AN INVESTIGATION OF THE ERGONOMICS AND BIOMECHANICS OF RIFLE SHOOTING FROM THE STANDING POSITION

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ABSTRACT

The purpose of this study was to investigate the ergonomics and biomechanics of rifle shooting from the standing position. At present, the scientific literature on shooting contains primarily qualitative descriptions of the various aspects of the sport.

Quantitative data on the kinetic and kinematic aspects of standing rifle shooting was collected in the present thesis. Transducers were developed to measure foot forces in the vertical and horizontal plane, recoil force on the shoulder and the grip force of the trigger hand. Kinematic data was collected with a video camera.

The study revealed that recoil energy was dependent on the attributes of the shooter. Handgrip forces were found to be well below the maximum handgrip strength. An exploratory investigation of the interrelationships among foot forces, rifle recoil and angular and linear displacements was carried out. No horizontal foot forces to counteract the recoil force were observed. A possible explanation for the finding is proposed.

The findings are discussed with reference to the ergonomic implications for rifle stock design. Further investigations of the relationships between shooting performance and the man-rifle interface are indicated.

CONTENTS

1. LIST OF ILLUSTRATIONS

2. LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA - Analysis of variance

BL - Difference between the barrel angles before and after shooting in [degrees]

d - differential

df - degrees of freedom

FDA - Feet distance apart in [m]

$F_R(t)$ - Recoil force as a function of time

F_{XL} - Horizontal force on the left foot

F_{XR} - Horizontal force on the right foot

F_{ZL} - Vertical force on the left foot

F_{ZR} - Vertical force on the right foot

GRIP - Grip force of the trigger hand in [N]

h - Interval between equally spaced points

HEIGHT - Height of subject in [m]

IMP - Recoil impulse in [Ns]

IT - Recoil impulse duration in [ms]

J - joule

kg - kilogram

LEL - Left elbow angle in [degrees]

LHA - Left horizontal foot force after shooting in [N]

LHB - Left horizontal foot force before shooting in [N]

LHD - Difference between LHA and LHB

LHP - Left hand position, horizontal displacement from trigger hand in [m]

LSD - Least significant difference

LVA - Left vertical foot force after shooting in [N]

LVB - Left vertical foot force before shooting in [N]

LVD - Difference between LVA and LVB

m - metre

ms - millisecond

mV - millivolt

MASS - Mass of subject and rifle in [kg]

MCD - Centre of mass of the subject-rifle combination displacement in [m]

n - counter

N - newton

Ns - newton.second

PRE - Preload of rifle against shoulder in [N]

PRL - Peak recoil load in [N]

RD - Recoil distance of rifle in [m]
RE - Recoil energy in [J]
REL - Right elbow angle in [degrees]
RF - Average recoil force in [N]
RHA - Right horizontal foot force after shooting in [N]
RHB - Right horizontal foot force before shooting in [N]
RHD - Difference between RHA and RHB
RVA - Right vertical foot force after shooting in [N]
RVB - Right vertical foot force before shooting in [N]
RVD - Difference between RVA and RVB
s - second
SD - Standard deviation
SHN - Shot number
SN - Subject number
SLOFA - Shoulder to line of fire angle after shooting in [degrees]
SLOFB - Shoulder to line of fire angle before shooting in [degrees]
SLOFD - Difference between SLOFB and SLOFA
t_o - Time = 0
t_n - Time = n
Σ - Summation
$\int$ - Integral

3. INTRODUCTION

3.1 General

Shooting has become a specialized sport. Not only has technical development contributed to specialization but research on aspects of the shooter has also contributed to knowledge of the sport. Few studies concerning the ergonomic and biomechanical aspects of shooting have been carried out. The scientific literature reveals primarily a qualitative description of the physiological, psychological, physical and biomechanical conditions associated with the sport. However, the general sports shooting literature, although it may lack scientific research, has contributed substantially to a better understanding of the ergonomics of sports shooting.

New quantitative data could contribute towards the comprehension of body movement and force transfer when the human body is experiencing the unique circumstances that are associated with firing a rifle. The scientific data on the biomechanics of rifle shooting is incomplete. At the same time quantitative data should not only benefit theoretical knowledge of the man-rifle interface, but also benefit the sports shooter in a practical way. Shooting comprises of a number of elements, integrated and coordinated by the shooter, to satisfy the basic condition for high performance. This can be achieved by the repeated reproduction and systematic control of all the actions of the shooter, including a high degree of stability of the man-rifle system, in the ability of the shooter to grip the rifle with identical force, to assure an identical posture from shot to shot and being aware of the variation in respiration pattern and heart rate.

Physiological studies have measured heart rate, oxygen consumption and blood pressure during shooting. Porsch and Sovinz (1974) measured the heart rate of shooters over an extended period during a major competition by using telemetric recording devices. They concluded that the performance of the shooter can be improved by lowering the heart rate 10% - 15%. However, the effect of an aroused state, created by the competition, is to increase heart rate. The degree to which shooters overcome this, depends on experience, temperament of the shooter, and pharmaceutical substances. Rogers (1984) reports the use by shooters of beta-blocker substances to slow the heart rate. Landers, Wang and Courtet (1985) suggest however, although this was not the purpose of their study, that shooters may benefit from shooting under moderately stressful conditions during practice and prior to competition to facilitate the transfer of this stress level to the actual competition.

The metabolic rate for both pistol and rifle shooting is minimal because the physical strain is limited to the muscles of the shoulder-arm region. This was demonstrated by oxygen consumption measurements by Bauer and Claasen (1975). This study also revealed considerable variations in respiration patterns among individuals. Daniels and Landers (1981) studied the use of biofeedback in developing awareness and control of autonomic patterns during rifle shooting. They concluded that biofeedback is beneficial for shooting performance in allowing individuals to perceive the previously undetectable physiological patterns of heart rate and respiration and to coordinate the motor actions of firing with these patterns. Of practical significance, training with biofeedback appears to be a useful tool in enhancing shooting performance.

In the light of the growing standard of shooters in competitions, Chugunov (1979) developed a system for selecting novice sport shooters by investigating static and dynamic tremor for determining the stability and steadiness of the man-rifle system. He showed that in a group of novices, 34% showed "tremographic" indices equal or better than those of experienced and skilled shooters. Although Rudin, Bik and Kudrjasov (1979) acknowledge the importance of stability in shooting, they emphasise that the coordination of the different components involved in shooting is probably the more important factor influencing performance.

Other studies have shown that there is a difference in postural balance when a shooter aims and when he shoots. When aiming, postural sway is slow and of great amplitude and when shooting, is fast and of small amplitude (Baron, Molinie and Vrillac, 1968). A correlation between the shooting results and the amplitude of postural sway was also found. For a small amplitude of postural sway, the shooting results were better than for a greater amplitude of sway. Although postural sway is a characteristic of an individual, the experienced shooter manages to keep the points of intersection of the line of aiming and the target constrained to a far smaller area than the inexperienced shooter (Arutyunyan, Gurfinkel' and Mirskii, 1968). Niinimaa and McAvoy (1983) concluded that shooters avoid using muscles to correct trunk rotations during postural sway, as attempts to hold the rifle at the aiming mark require maximal relaxation. Consequently, horizontal and vertical scattering of hits can be directly related to anterioposterior and lateral postural sway.

From the discussion above it should be clear that a stable standing posture is very important in shooting, firstly, to enable the shooter to reduce postural sway and secondly to resist rifle recoil in an efficient way. From the experimental results of Kobayashi and Matsui (1976) it may be concluded that the standing posture in the impulse resisting condition, similar to the recoil of a rifle, is more unstable than a static resisting condition. Stability of the shooter's static posture should therefore be aimed at efficiently reducing postural sway and resisting the recoil impulse.

In the classic standing rifle shooting position the shooter stands half-faced to the target with the weight equally distributed on both legs and with the trunk erect. The feet are shoulder width apart. For the right-handed shooter the left forearm and elbow are well under and supporting the rifle. The left elbow and arm can also be rested against the rib cage. The right elbow is at the height of the right shoulder and the cheek against the stock. Variations of this position are adopted to suit the individual. In order to accomplish a stable relaxed standing shooting position it is usually necessary to lean back from the hips and twist the trunk. This will increase the curvature of the lumbar spine (hyperlordosis) and force a twist which extends into the thoracic segment of the vertebral column. In order to keep the head in a vertical position, the upper thoracic or cervical segments will increase the curvature in the opposite direction (kyphosis). However, in the frontal plane scoliosis of the vertebral column may be observed. Lafortune (1975) and Lösel (1981) states that spine malformation is a real possibility in regular shooters, especially children. Lafortune also confirms that relatively weak intervertebral ligaments could lead to discal hernia in regular shooters. However, both authors also state that suitable and compensatory physical exercise and an alternative and unrelated sport should alleviate such possibilities.

Another medical aspect to be considered is the recoil impulse on the shoulder of the shooter. When a rifle is fired, equal and opposite forces are exerted against the projectile and the rifle. Because the mass of the bullet is small, it obtains a high velocity as a result of the explosive force exerted on it. The rifle being of greater mass, acquires a lesser velocity. Hay (1978) states that the effective mass of the rifle can be increased by holding it firmly to the shoulder. The result of the increase in mass is a reduction in the velocity of the rifle. The recoil impulse commences when the projectile accelerates from its static position. According to Askins (1981) the recoil strikes the shooter in a series of waves. These impulses are not sensed as separate entities, but the full effect is sensed when the rapidly expanding propellant gasses strike the atmosphere after the projectile has left the barrel.

Experienced shooters are rarely seriously injured by the recoil. Common injuries are limited to contusion of the pressure bearing tissues surrounding the shoulder joint. Injuries to the eyebrow-ridge due to the impact of a telescopic sight and contusion of the tissue covering the zygomatic bone may be attributed to inexperience. However, Wanamaker (1974) reported three cases where subjects suffered injury to the upper trunk of the right brachial plexus due to firearm recoil. Although it is stated that direct concussion to the plexus seems unlikely, the rearward recoil force must be dissipated by motion and/or compression of the shoulder structures and the acceleration of the trunk backward. The recoil movement causes violent retraction of the lateral part of the clavicle and may cause the upper trunk of the plexus to be pinched between the clavicle and the underlying scalene muscles. Wanamaker states that any abducted and extended position of the right arm mildly stretches the brachial plexus and with the neck muscles tensed in anticipation of the recoil, may be contributing factors in causing trauma.

It is generally accepted that a recoil energy of about 20 joule is the average recoil that a shooter can absorb without too much inconvenience. Some shooters seem to have a high tolerance for absorbing recoil energy and may sustain energies of four times the average without showing any adverse effects. The recoil energy of a rifle is calculated from the reaction of the acceleration of the projectile, the acceleration of the propellant gasses and the effect of the gasses leaving the barrel. This calculation results in a theoretical value of recoil energy based on the mass of the rifle, mass of the projectile, mass of the propellant and the velocity of the projectile. As the recoil energy of a rifle seems to be of use when comparing different rifles, a subjective estimate of the magnitude of the recoil that is transferred to the body of the shooter is usually made. If the calculated recoil energy value is used as criterion of the recoil transferred to the body, then it may be deduced that the recoil energy values of any one rifle will be the same for any number of shooters. This calculated value does not include the effect of recoil energy absorbing pads (recoil pads), nor does it take the effect of the supporting hands of the shooter into account. The perceived recoil however would depend not only on the recoil energy value but also on the recoil pad, position and grip of the supporting hand, the clothing of the shooter, the dimensions and style of the rifle and the posture of the shooter. The quantitative data on recoil energy is incomplete. It is suspected that the published data on the recoil energies for rifles of different weight and calibre is of little value to the shooter to determine perceived recoil. In order to investigate the magnitude of the recoil energy on the shoulder of the shooter, it would be necessary to measure the impulse generated by the rifle. The recoil energy is expected to be dependent on the shooter as shooters show variations in posture and ways of absorbing recoil energy. Some shooters tend to lean into the rifle and resist the backward movement of the rifle while others would stand quite relaxed and allow the rifle to move backwards and lift with a minimum of active resistance.

Four contact areas can be identified when the man-rifle interface is examined; the grip of the rifle stock held by the trigger hand, the fore-end of the rifle in contact with the supporting hand, the butt plate or recoil pad in contact with the shoulder and the cheek held tightly to the side of the stock. All four contact areas contribute to the stability of the interface. The grip of the trigger hand warrants further investigation.

Several approaches have been made toward defining the characteristics of hand grip. A simple and classic viewpoint has been outlined by Napier (1965). He defined the prehensile movements of the hand in terms of a power grip and a precision grip. In a power grip the object is held in a clamp formed by the fingers and the palm and thumb. In a precision grip the object is pinched between the flexor parts of the fingers and the thumb. The grip of the trigger hand by which a rifle is held is essentially a power grip. Because the trigger is operated by the index finger of the gripping hand, the characteristics of the grip changes. A grip function is now combined with a control function. According to Fraser (1980) it is a difficult task to combine these two functions, both in operation and design. However, if the grip and control functions are combined, prolonged and intensive activity of the small muscles of the hand and the flexor muscles in the forearm should be avoided. The activity of the index finger during trigger manipulation is not intensive or prolonged.

