridge. You will fire two different weight shotguns, one as a baseline and the other as the test weapon. You will fire one or both of two different 12-gauge cartridges, possibly as many as 50 times. One cartridge will be a moderate energy load, and the other may be a 3-inch magnum load.

Each test weapon will be equipped with iron (post and peep) sights similar to the sights on the M16A2 rifle. Each shotgun will have a CCD micro TV camera mounted to it for data-gathering purposes.

Fifty meters down range will be a black steel disc mounted on a post to be used as a target. Your aiming error can be continuously recorded before and at the instant of firing.

Your height and weight and your level of rifle marksmanship, based on your last qualification score, will be recorded at the time of testing.

The testing will be conducted at the HRED small arms test facility known as "M range."

Shooting in this test will only be done from the standing off-hand firing position, from the shoulder, and only at a nominal 5 degrees superelevation.

When you come to the firing line, a range safety officer will instruct you in how to properly shoulder, hold, aim, and fire weapons of these levels of recoil. You will be allowed to aim and dry fire the baseline weapon until you are familiar with the procedure. This will be followed by firing five rounds with the baseline weapon. You will fire at a rate of one round every 30 seconds. You will then fire five test rounds from the test weapon, after which you will be asked to rate the test weapon-cartridge with respect to the baseline. The baseline weapon will be considered to be midpoint (5) on a nine-point scale. Having done this, you will continue firing the test weapon-cartridge until you have fired 50 rounds or withdrawn yourself from the test.

You have already been instructed to stop firing and terminate the trial if you reach a point where you feel you are no longer willing to tolerate the recoil effects of the weapon that you are firing. You have also been instructed in range safety during your participation in this test.

There will be a person at each firing point who will be responsible for safety, instruction, and seeing that each trial is properly conducted. This person will also administer the rating of the weapons.

You will be firing lightened or additionally weighted commercially available weapons and commercially available ammunition. The values for recoil impulse, velocity, and energy have been selected to not exceed values for existing, widely distributed military and civilian weapons and ammunition. No test condition will subject you to more recoil energy than 60 ft-lb; the maximum established by CSTA and approved by TECOM. You can withdraw from firing at any time if you so choose.

Your participation in this test will be considered confidential; your identity will not be associated with published results. You have the right of access to any of the data collected about you. Any questions about these data or anything else should be directed to either Paul Ellis or William Hanlon.

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