The grip of a rifle can be considered a hand function in which the little, ring and long fingers supply the grip force while the index finger supply the necessary precision. The thumb may assist both the functions of power and precision in the grip. Although the index finger does not contribute extensively to the grip action, the position of the index finger on the trigger assists in the positioning of the hand to ensure an efficient grip. The advantages of an efficient grip on the rifle stock would be to create a stable platform for the trigger finger to operate from and to enable the rifle to be drawn into the shoulder, enhancing stability and possibly reducing recoil.

The influence of wrist position on the force produced by the finger flexors was investigated by Hazelton et al, (1975). Hazelton et al concluded that ulnar deviation allows the greatest force to be exerted at the middle and distal phalanx of the fingers. In the standing shooting position described earlier, the hand, which is in flexion and ulnar deviation, forces the elbow to be near shoulder height. This orientation of the hand can be attributed to the configuration of the stock. By changing the stock grip to an orientation of approximately 90° to the barrel the orientation of the hand will change accordingly and result in less ulnar deviation and the elbow below shoulder height. It might be argued that the high elbow position assists in the establishment of a stable man-rifle interface. On the other hand, a lower elbow position will reduce strain of the arm and shoulder muscles during aiming and thereby contribute towards shooting performance.

Handgrip strength differs greatly among individuals. According to Petrofsky et al (1980), the handgrip strength is greatest at a specific hand span for each individual. It was found that the grip endurance was 30%-35% longer for any sustained submaximal grip action when the contractions were performed at the hand span where the greatest grip strength occurred. It is clear that a substantial advantage may be gained by designing the span of the rifle grip to allow for the maximum strength of the user. As no data on the grip forces of shooters is available, the advantage of a larger grip force to be gained with the hand in ulnar deviation or the span of the grip designed for maximum strength, is unclear.An investigation into the magnitude of grip forces during shooting should enlighten this aspect. It is also expected that the grip force of the trigger hand will be influenced by the support of the other hand.

3.2 Objectives

Very few studies have investigated the ergonomics and biomechanics of shooting. These studies were primarily concerned with qualitative descriptions of the sport. There is nothing in the literature that quantitatively and collectively investigates the posture and the forces exerted and experienced by shooters when firing a rifle.

The general goal of the present study was to carry out a quantitative analysis of the ergonomic and biomechanical aspects of rifle shooting from the standing position. In order to conduct such an investigation it was necessary to develop a measurement system for the quantification of the forces involved in shooting and the associated postures of the shooters in the standing position. The analysis was approached by means of four specific goals. As the study was aimed at collecting new data, the goals were chosen to benefit the shooter in a practical way and to clarify possible misconceptions of rifle shooting. This was realized by emphasizing the relevant aspects of shooting over which the shooter has direct and easy control.

The first major goal of this study was to determine whether the recoil energy transferred to the shoulder of the shooter would be dependent on the attributes of the shooter, as was expected, rather than only being dependent on the attributes of the rifle and ammunition. Recoil energy is frequently used as reference quantity to describe, independent of the shooter, the recoil of rifles. If recoil energy was dependent on the shooter, it would appear that comparisons of recoil energy should rather be based on the attributes of the shooter. It was assumed that whatever variation exists between the shooters could be attributed to two causes. The first cause would be the variation due to the peculiar characteristics among shooters and the second, the random variation of recoil energy values for each shooter. Part of the goal was to determine if the differences (if any) between the mean energy values were what would be expected due to this random variation alone or if a contribution from a systematic variation could be attributed to the shooters.

The second goal, and related to the investigation of the recoil energy, was to establish the relationships of the preload force (force with which the rifle is held to the shoulder before firing) to the impulse duration and the recoil force. Such relationships would indicate the possibility of manipulation of the elements of the recoil impulse by the shooter. The preload force is a parameter over which the shooter has direct control. If it was found that the preload force has a significant relationship with the elements of recoil impulse (recoil force and impulse duration), it should be possible for the shooter to manipulate these elements to his advantage. It was expected that a lower preload force would result in longer impulse durations. Furthermore, it was previously stated that the effective mass of the rifle can be increased by holding it firmly to the shoulder. The result would be to decrease the velocity of the rifle and therefore decrease the kinetic energy. Analogous to this reasoning, it was expected that a shooter exerting a high preload force would experience a low recoil force. A low average recoil force would indicate an advantage when related to perceived recoil. The second part of this goal was to investigate the relationship between the preload force and the average recoil force.

The third goal was to see if any advantage in the grip of the trigger hand could be gained with the hand in ulnar deviation. The grip force and the position of the supporting hand are parameters over which the shooter has direct control. Specifically, if the handgrip of the trigger hand was found to be close to the maximum handgrip strength there would be reason to argue that grip designs be adopted to facilitate the positioning of the hand to allow for ulnar deviation. The position of the supporting hand was thought to influence the grip force. The second part of this goal was to investigate the relationship of the position of the supporting hand, as indicated by the difference in the distance between the wrists, to the grip force.

The last goal of the study was to investigate the effect rifle recoil has on the reaction forces on the feet and the associated displacement of the centre of mass of the body. This was an exploratory exercise and was aimed at gaining further insight into the standing shooting posture.

No attempt was made to analyze or determine anthropometrically optimized dimensions for a rifle. A thorough anthropometric analysis, although of great practical value to shooters, will necessitate the time consuming and costly exercise of establishing and validating applicable dimensions of the sport shooting population, a population openly confessing to subjective preferences regarding the style, shape and dimension of a rifle stock.

4. METHODS

The study required quantitative data collection on the standing shooting posture. As little data from similar studies was available, the data collection and verification method became an important part of the study.

In a biomechanical analysis of this nature, two types of data were required:

- Kinetic data in the form of foot forces and the recoil and grip forces during shooting.

- Kinematic data in the form of photographic images of the subjects during shooting.

4.1 Kinetic data

The kinetic information identified for the study included the following forces:

a) vertical force of the left foot on the base
b) vertical force of the right foot on the base
c) horizontal force of the left foot on the base
d) horizontal force of the right foot on the base
e) grip force of the trigger hand
f) recoil force of the rifle on the shoulder

These forces are presented in Figure 1.

All the transducers for the kinetic data were developed by the author and are discussed in Appendix A.

4.2 Kinematic data

The kinematic data collection procedure consisted of a video camera recording of the subjects during shooting. The camera was placed in a position 90° to the direction of aim. Additionally a mirror was installed to capture

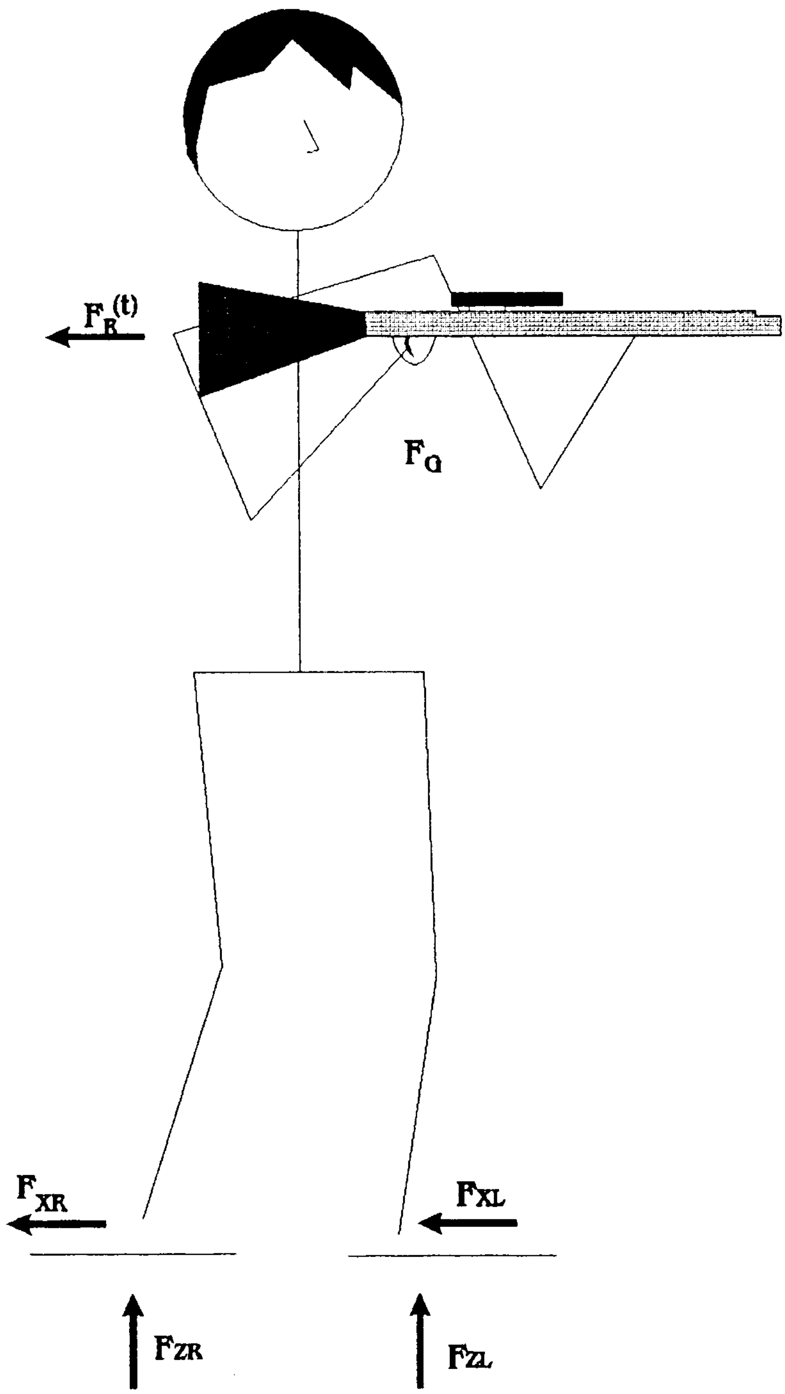

Figure 1: Forces for kinetic data collection

kinematic data from a top view perspective. The two images were recorded simultaneously. The subjects were lightly clothed and white paper markers were placed on the body and clothing to identify the following anatomical landmarks:

a) right lateral malleolus
b) left medial malleolus
c) right lateral epicondyle of femur
d) left medial epicondyle of femur
e) right greater trochanter
f) right acromion
g) right lateral epicondyle of humerus
h) left medial epicondyle of the humerus
i) right dorsal side of the wrist
j) left ventral side of the wrist.

Although the marking of landmarks on clothing could result in inaccurate measurements the nature of the static posture and the quality of the image was not thought to reduce the accuracy significantly.

4.3 Experimental procedure

4.3.1 Location

The experiment was conducted during a Provincial Silhouette Shooting Championship event. The location of the event was the Milnerton Shooting Range. The range is at sea level and the ambient dry bulb temperature on the day of the experiment was 27°C.

4.3.2 Apparatus

Two force plates, each capable of measurement in two axes, the grip force transducer and the recoil force transducer were connected to a 8 channel strain gauge amplifier. (US 8 Channel Strain Gauge Amplifier, supplied and manufactured by the Department for Mechanical Engineering, Electronic Instrumentation Division, University of Stellenbosch). The four amplifier output channels of the two force plates were recorded on two Beckman Dual Channel chart recorders. The single amplifier output of the grip force transducer was recorded on an additional Beckman chart recorder.

The recoil force amplifier output was recorded on a Textronics Dual Channel Storage Oscilloscope. A microswitch, mounted in close contact with the rear end of the firing pin of the rifle was used to trigger the trace on the oscilloscope. (A full description of the transducers appears in Appendix A.) After each shot the stored oscilloscope trace was photographed with a 35mm Pentax ME Super camera fitted with a sun screen and short range compensating lens.

The rifle was a standard silhouette rifle (Rifle no M301-786) in .308 Winchester calibre and was supplied and manufactured by Musgrave Manufacturers and Distributors (Pty) Ltd of Bloemfontein. The rifle was fitted with a recoil force transducer, a grip force transducer and a microswitch for oscilloscope trace triggering. The 9.3g full jacket .308 Winchester (Batch no 005 LA 06/81) ammunition was manufactured according to Sporting Arms and Ammunition Manufacturer's Institute specifications by Pretoria Metal Pressings (Pty) Ltd and was supplied by Musgrave. All safety precautions in the handling and operation of the rifle and ammunition and the safety rules enforced by the shooting range officials were strictly adhered to.

An iron plate target was placed 25m in front of the shooter's position.

A National Panasonic video camera and recorder were positioned 90^0 to the line of aim and at a suitable distance to include the force plates on the ground and the top view mirror in the image of the viewfinder. The mirror was positioned on a stand directly above the subjects to produce an image of the shoulders, head and rifle when viewed from the camera position. A shatterproof film was

applied to the glass mirror to prevent injury in the event of breakage during the experiment.
The complete layout of the equipment for the experiment is presented in Figure 2.

4.3.3 Subjects

Nine competitors in the provincial championship event were used as subjects. The subjects were aged between 22 and 58 years old. The subjects were all right handed. The experience of the subjects ranged from novice (1 subject), bronze class (3 subjects), silver class (4 subjects) to gold class (1 subject). (The classification of the classes is according to the official rules of the South African Metallic Silhouette Shooting Association).

4.3.4 Procedure

Each subject's weight and height were measured and recorded.

The subjects then assumed their individual standing posture next to the force plates holding the unloaded rifle in the aiming position. This procedure allowed for the force plates to be positioned according the foot positions of individual subjects. The force plates were then leveled with the help of leveling adjustment screws fitted to the force plates. The subject then took up position on the force plates. The fully instrumented rifle was handed to the subject, one round of ammunition was chambered, the oscilloscope trace triggering microswitch was fitted to the rear of the firing pin and all the equipment set to recording mode. The subject then aimed and fired at the target.

Each subject fired ten shots. The data for each shot was recorded for later analysis.

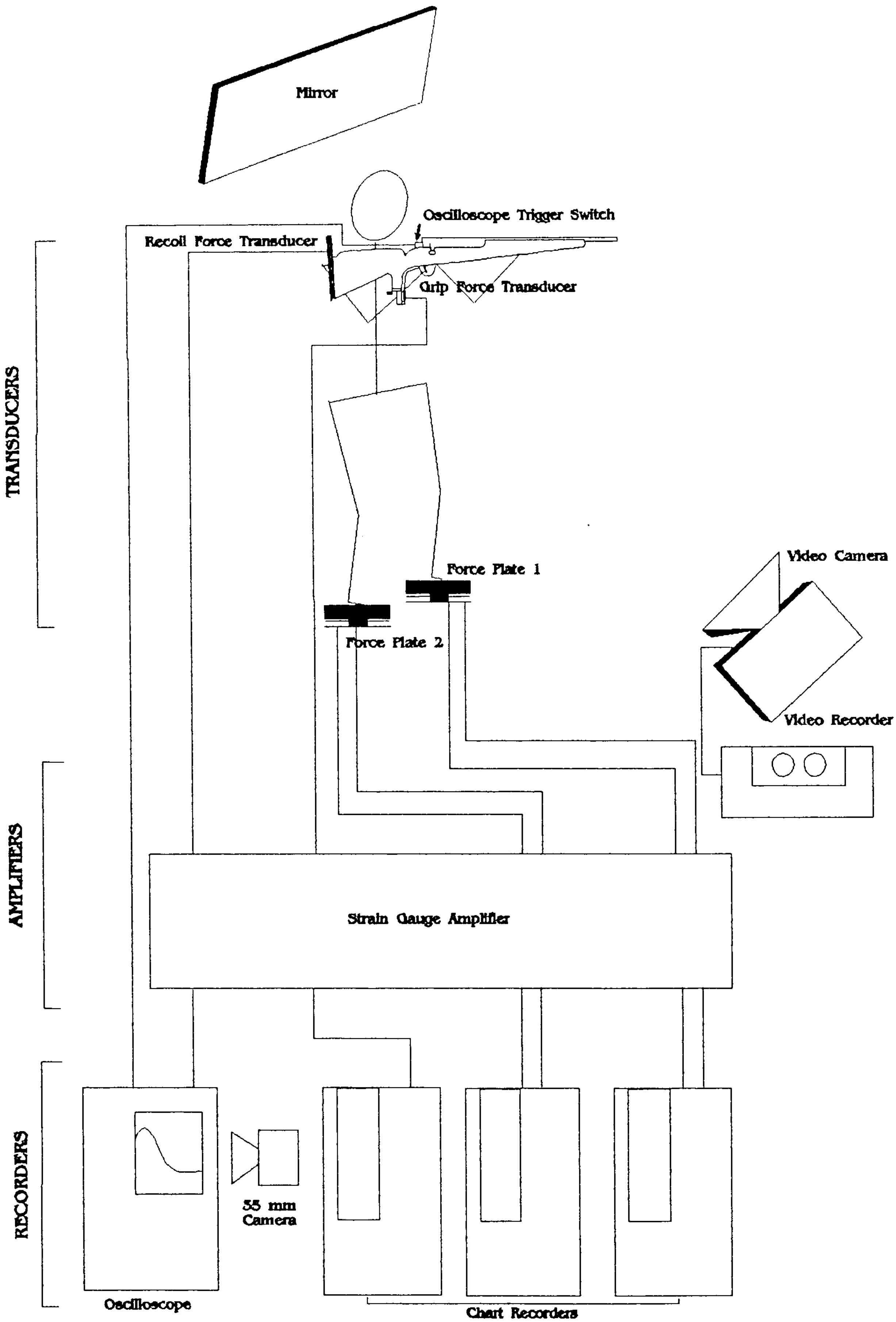

Figure 2: Equipment layout

4.4 Analysis of data

4.4.1 Kinetic data analysis

4.4.1.1 Foot forces

The horizontal and vertical foot force traces which were recorded on the chart recorders were measured immediately before a shot was fired during aiming and at corresponding positions on the traces when the maximum deflection of the right foot force trace occurred. The horizontal and vertical foot forces during aiming provided stable traces and were easy to identify and measure. During firing the maximum deflection point of the vertical right foot force trace was used as the reference time to obtain the measurements on the other traces. The reference time provided an identifiable position for measurements. The measured values were transformed to force values according to the calibration constants for each transducer. The values were tabulated.

4.4.1.2 Grip force

The grip force of the trigger hand during aiming was recorded on a chart recorder. The trace of the magnitude of the force immediately before firing was measured and transformed to a force value by applying the calibration constant for the grip transducer. The values were tabulated.

4.4.1.3 Recoil force

The force applied to the shoulder of each subject was recorded from the oscilloscope on 35 mm negative photographic film. The films were developed and positive enlargements were made for the data analysis. The photographs produced a trace of the force during aiming and during firing. The trace during aiming was stable and produced a force value equivalent to the preloading force with which the rifle was held to the shoulder before firing. The trace during firing represented a curve of the recoil force as a result of the acceleration of the rifle against time. As the recoil force is a function of time, the recoil impulse can be presented as the integral of this function.

Thus: $$IMP = \int_{t_0}^{t_n} F_R(t)\,dt$$

Where IMP = Recoil impulse

$F_R(t)$ = Recoil force as a function of time

However the integral: $\int_{t_0}^{t_n} F_R(t)\,dt$ may be approximated by using numerical integration by discrete points. Using the trapezoidal rule, the recoil impulse can be presented as:

$$IMP \approx (h/2)[F_R(t_0) + 2\ (\textstyle\sum_{j=1}^{j=n-1} F_R(t_j)) + F_R(t_n)]$$

where h = interval between equally spaced points and t_o, t_1, ... t_n is n+1 equally spaced points ($t_j = t_o + j.h$, $j = 0,1,2,...,n$) at which corresponding values $F_R(t_o)$, $F_R(t_1)$,..., $F_R(t_n)$ of the function $F_R(t)$ are known.

The trapezoidal rule was used to calculate the recoil impulse value for each shot from the recordings. Additionally the recoil force peak and recoil duration (time taken for the recoil force to return to the preload value) were calculated. The average recoil force was calculated by dividing the recoil impulse by the impulse duration. The preload force, the average recoil force, the peak recoil force, the recoil impulse and the recoil duration were tabulated.

4.4.2 Kinematic Data Analysis

The kinematic data analysis involved the use of a video monitor and recorder. The video image of a side and top view of subjects before and after firing the rifle were recorded on transparent paper. Anatomical landmarks as marked on the body of each subject were linked to produce stick figures. As these figures were drawn to a known scale various distance measurements could be made. The following measurements were recorded for each shot and tabulated:

- recoil distance (distance of rifle movement during firing)
- horizontal distance between the wrists of the left and right hand
- the subject's feet distance apart
- barrel lift of the rifle during firing
- elbow angles of the shooter

The top view image allowed the angle formed by a line drawn through the shoulders of the subjects and the line of aiming (as presented by the barrel direction) to be measured, both during aiming and during shooting. These angle values were then tabulated.

4.4.3 Combination of Kinetic and Kinematic data

The combination of kinetic and kinematic data resulted in additional data and further analysis. As the foot forces were known during aiming and firing and the feet distances apart remained constant during this period, it was possible to calculate the centre of mass displacement in the horizontal plane by taking moments around a fixed point i.e. the right foot.

MCD = LVB.FDA/(LVB+RVB) - LVA.FDA/(LVA+RVA)

where:

MCD = centre of mass displacement in [m]
LVB = vertical left foot force before shooting in [N]
RVB = vertical right foot force before shooting in [N]
LVA = vertical left foot force after shooting in [N]
RVB = vertical right foot force before shooting in [N]
FDA = feet distance apart in [m]

This calculation does not make provision for the centre of mass displacement in any of the other dimensions. As the recoil impulse is directed in one direction, the components of the impulse in the other directions could be assumed to be very small by comparison and should not influence the results substantially.

The recoil distance, the recoil time and the impulse result in an energy value:

RE = IMP.RD/IT

where:

RE = Energy to displace the rifle in [J]
IMP = Recoil impulse in [Ns]
RD = Recoil distance of rifle in [m]
IT = Impulse duration in [s]

5. RESULTS

The kinetic data, kinematic data and the combination of kinetic and kinematic data are presented in tabular form for each subject in Table B1 to Table B9 in Appendix B. Diagrammatic presentations of the postures of subjects before and after firing is presented in Figure B1 to Figure B9 of the same appendix. The results of the statistical analysis are discussed in the paragraphs below. More detailed statistical analysis results are presented in paragraph B1.3 of Appendix B.

5.1 Recoil energy

Table 1 presents the mean recoil energy values for all 10 shots fired by each of the 9 subjects.

Table 1

Mean Recoil energy in [J]

Subject number	*Mean*	*Standard deviation*
1	*17.25*	*3.60*
2	*20.46*	*1.88*
3	*43.32*	*3.10*
4	*27.13*	*1.76*
5	*24.20*	*0.95*
6	*24.82*	*2.02*
7	*24.19*	*1.31*
8	*16.78*	*0.73*
9	*21.60*	*1.88*

The data were analyzed by ANOVA (Table B10) and the differences among the means were statistically significant,with $F(8,81)=140.07$, $p<0.01$. For 8 and 81 degrees of freedom, the critical values for F are 2.74 and 2.05 at the 0.01 and 0.05 levels respectively.

As statistically significant differences were found, the recoil energy means were divided into subgroups such that the means for any two subjects in a subgroup did not differ significantly. The LSD (Least Significant Difference) multiple-range test at a significance level of 0.05 was used. The result of the test is presented in Table 2.

Out of the group of 9 subjects the recoil energies fell into 5 groups. It can be observed from this result that the mean recoil energy for subjects 8 and 1, subjects 2 and 9 and subjects 7, 5 and 9 respectively, are not significantly different, while all other pairs are considered significantly different.

Table 2

Multiple-range analysis for recoil energy in [J] by subjects

LSD group	*Mean*	*Subject number*
A	*16.78*	*8*
A	*17.25*	*1*
B	*20.46*	*2*
B	*21.60*	*9*
C	*24.19*	*7*
C	*24.20*	*5*
C	*24.82*	*6*
D	*27.13*	*4*
E	*43.32*	*3*

5.2 Preload, impulse duration and recoil force

Table 3 presents mean values of preload forces, impulse durations and recoil forces for each of the subjects.

The data were analyzed using ANOVA (Table B11,B12,B13), and statistically significant differences were found between the means of each of the variables. The F-ratios were $F(8,81)=46.02$, $p<0.01$ for the preload force, $F(8,81)=53.14$, $p<0.01$ for impulse duration and $F(8,81)=11.24$, $p<0.01$ for the recoil force. (Critical values for F are: $F_{0.01}(8,81)=2.74$ and $F_{0.05}(8,81)=2.05$)

Table 3

Mean preload forces in [N], impulse durations in [ms] and recoil forces in [N]

Subject number	*Preload force in [N]*		*Impulse duration in [ms]*		*Recoil force in [N]*	
	Mean	*SD**	*Mean*	*SD**	*Mean*	*SD**
1	*115.1*	*8.2*	*24.2*	*2.9*	*293.82*	*61.68*
2	*160.2*	*21.9*	*29.7*	*1.3*	*232.08*	*20.85*
3	*109.3*	*13.7*	*29.8*	*1.0*	*263.73*	*15.29*
4	*61.3*	*12.9*	*34.6*	*1.3*	*222.15*	*10.07*
5	*76.2*	*3.1*	*33.7*	*0.9*	*237.54*	*10.34*
6	*99.9*	*14.4*	*33.3*	*1.4*	*212.18*	*16.47*
7	*96.9*	*15.1*	*33.4*	*0.5*	*252.38*	*13.86*
8	*96.3*	*8.8*	*30.2*	*1.1*	*274.99*	*11.16*
9	*60.2*	*20.5*	*33.5*	*1.1*	*237.69*	*14.64*

** SD = Standard deviation*

In order to establish the relationship between the variables, regression analysis of the variables was carried out for each of the 9 subjects. Firstly, the impulse duration was taken as dependent variable and preload force as independent variable. Secondly, the recoil force was taken as the dependent variable and the preload force again as independent variable. The regression analyses attempted to fit the linear function, Y=a+bX, to the data. The data were analyzed separately for each of the subjects and for each of the two dependent variables (Table B14 to B22 and B24 to B32 respectively). The results of the linear regression analyses of impulse duration and recoil force against preload force are presented in Table 4 and Table 6 respectively.

The results of the regression analyses should not be misinterpreted. Although it might indicate that the regressions explained by the models are statistically significant, this does not rule out the possibility that a linear regression model is the only model that can be used to explain the data. There might be other models that might give a larger value of the F statistic.

Table 4

Linear regression analysis of impulse duration in [ms] and preload force in [N] for each subject

Subject number	Y-intercept	Slope	Correlation	F-ratio
1	29.53	-0.046	-0.13	0.14
2	29.45	0.002	0.03	0.01
3	26.87	0.027	0.36	1.17
4	38.70	-0.067	-0.64	5.49
5	39.27	-0.073	-0.24	0.49
6	40.37	-0.071	-0.72	8.63
7	34.99	-0.016	-0.48	2.39
8	61.52	-0.014	-0.11	0.09
9	36.03	-0.042	-0.80	13.94

For 1 and 8 degrees of freedom, F values greater than 11.26 and 5.32 are statistically significant for levels 0.01 and 0.05 respectively.

Only for subjects 4, 6 and 9 was the linear relationship between impulse duration and preload force statistically significant. For these subjects the results suggest that a shooter exerting a high preload force will experience a short impulse duration. Linear regression analysis was then calculated for all the subjects together. As the ANOVA results of impulse duration and preload force indicated statistically significant differences between the means for the subjects, the mean values for each subject were used in the analysis (Table B23). Table 5 presents the results of this analysis.

Table 5

Linear regression analysis of impulse duration in [ms] and preload force in [N] for all subjects together.

Y-intercept	Slope	Correlation	F-ratio
37.70	-0.065	-0.61	4.12

For 1 and 7 degrees of freedom F values greater than 12.25 and 5.59 are statistically significant for levels 0.01 and 0.05 respectively.

This result indicates that the linear relationship between impulse duration and preload force for between subject analysis is not statistically significant and would indicate that there is no linear relationship between impulse duration and preload force.

Table 6

Linear regression analysis of recoil force in [N] and preload force in [N] for each subject

Subject number	Y-intercept	Slope	Correlation	F-ratio
1	209.3	0.73	0.10	0.08
2	267.7	-0.22	-0.23	0.46
3	309.5	-0.43	-0.39	1.39
4	187.0	0.57	0.73	9.25
5	155.5	1.08	0.32	0.94
6	132.6	0.80	0.69	7.61
7	305.0	-0.54	-0.59	4.29
8	280.5	-0.06	-0.04	0.02
9	254.4	-0.28	-0.39	1.43

F values greater than 11.26 and 5.32 are statistically significant at the levels 0.01 and 0.05 respectively, for 1 and 8 degrees of freedom.

The linear relationship between recoil force and preload force was, except for subjects 4 and 6, not statistically significant. The results suggest that, for subjects 4 and 6, the recoil force will increase with an increase in the preload force. This is contrary to the expected result. Linear regression analysis between recoil and preload force (Table B33) for all the subjects together was not statistically significant with the F-ratio=0.35, correlation =0.22, Y-intercept=229.2 and slope =0.18 ($F_{0.01}(1,7)=12.25$; $F_{0.05}(1,7)=5.59$).

5.3 Handgrip force

Table 7 presents the mean values of the handgrip force for each of the 9 subjects.

Table 7

Mean handgrip force in [N]

Subject number	Mean	Standard deviation
1	74.63	9.19
2	99.63	9.05
3	92.41	16.36
4	41.27	10.89
5	26.45	6.95
6	61.83	17.32
7	44.66	10.03
8	54.09	6.44
9	49.38	16.13

The data were analyzed by ANOVA (Table B34) and the differences among the means were statistically significant, with $F(8,81)=40.53$, $p<0.01$. For 8 and 81 degrees of freedom, the critical values for F are 2.74 and 2.05 at the 0.01 and 0.05 levels respectively.

A LSD multiple range test at a significance level of 0.05 was used to divide the mean values into subgroups so that the means for any two subjects in a subgroup did not differ significantly from each other. The result is presented in Table 8.

Table 8

Multiple-Range analysis of grip force in [N] by subject number

LSD group	*Mean*	*Subject number*
A	*26.45*	*5*
B	*41.27*	*4*
B C	*44.66*	*7*
B C	*49.38*	*9*
C D	*54.09*	*8*
D	*61.83*	*6*
E	*74.63*	*1*
F	*92.41*	*3*
F	*99.63*	*2*

It can be observed from this result that the mean grip force varied considerably among the subjects. Six subgroups were formed and the largest mean value is more than three times that of the smallest.

Two ways of supporting the rifle with the non trigger hand were observed. The first variation showed that the supporting hand was placed well forward on the fore-end of the stock. This was associated with active gripping of the stock. The second variation showed that the hand was placed closer to the trigger hand and no apparent active gripping was observed for the subjects who adopted this posture. The relative position of the supporting hand (the left hand; all the subjects were right handed) could be related to the horizontal distance between the wrist of the right hand on the grip and the supporting hand on the fore-end of the stock. Table 9 presents the mean values of the left hand position in relation to the right hand for each of the 9 subjects.

Table 9

Mean left hand position distances in [m]

Subject Number	*Mean*	*Standard deviation*
1	*0.232*	*0.015*
2	*0.336*	*0.018*
3	*0.285*	*0.012*
4	*0.207*	*0.005*
5	*0.164*	*0.005*
6	*0.200*	*0.014*
7	*0.277*	*0.013*
8	*0.321*	*0.010*
9	*0.268*	*0.004*

The data was analyzed by ANOVA (Table B35) and the differences among the means were statistically significant, with $F(8,81)=245.79$ $p<0.01$. (Critical values for F are: $F_{0.01}(8,81)=2.74$ and $F_{0.05}(8,81)=2.05$).

The relationship between the grip force and the position of the supporting hand was investigated by using linear regression analysis. The grip force was taken as dependent variable and the left hand position as independent variable (Table B36). The mean values of the two variables for each subject were used. The result is presented in Table 10.

Table 10

Linear regression analysis of grip force in [N] and the position of the supporting hand in [m] for all the subjects together.

Y-intercept	*Slope*	*Correlation*	*F-ratio*
-4.873	*256.9*	*0.61*	*4.18*

For 1 and 7 degrees of freedom F values greater than 12.25 and 5.59 are statistically significant for levels 0.01 and 0.05 respectively.

The result indicates that the regression explained by the model is not statistically significant. The result suggests that there is no linear relationship between grip force and the position of the supporting hand on the stock.

5.4 <u>Foot forces, rifle recoil, angular and linear displacements</u>

The mean values of the horizontal foot forces, before and after shooting, for each subject are presented in Table 11.

The differences between the force values (after shooting - before shooting) for each foot are also presented. (The "after shooting" expression should not be misinterpreted. These values were measured when the maximum vertical foot force was observed).

Table 11

Mean horizontal foot forces in [N]

Subject no	Left foot			Right foot		
	Before	After	Diff.*	Before	After	Diff.*
1	-20.4(4.5)	-32.4(3.6)	-12.0	20.2(3.5)	33.0(4.0)	12.8
2	-16.0(1.6)	-11.1(10.1)	4.9	16.6(1.6)	23.1(3.4)	6.5
3	-10.2(2.5)	-18.1(6.2)	-7.9	9.7(3.2)	18.2(6.1)	8.5
4	-38.0(3.8)	-41.1(2.6)	-3.1	38.4(4.5)	30.6(8.9)	-7.8
5	-19.3(2.3)	-30.9(11.5)	-11.6	19.3(2.5)	34.3(8.2)	15.0
6	-22.3(3.6)	-27.4(2.3)	-5.1	22.8(2.5)	27.0(4.1)	4.2
7	-41.9(4.1)	-45.2(6.9)	-3.3	42.0(5.0)	42.7(7.8)	0.7
8	-31.3(6.2)	-49.8(6.9)	-18.5	32.5(7.2)	47.7(7.5)	15.2
9	-32.3(1.6)	-33.4(1.5)	-1.1	32.8(1.2)	31.7(5.2)	-1.1

* *Diff = Difference*
() Standard deviations in parenthesis

The left horizontal foot forces before shooting have negative signs. This indicates that a horizontal force is exerted by the left foot in the direction of the target (direction in which the rifle is aimed). The right foot force values indicate that the horizontal force of the right foot is exerted in the opposite direction. Statistical analysis indicates no statistical significant difference between the absolute values of the horizontal foot forces before shooting. (See Appendix B, paragraph B.1.3.4 and Table B37). Linear regression analysis of the horizontal foot forces before shooting was statistically significant with the F-ratio=3557.77, correlation=-0.99 and slope=-0.96 (Table B38). With the slope ≈-1, high correlation and no statistically significant differences between the absolute values of the variables, the left and right horizontal foot forces during aiming are statistically equal in magnitude and opposite in direction.

The difference between the values for the left foot before and after shooting indicates that the force increased in the direction of the target for all the subjects except subject number two. Except for subjects 4 and 9 the difference in the horizontal forces of the right foot increased in the opposite direction. Table 12 presents the change in horizontal force and the horizontal resultant force for both feet during shooting for each subject. (Resultant force = (left horizontal foot force after shooting) + (right horizontal foot force after shooting); Change in force =|left horizontal foot force difference| + |right horizontal foot force|; the mean values of the variables are presented in Table 11.)

Table 12

Mean change in horizontal force in [N] and mean horizontal resultant force in [N] for both feet during shooting

Subject number	*Change in horizontal force*	*Resultant force*
1	*24.8*	*0.6*
2	*11.4*	*12.0*
3	*16.4*	*0.1*
4	*10.9*	*-10.5*
5	*26.6*	*3.4*
6	*9.3*	*-0.4*
7	*4.0*	*-2.5*
8	*33.7*	*-2.1*
9	*2.2*	*-1.7*

For the resultant force negative values indicate that the force is exerted in the direction of the target. A resultant force with a positive value indicates the opposite direction.

During the recoil action the maximum mean change in the horizontal force on the feet was 33.7N for subject number 8. The maximum horizontal resultant force was 12N for subject number 2 and the minimum 0.1N for subject number 3. With the exception of the foot forces, the recoil force is the only external force exerted on the body. The comparison of both the change in horizontal force and the resultant force during recoil with the mean recoil force values of Table 3 reveals that no horizontal reaction force is present at the feet to counteract the recoil. The recoil force is an order of magnitude larger than the change in the horizontal force and the horizontal resultant force on the feet.

Pearson product-moment correlation coefficients were calculated to investigate the interrelationships among the foot forces, rifle recoil and angular and linear displacements associated with the postures of the subjects during shooting. The variables of interest were the right vertical foot force difference, left vertical foot force difference, right horizontal foot force difference, left horizontal foot force difference, recoil energy, recoil force, recoil distance, centre of mass displacement, distance of the feet apart, shoulder angle to line of fire difference, barrel lift,right elbow angle and the left elbow angle. The means and standard deviations taken for all the subjects together are given in Table 13. The matrix of Pearson correlations is presented in Table 14.

Interpretation of the correlation results should be treated with caution. It is possible that spurious results can be obtained because some of the correlations may be statistically significant due to the number of coefficients calculated.

Table 13

Means and standard deviations of foot forces, rifle recoil and angular and linear displacements for all the subjects together

Variable	*Units*	*Mean*	*Standard deviation*
Right vertical foot force difference (RVD)	*N*	*203.7*	*57.8*
Left vertical foot force difference (LVD)	*N*	*-196.8*	*47.9*
Right horizontal foot force difference(RHD)	*N*	*6.0*	*9.1*
Left horizontal foot force difference (LHD)	*N*	*-6.4*	*8.6*
Recoil energy (RE)	*J*	*24.42*	*7.75*
Recoil force (RF)	*N*	*247.28*	*34.21*
Recoil distance (RD)	*m*	*0.100*	*0.031*
Centre of mass displacement (MCD)	*m*	*0.076*	*0.026*
Distance of feet apart (FDA)	*m*	*0.369*	*0.036*
Shoulder angle to line of fire difference (SLOFD)	*degree*	*5.2*	*3.6*
Barrel lift (BL)	*degree*	*4.1*	*4.5*
Right elbow angle (REL)	*degree*	*124.6*	*17.6*
Left elbow angle (LEL)	*degree*	*53.2*	*25.6*

Table 14

Correlation matrix of foot forces, rifle recoil and angular and linear displacements

	RVD	LVD	RHD	LHD	RE	RF	RD	MCD	FDA	SLOFD	BL	REL
LVD	-0.54											
RHD	0.08	-0.27										
LHD	-0.18	0.29	-0.57									
RE	-0.16	0.71	-0.17	0.12								
RF	-0.01	-0.08	0.33	-0.27	0.04							
RD	-0.14	0.67	-0.30	0.21	0.93	-0.32						
MCD	0.77	-0.63	0.26	-0.17	-0.23	-0.21	-0.14					
FDA	0.61	-0.60	0.07	-0.33	-0.57	-0.06	-0.50	0.61				
SLOFD	-0.15	0.64	-0.13	-0.01	0.89	-0.03	0.86	-0.31	-0.50			
BL	-0.15	0.70	-0.17	0.06	0.93	-0.01	0.87	-0.33	-0.60	0.92		
REL	0.24	0.04	0.52	-0.34	0.39	0.28	0.24	0.34	-0.13	0.31	0.36	
LEL	-0.42	-0.18	0.37	-0.02	-0.35	0.43	-0.50	-0.37	-0.44	-0.35	-0.30	0.04
	RVD	LVD	RHD	LHD	RE	RF	RD	MCD	FDA	SLOFD	BL	REL

For a sample size of n=90, correlations coefficients greater than 0.208 and 0.279 are statistically significant for levels 0.05 and 0.01 respectively. (Hoel, 1976)

Recoil energy correlated with the left vertically foot force difference, recoil distance,distance of the feet apart, the left and right elbow angles, shoulder angle to the line of fire difference and barrel lift. The recoil distance correlated, in addition to the left horizontal foot force difference and recoil force, with all of the variables above. This is not surprising as the recoil distance was used in the calculation of the recoil energy. The recoil force correlates with the right horizontal foot force difference, recoil distance and the right and left elbow angles. A sequential procedure for regression model selection was used to screen the variables and determine which have a significant effect on rifle recoil. This procedure is helpful in building a model when such a large number of independent variables are present. Recoil energy was taken as dependent variable. The independent variables which were introduced for the selection procedure were the left and right vertical and horizontal foot force differences, centre of mass displacement, distance of the feet apart, shoulder angle to line of fire difference, barrel lift, and the left and right elbow angles. Variables which were derived from or used in the calculation of the dependent variable were excluded from the selection procedure. Recoil force and recoil distance were excluded.

A least squares method was used to determine which of the given set of independent variables contributed significantly towards explaining the recoil energy. The independent variable with the largest contribution and which contributed significantly was repeatedly introduced to the model. At each stage, checks were made to see that previously selected variables were still significant. The variables that became insignificant in contributing to the model were removed. The procedure was repeated until only those independent variables which contributed significantly in explaining the variation of the recoil energy were left in the model. Table 15 presents a summary of the results of the variable selection procedure and the regression results of the analysis. (Detailed results are presented in Table B39 to Table B42).

Table 15

Summary of the results of the stepwise selection procedure and the multiple regression analysis of the selected variables

Dependent variable	Independent variables introduced to the model	Independent variables selected for the model	Coefficients	R-squared
RE	RVD LVD RHD LHD MCD FDA SLOFD BL REL LEL	LVD MCD FDA SLOFD BL	0.043 82.864 -33.897 0.679 0.765	0.9145

Analysis of variance for the model was statistically significant, with F-ratio=179.75, $p<0.01$ (For 5 and 84 degrees of freedom, F values greater than 3.24 and 2.32 are statistically significant for levels 0.01 and 0.05 respectively.) The result indicates that 91.45% of the variation in the recoil energy is accounted for by the variation of the five selected variables. The variables which were included in the model are the left vertical foot force difference, the centre of mass displacement, the feet distance apart, the difference in the shoulder angles to the line of fire before and after shooting and the angle of barrel elevation during firing.

The left vertical foot force difference is a force value. The centre of mass displacement and the feet distance apart are linear displacement values while the shoulder to line of fire difference and the barrel lift are angular displacements. The two angular displacement variables are thought to be indicative of the amount of rotation of the body around a horizontal and vertical axes. The selection of these variables is perhaps not surprising as the recoil energy was calculated from force and linear displacement values.

6. DISCUSSION

6.1 Recoil energy

The energy transferred to the shoulder of the shooter, is equivalent to the recoil energy values tabulated in the results. The mean recoil energy values of Table 1 indicate a minimum of 16.78J and a maximum of 43.32J. This is in general agreement with the order of magnitude of calculated recoil energy values for a .308 Winchester calibre rifle as stated by Askins (1981).

The variation of the recoil energy values could be attributed to a systematic variation among the subjects. The variation among subjects may be ascribed to the inherent characteristics of the subject, be it posture, clothing, muscle tension or joint mobility. Consequently, the recoil energy transferred to the shoulder of the shooter is dependent on the attributes of the shooter rather than only on the attributes of the rifle and ammunition. This finding would indicate that, for any population of shooters using the same rifle and ammunition, the recoil energy could differ. The minimum and maximum values of the recoil energy and the distribution of significantly different groups obtained in the present experiment could give some indication of the range that can be expected, but due to the sample size any further deductions should be made with caution.

The discussion of recoil energy in the previous paragraphs was based on the recoil energy transferred to the shoulder of the shooter. However, three other contact areas contribute to the man-rifle interface. Forces transmitted through the cheek, held to the side of the stock, and the supporting hand, on the fore-end of the stock, were not measured as part of the present experiment. The force measured on the trigger hand was concerned only with the hand grip immediately before shooting. The effects of these contact areas does not influence the validity of the previous finding as it was limited to that part of the recoil energy which was transferred to the shoulder of the shooter. The presence of other contact areas together with the inherent characteristics of the shooter mentioned earlier may well be considered in an attempt to explain the causes of the variation of recoil energy on the shoulder but these considerations were beyond the scope of the present study.

6.2 Preload, impulse duration and recoil force

The force with which the rifle is held to the shoulder before firing (preload force) was compared with the duration of the recoil force and the magnitude of the average recoil force for each of the 9 subjects. Within subject analyses show that a linear relationship between impulse duration and preload force was statistically significant for only three subjects. For these three subjects a negative correlation between impulse duration and preload force was observed, which indicates that a subject with a higher preload force would experience a shorter impulse duration. However, this relationship was not statistically significant for the rest of the subjects. The result of the linear regression of impulse duration and preload force for between subject analysis was not statistically significant. It appears that a generally statistically significant linear relationship does not not exist between impulse duration and preload force for between subject analysis and that within subject analyses are significant for only some of the subjects.

The relationship between the preload force and the average recoil force for all the subjects together was not statistically significant. Within subject analysis did show a positive linear statistical significant relationship for two of the subjects. It should be noted that the two subjects who indicated a statistical significant relationship between the preload force and average recoil force, also indicated a statistically significant relationship between impulse duration and preload force.

The present results suggest that for some shooters higher preload forces may result in shorter impulse durations. Some shooters who exert higher preload forces may experience higher average recoil forces. These statements cannot be generalized to include the whole shooting population.

The present findings suggest that an advantage may be gained in reducing the average recoil force by reducing the force with which the rifle is held to the shoulder before firing. As a positive relationship between these two parameters could be found for only two of the subjects and no relationship at all for the rest, there is no indication that a high preload force will reduce the average recoil force.

The recoil force is distributed over the area of the recoil pad against the shoulder and is responsible for the compression of the tissues of the shoulder. A low pressure value could be seen as advantageous in reducing contusion of the pressure bearing tissues. This dynamic pressure can be reduced in two ways, firstly by increasing the area and secondly by reducing the force. If the force is transmitted over an elastic and contoured area, such as the recoil pad against the shoulder, the area may effectively be increased by applying a static force similar to the preload force. It is thought that very little increase in the area (recoil pad against shoulder) can be gained by increasing the preload force because the stiffness of the elastic pads is relatively high. It is therefore suggested that the only way to effectively reduce the pressure on the shoulder would be to reduce the recoil force. This may be effected in some shooters by reducing the preload force. For other shooters, where no relationship between recoil and preload force can be established, a reduction in preload force may contribute to a more relaxed shooting posture. It would seem that it could be advantageous for both groups of shooters, for those who will experience a lower recoil force and for those where a more relaxed posture is indicated, to reduce the preload force.

Although the previous deductions suggest some of the advantages of reducing the preload force, the role of the preload force in the establishment of a stable man-rifle interface should also be considered. However, this aspect is beyond the scope of the present investigation.

6.3 Handgrip force

The handgrip force showed considerable variation among subjects; from a mean value of 99.63 N for subject number 2, to 26.45 N for subject number 5. The data clearly indicates that no advantage is to be gained by the capability of the hand to exert a higher grip force with the hand in ulnar deviation. The maximum mean handgrip force of 99.63 N by subject number 2, being a 20th percentile male by height and 80th percentile by mass, is five times smaller than the maximum right hand grip forces measured by Straub (1979). From a handgrip strength point of view, there would be no reason to argue that rifle grip designs or the posture of shooters be adapted to incorporate ulnar deviation in the positioning of the trigger hand on the rifle.

It would seem that the way the rifle is supported by the left hand, has no direct influence on the magnitude of the handgrip force. The regression analysis of the handgrip force and left hand position indicates that there is no statistically significant linear relationship. If the observation, that active gripping of the stock by the left hand was associated with a forward hand position (and therefore a large elbow angle), was correct, the implication would be that the rifle is held more rigidly and muscle tension in the arm will be higher than for support closer to the trigger hand where support of the left upper arm against the trunk is possible.

These findings are in general agreement with Wilkins' (1981) views on the position of the left hand and the muscle strain of the grip force of the right hand to achieve a stable and efficient shooting posture.

An aspect not reflected in the results and supported by another study is that the grip force declined during aiming up to the point of trigger activation, where the grip force values for this study were measured. Zhilina, Shalmanov and Aktov (1981) also found that the grip force declined as the pressure on the trigger increased and added that performance could be increased if the grip force stays constant during aiming.

6.4 Foot forces, rifle recoil, angular and linear displacement

When a body is in equilibrium, the resultant of all the forces acting on it is zero. This statement is frequently referred to as the first condition of equilibrium and is derived from Newton's first law of motion. During aiming in the standing shooting position the shooter attempts to place the body in equilibrium so that the resultant of all the vertical and horizontal force components is zero.

It is evident from the results that, during aiming, equal and opposite horizontal forces are exerted by the left foot and the right foot. However, during shooting the left horizontal foot force increased for all but one subject. The right horizontal foot force increased in the opposite direction for all except two of the subjects. This change in the magnitude of the horizontal foot forces is the result of the recoil force generated by the rifle. For a rigid body it may be proposed that a horizontal reaction force on the feet of equal magnitude and opposite in direction to the horizontal recoil force, will be observed to maintain equilibrium. However, the results indicate that no horizontal reaction force of sufficient magnitude is present at the feet to counteract the recoil force.

The present findings suggest that the difference between vertical foot force during aiming and shooting, the displacement of the centre of mass, the distance of the feet apart, the difference between the shoulder angles during aiming and shooting and the degree of elevation of the barrel during shooting, can all significantly influence the recoil energy. The recoil energy values was calculated from the recoil force and distance. Rotation of the shoulders in a vertical axis and the elevation of the barrel associated with rotation in a horizontal axis would account for the displacement aspect of recoil energy. The recoil force would account for the change in the left vertical foot force. The displacement of the centre of mass of the shooter correlates with the distance of the feet apart and both these variables were included in the regression model for the recoil energy. The posture diagrams show that subject 5 (Figure B5) had the largest displacement of the centre of mass, while subject 3 (Figure B3) had the smallest. The diagrams also suggest that subject 5 had a rigid posture against movement in the arms and legs. Rotation of the trunk in the vertical axis is evident (from the value for the shoulder angle to the line of fire), but the rifle is held in a horizontal orientation during the recoil action. Subject 3 allows for more flexibility. Movement in the knee and shoulder joints is indicated with little resistance to the elevation of the barrel. Trunk rotation in both the vertical axis and the horizontal axis through the lumbar region is evident. It would seem that hyperlordosis of the spine during shooting has the effect of reducing the linear displacement of the trunk through angular displacement around a vertical and horizontal axis.

These findings suggest that a shooter who allows hyperlordosis to develop during the shooting sequence will experience a reduction in the displacement of the centre of mass. From this follows a possible explanation for a previously unexplained finding. The results indicated that there was no horizontal reaction force present at the feet to counteract the recoil force. It is suggested that the recoil force generates a force couple with a rotation point at the centre of mass. The effect would be rotation around the centre of mass. The rotation of the trunk is counteracted at the hip joints by the resistance to movement of the joint structures (ligaments and muscle attachments) and the inertia of the legs. The resistance to the rotation causes the centre of mass to be linearly displaced in the direction of the recoil force. As the body is still supported by the legs, the linear displacement of the centre of mass results in a rise in the right vertical foot force and a reduction in the left vertical foot force. The change in the vertical foot force is supported by the data.

6.5 Ergonomic implications

Several authors have discussed the concept of perceived recoil (Askins,1981; Daley,1982; Jamison,1982; Ruel,1988; Seyfried,1990). Perceived recoil can be a serious limiting factor in a shooter's performance. Perceived recoil has two main elements. The one element is psychological and the other physical in nature. Various mechanical methods of reducing recoil are possible, but the present discussion is concerned only with possible postural or force adaptations to effect the same result. It is commonly believed that perceived recoil can be reduced if the rifle is held firmly to the shoulder. However, the present findings suggest that it could be advantageous for shooters to reduce the preload force. Some shooters may benefit from a low preload force in that the average recoil force will be reduced. The performance of other shooters may benefit from a more relaxed shooting posture. However, the reduction in the preload force should not negatively influence the stability of the man-rifle interface.

The present findings suggest that handgrip strength does not dictate the orientation or span of the rifle grip. It would seem that rifle stock designers should be allowed more freedom with regard to these aspects. A change in the orientation of the stock grip to be approximately perpendicular to the barrel will result in less ulnar deviation of the hand. A more vertical grip will also assist in the location of the trigger hand for uniform trigger pull (Fajen,1981). Furthermore, less elbow elevation will be apparent. The trigger hand will still be in flexion but the strain in the fore-arm due to ulnar deviation will be relieved. The lower elbow position will reduce the strain of the arm and shoulder muscles. Collectively the arm and hand will be more relaxed and thereby contribute towards shooting performance.

The findings also suggest that muscle strain in the supporting hand and fore-arm can be relieved by positioning the supporting hand closer to the trigger. This could benefit the training of novice shooters. If rifle stocks were designed with very short fore-ends, the supporting hand would have to be positioned closer to the trigger. This would, together with a perpendicular grip, allow the novice little variation and would facilitate the shooter to locate the hand in identical positions each time. The location of the hands in exactly the same position each time is one of the basic conditions for high performance in shooting.

6.6 Further research

The man-rifle interface has four major contact areas. Two areas, shoulder contact and handgrip, were quantitatively investigated in the present study. Quantification of the contribution of the supporting hand and the cheek to the interface is desirable. Furthermore, the contribution of the elevated elbow to the stability of the interface is unknown. An investigation of the relationships between shooting performance and the variables of the interface would be useful in the formulation of further concepts for the design of rifle stocks, and would contribute towards the theory of shooting.

7. CONCLUSIONS

The general goal of the present study was achieved successfully by means of a measurement system which provided new quantitative data on the standing shooting position. The data was used to test specific hypotheses about aspects of shooting which could benefit the shooter.

The recoil energy which is transferred to the shoulder of the shooter is dependent on the attributes of the shooter rather than only on the characteristics of the rifle and ammunition. The relationships of the preload force (force with which the rifle is held to the shoulder before firing) and the impulse duration and recoil force, suggest that for some shooters the average recoil force may be reduced by reducing the preload force. Mean handgrip force values for the subjects ranged from 26N to 100N. These values are well below the maximum handgrip strength. No horizontal reaction force of sufficient magnitude is present at the feet to counteract the recoil force. It appears that the effect of the recoil force is to generate a force couple in the trunk and when associated with hyperlordosis of the spine in the firing sequence, can account for a smaller displacement of the centre of mass.

It appears that perpendicular orientation of the rifle grip could benefit the shooter by reducing muscle strain in the arm and shoulder. Rifle stock designs should facilitate the shooter to assume identical postures each time and contribute towards a stable but relaxed man-rifle interface. Relationships between shooting performance and the contributions of the contact areas to the interface would be useful inputs for the design of rifle stocks.

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APPENDIX A

A.1 TRANSDUCER DESCRIPTION

A.1.1 Force plates

Two force plates were developed to measure forces in two dimensions only, namely a vertical component and a horizontal component.

The force plates consisted of a 253mm by 350mm by 19mm rectangular aluminium top plate supported by four square steel cantilever beams each with a 12mm by 12mm measurement section. Each cantilever beam was rigidly fastened to the top plate and to a steel frame base structure. Height adjustment devices were provided on the four corners of the base structure. The component parts are shown in Figure A1. Strains in the four beams under the action of forces on the top plate are a function of the applied forces.

This construction was used to minimize errors due to moving parts, to provide an instrument with a high sensitivity with very small displacement of the top plate, to be simple and easy to manufacture and to be cheap.

The cantilever beams were machined from a square solid bar of En 3A steel to produce a 12mm by 12mm measurement section (Figure A2) for the application of resistance strain gauges. The strain gauges used were Kyowa type KFC-5-C1-11.

The principles of force measurement used for the vertical and horizontal components of the force were similar. The full Wheatstone bridge design is presented in Figure A3. The configuration of the strain gauges allows for the measurement of the total strain in the four beams so that they are not affected by the position of the load. Additionally, any applied torque about an axis of the

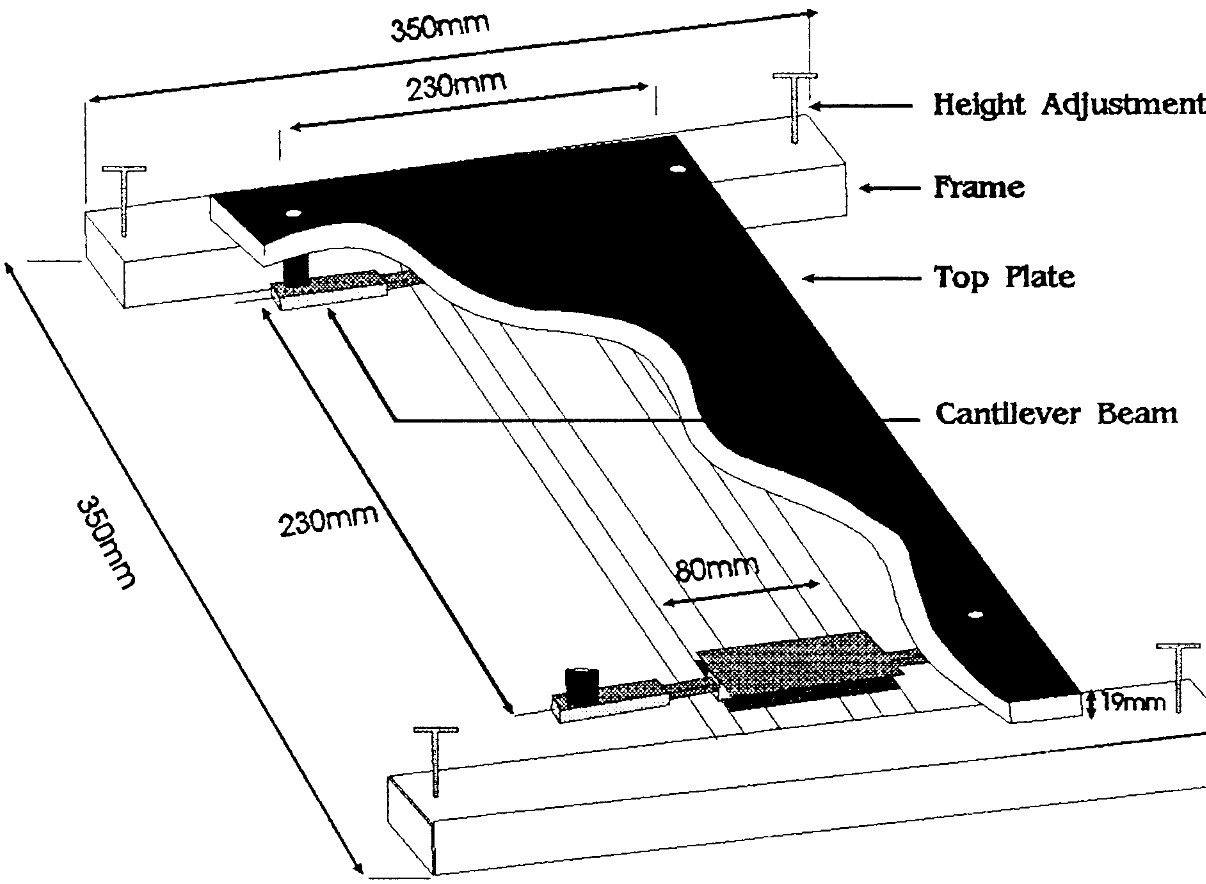


Figure A1: Component parts of the force plate

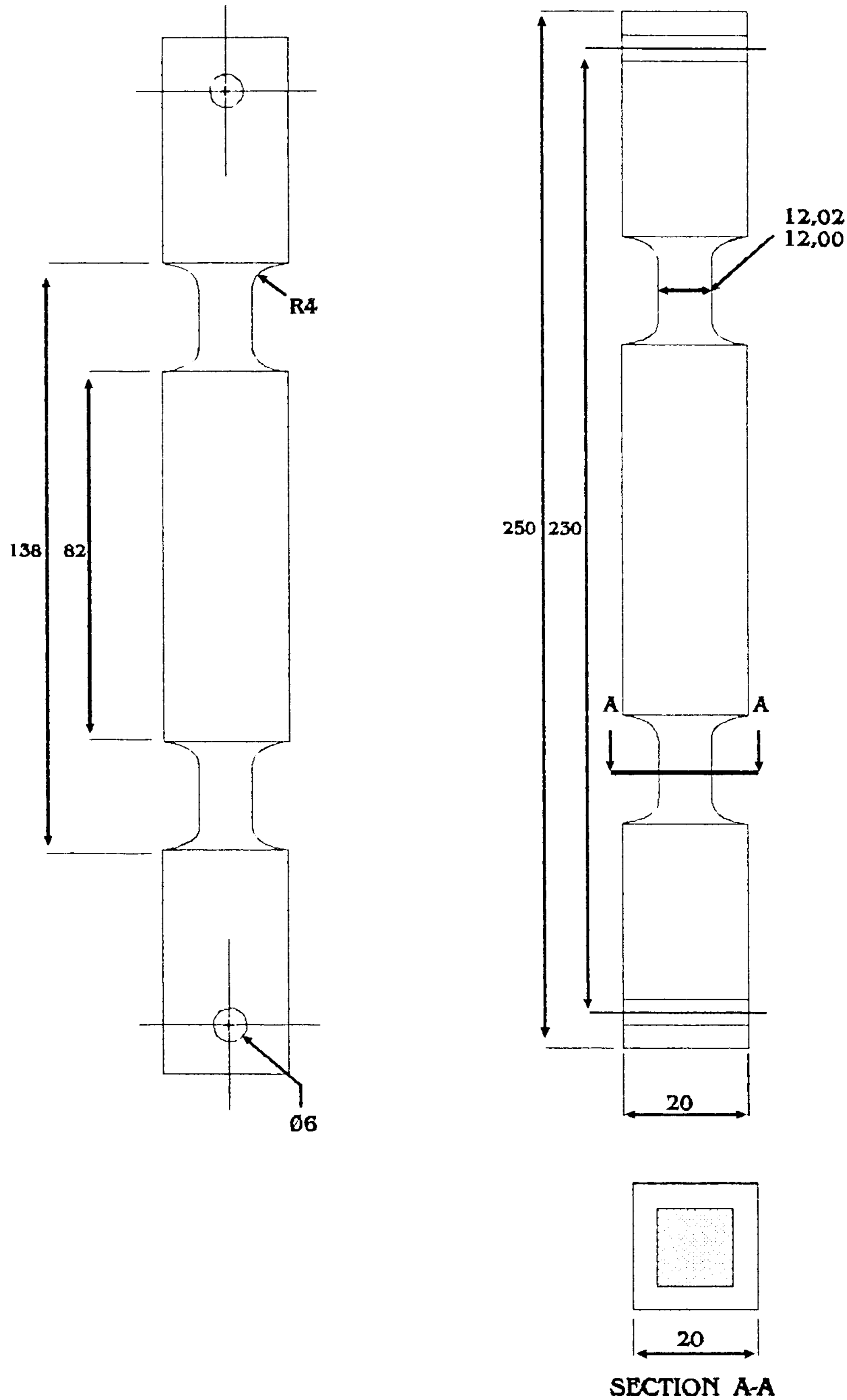


Figure A2: Force plate cantilever beam

force plate would not produce interference in the measurement of the force. Because only one component of the horizontal force is measured by the force plate, the positioning of the force plate in relation to the line of fire was important. Any misalignment of the force plate would result in a measurement smaller than the applied force.

The force plates were calibrated in both axes by cumulative loading with known weights while connected to the strain gauge amplifier. The calibration results are presented in Table A1 and Table A2.

Table A1

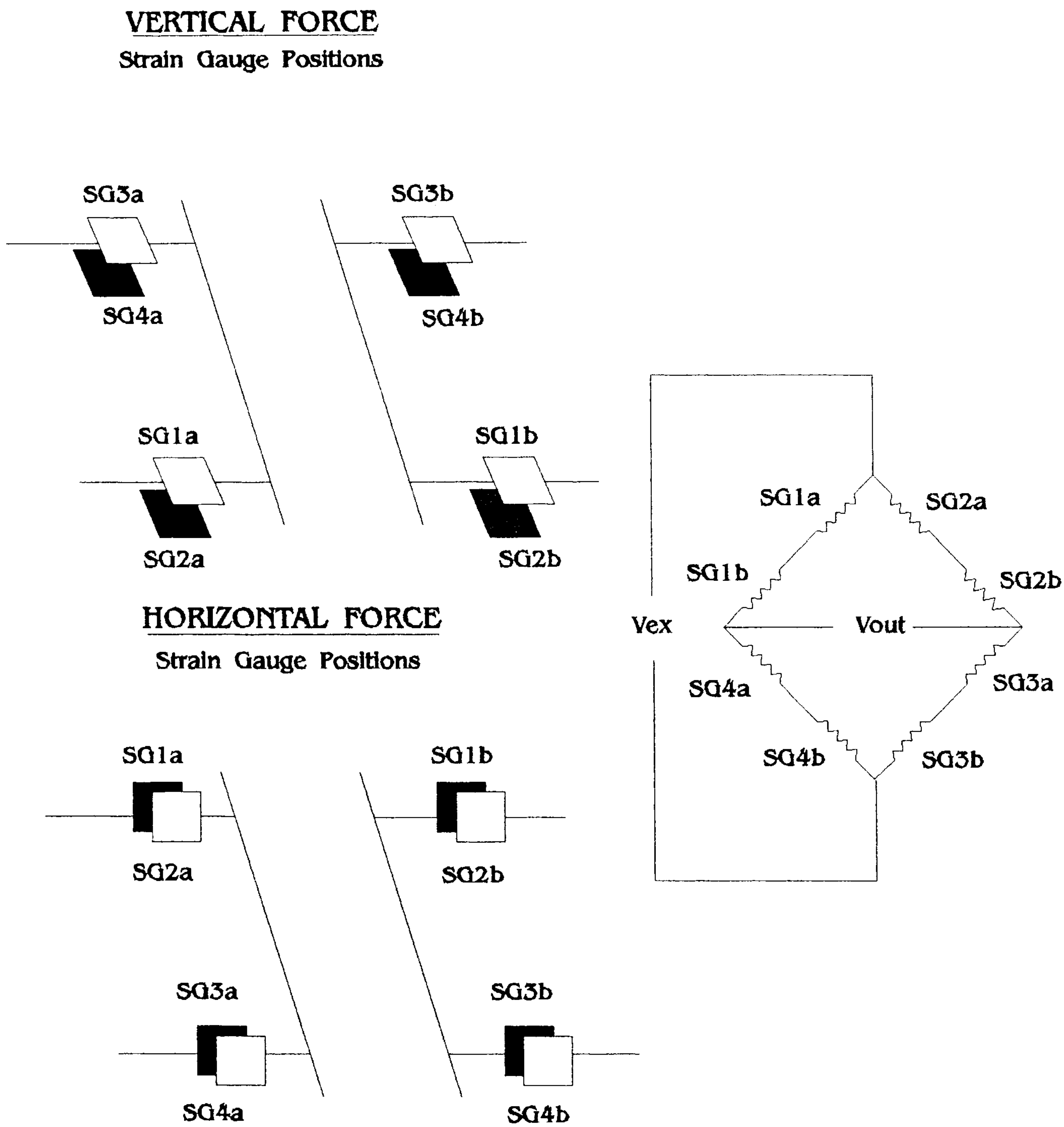
Calibration results for the vertical loading of the force plates

Force Plate 1				Force Plate 2			
Mass in [kg]	Force in [N]	Output Voltage in [mV]	Output/ Force in [mV/N]	Mass in [kg]	Force in [N]	Output Voltage in [mV]	Output/ Force in [mV/N]
0.00	0.0	0		0.00	0.0	0	
4.86	47.6	73	1.53	5.22	51.2	82	1.60
9.92	97.2	149	1.53	10.44	102.3	167	1.63
15.27	149.6	231	1.54	15.46	151.5	248	1.64
20.63	202.2	313	1.55	20.16	197.6	324	1.64
25.78	252.6	391	1.55	25.32	248.1	408	1.64
30.79	301.7	471	1.56	30.67	300.6	495	1.65
35.84	351.2	548	1.56	35.82	351.0	578	1.65
41.00	401.8	626	1.56	40.83	400.1	660	1.65
46.22	453.0	707	1.56	46.19	452.7	746	1.65
51.44	504.1	786	1.56	51.25	502.3	827	1.65
56.46	553.3	860	1.55	56.11	549.9	907	1.65
61.16	599.4	929	1.55	61.16	599.4	989	1.65
66.02	647.0	1002	1.55	66.38	650.5	1071	1.65
71.08	696.6	1078	1.55	71.60	701.7	1156	1.65
76.43	749.0	1160	1.55	76.62	750.9	1237	1.65
81.79	801.5	1242	1.55	81.32	796.9	1313	1.65
86.94	852.0	1320	1.55	86.48	847.5	1397	1.65
91.95	901.0	1400	1.55	91.83	899.9	1484	1.65
97.00	950.6	1477	1.55	96.98	950.4	1567	1.65
102.16	1001.2	1555	1.55	101.99	999.5	1649	1.65
CALIBRATION VALUE			1.551	CALIBRATION VALUE			1.644

Table A2

Calibration results for the horizontal loading of the force plates

Force Plate 1				Force Plate 2			
Mass in [kg]	Force in [N]	Output Voltage in [mV]	Output/ Force in [mV/N]	Mass in [kg]	Force in [N]	Output Voltage in [mV]	Output/ Force in [mV/N]
0	0	0		0	0	0	
5.05	49.5	108	2.18	5.05	49.5	118	2.38
9.87	96.7	206	2.13	9.87	96.7	227	2.35
15.09	147.9	317	2.14	15.09	147.9	348	2.35
20.24	198.4	429	2.16	20.24	198.4	474	2.39
25.26	247.5	536	2.17	25.46	249.5	595	2.38
30.48	298.7	659	2.21	30.48	298.7	715	2.39
35.64	349.3	775	2.22	35.64	349.3	838	2.40
40.34	395.3	882	2.23	40.34	395.3	965	2.44
CALIBRATION VALUE			2.180	CALIBRATION VALUE			2.387



SG1a to 4b = Strain gauges one a to four b
Vout = Output voltage
Vex = Excitation voltage

Figure A3: Strain gauge bridge and strain gauge positions for the force plates

A.1.2 Recoil force transducer

One recoil force transducer was developed to measure the recoil force of the rifle on the shoulder of the shooter.

The recoil force transducer consisted of two steel beams, measuring 240mm by 40mm by 6mm bolted to a 25mm aluminium spacing block. One beam was glued to a Pachmayr "White Line" recoil pad which could be fastened to the rifle stock in the conventional way. The other beam was furnished with a thin shoulder contact part of the recoil pad below the measurement section of 60mm. The component parts are shown in Figure A4. The beam with the measurement section would essentially operate as a cantilever beam. The strain in the beam under the action of forces is a function of the applied forces.

This construction for measuring the recoil force was decided on to ensure high repeatability in measurement, easy construction and a resultant decrease in costs.

The cantilever beam was machined from annealed En 45 steel after which the beam was tempered. The measurement section allowed the strain gauges to be bonded 54,5mm apart and on opposite sides of the beam. The resistance strain gauges used were Kyowa type KFC-5-C1-11.

The principle of force measurement used for the recoil force transducer is based on the turning moments around the strain gauge positions. Strain at a point in a beam of uniform dimension and composition, subjected to bending only, is directly proportional to the moment at that point. A force applied to the beam beyond the measurement section will result in different moments around the strain gauge positions. By careful configuration of the strain gauges, the resultant measurement of the bridge

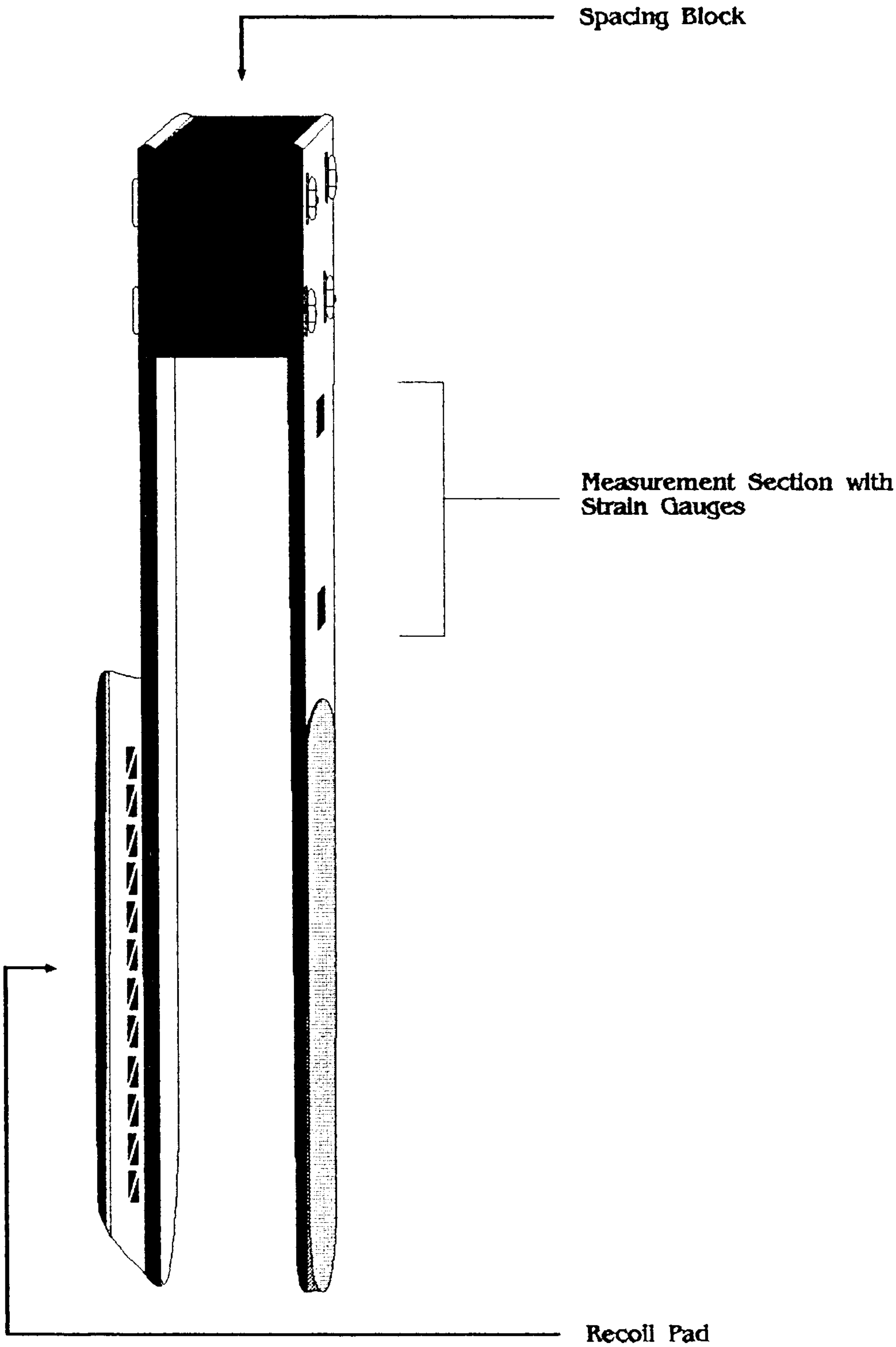


Figure A4: Component parts of the recoil force transducer will be independent of the distance of the applied force from the measurement section. The full Wheatstone bridge design is presented in Figure A5.

The recoil force transducer was calibrated by cumulative loading with known weights while connected to the strain gauge amplifier. The calibration results are presented in Table A3.

The natural frequency of the transducer was determined by suspending the rifle with the recoil force transducer from two parallel wires, and recording the unloaded transducer output during the firing of a shot. From the oscilloscope trace it was possible to determine the period of the natural wave form. The natural frequency was found to be 90Hz.

The mass of the recoil force transducer was 1.235kg.

Table A3

Calibration results for the recoil force transducer

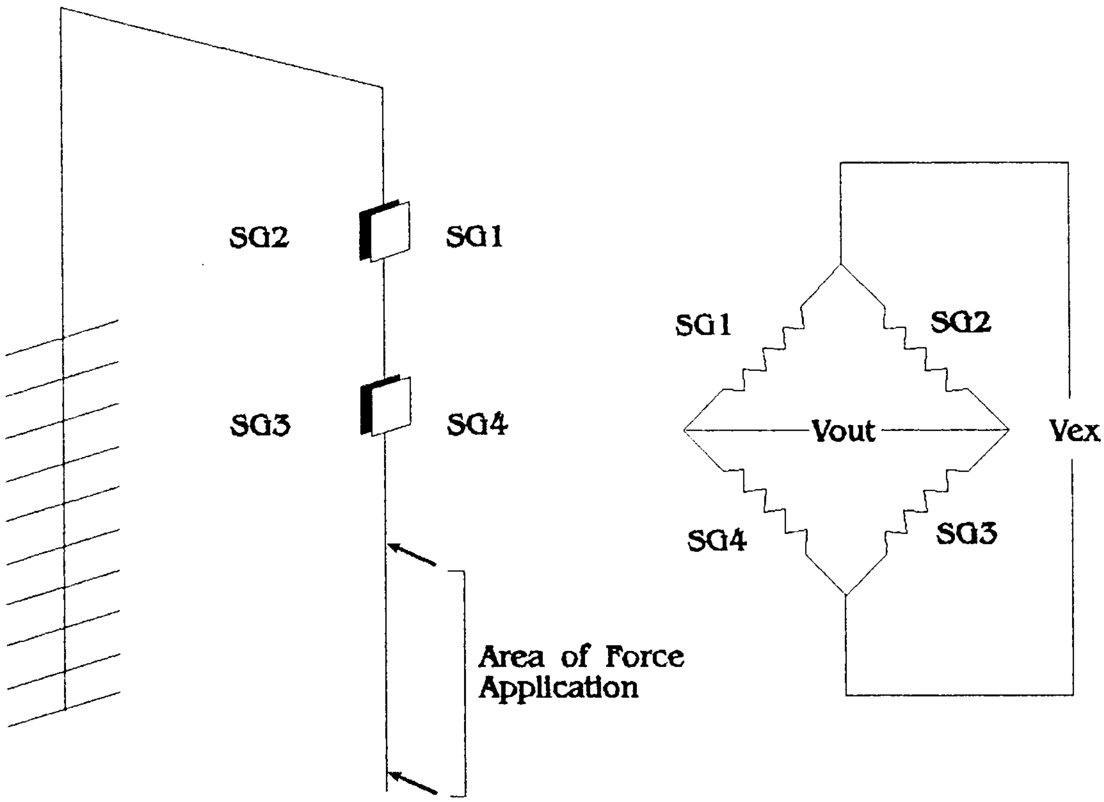
Mass in [kg]	*Force in [N]*	*Output Voltage in [mV]*	*Output/ Force in [mV/N]*
0.00	0.0	0	
5.22	51.2	433	8.46
10.24	100.4	853	8.50
15.10	148.0	1258	8.50
20.32	199.1	1699	8.53
25.33	248.2	2096	8.44
30.38	297.7	2525	8.48
35.74	350.3	2970	8.48
40.80	399.8	3340	8.35
46.02	451.0	3773	8.37
51.04	500.2	4193	8.38
55.90	547.8	4598	8.39
61.12	599.0	5039	8.41
CALIBRATION VALUE			8.442

A.1.3 Grip force transducer

One grip force transducer was developed to measure the force exerted by the trigger hand to position and hold the rifle during aiming and shooting.

The grip force transducer consisted of a steel beam measuring 5,8mm by 9,5mm by 150mm bolted to a mild steel support which could be fastened to the rifle stock. The beam allowed for a measurement section of 58mm. The

Recoil Force
Strain Gauge Positions



SG1 to 4 - Strain Gauges one to four
Vex = Excitation Voltage
Vout = Output Voltage

Figure A5: Strain gauge bridge and strain gauge positions for the recoil force transducer grip section of the beam was bent to the curvature of the rifle stock grip. The component parts of the transducer are shown in figure A6. The beam operates as a cantilever beam where the strain in the beam is a function of the applied forces.

The recoil force transducer beam was machined from annealed En 45 steel. Tempering of the steel beam produced a measurement section of high repeatability.

Resistance strain gauges (Kyowa type KFC-5-C1-11) were bounded 50,0mm apart and on opposite sides of the beam. The principle of force measurement used for the grip force transducer is similar to that used for the recoil force transducer as discussed previously. The full Wheatstone bridge design is similar in every respect to that presented in Figure A5.

The grip force transducer was calibrated by cumulative loading with known weights while connected to the strain gauge amplifier. Due to the curved nature of the grip section of the beam, the configuration of the rifle stock and the hand position and grip force direction as measured by the transducer, the calibration loading was done with the measurement section elevated 45°. The calibration results are presented in Table A4.

Table A4

Calibration results for the grip force transducer

Mass in [kg]	*Force in [N]*	*Output Voltage in [mV]*	*Output/ Force in [mV/N]*
0	*0*	*0*	
5.35	*52.4*	*935*	*17.83*
10.40	*101.9*	*1795*	*17.61*
15.62	*153.1*	*2655*	*17.34*
20.63	*202.2*	*3415*	*16.89*
CALIBRATION VALUE			*17.422*

The acceleration of the rifle during firing excluded measurements to be taken during the firing period. However, during aiming and up to the time of trigger ac-

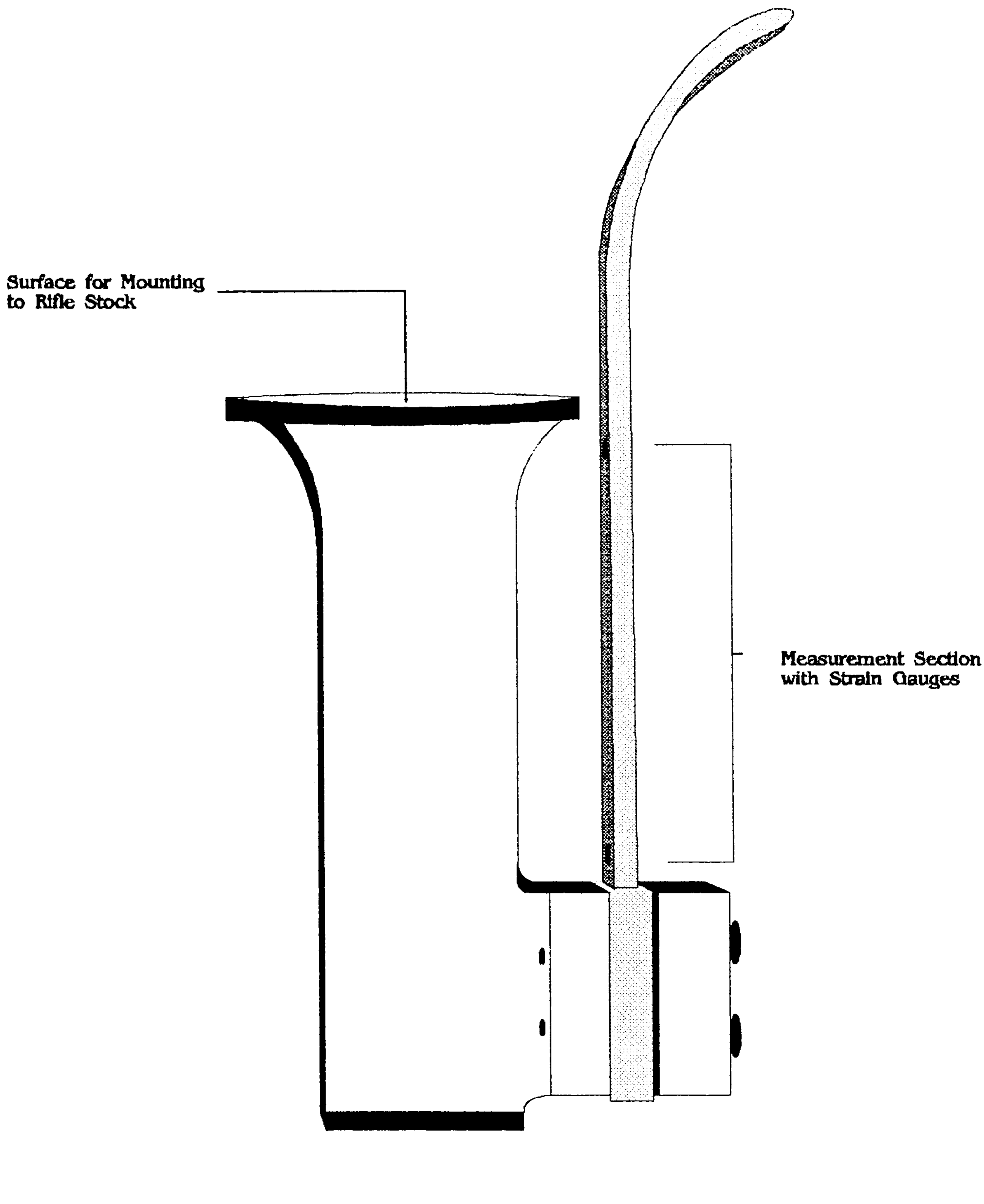


Figure A6: Component parts of the grip force transducer tivation, the transducer would produce accurate measurements. In this case the measurement of natural frequency was not critical.

The mass of the grip force transducer was 0,375kg.

A.1.4 Oscilloscope trigger switch

A switch was constructed to trigger the oscilloscope trace of the recoil force immediately before a shot was fired. A miniature general purpose micro switch was mounted on a machined nylon mounting block. The switch assembly could then be mounted into the bolt sliding grove of the rifle action with the plunger of the micro switch pressed against the back edge of the firing pin. During firing the microswitch plunger would follow the forward movement of the firing pin, resulting in an electrical pulse to the oscilloscope to trigger the trace. The component parts of the switch assembly is shown in Figure A7.

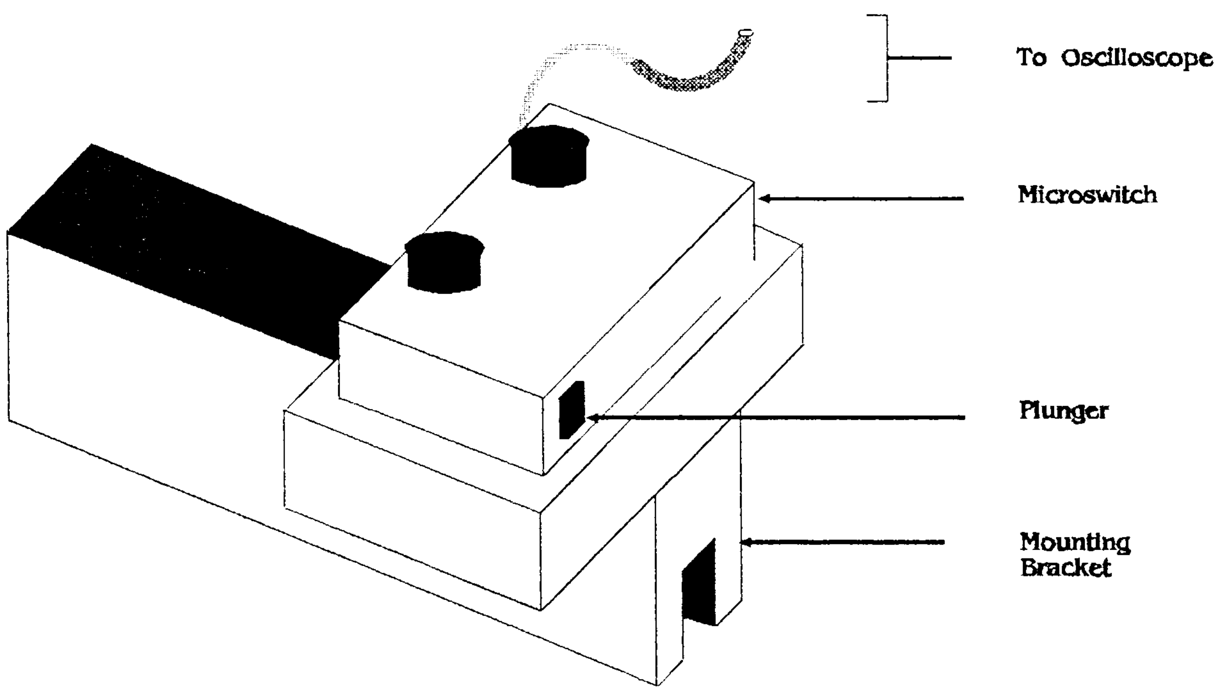


Figure A7: Component parts of the oscilloscope trigger switch

APPENDIX B

B.1 RESULTS

B.1.1 Kinetic and Kinematic data

The kinetic data, kinematic data and the combination of kinetic and kinematic data are presented in tabular form for each subject in Table B1 to Table B9.

B.1.2 Posture diagrams

Diagrammatic presentations of the posture of subjects before and after shooting is presented in Figure B1 to Figure B9.

B.1.3 Statistical Analysis Results

This section presents the detailed results of the statistical analyses discussed in paragraph 5 of the main section of this document.

Table B1

Kinetic and Kinematic Data for Subject Number 1

Subject Number SN	Shot Number SHN	Mass [kg] MASS	Height [m] HEIGHT	Impulse [Ns] IMP	Recoil Distance [m] RD	Impulse Duration [ms] IT	Preload [N] PRE	Peak Recoil Load [N] PRL	Grip force [N] GRIP	Foot Forces Left Vertical Before [N] LVB	Foot Forces Left Vertical After [N] LVA
1	1	132	1.82	5.081	0.060	28	113	424	74.6	921	670
1	2	132	1.82	6.453	0.059	29	118	471	74.9	930	736
1	3	132	1.82	6.959	0.060	24	115	488	51.6	953	747
1	4	132	1.82	6.970	0.059	24	115	487	71.0	1001	737
1	5	132	1.82	7.557	0.059	25	96	504	80.4	1039	817
1	6	132	1.82	7.386	0.057	24	130	497	71.7	1001	769
1	7	132	1.82	8.003	0.059	20	118	509	78.6	1007	750
1	8	132	1.82	7.276	0.059	20	116	522	83.5	978	743
1	9	132	1.82	6.958	0.057	24	115	488	83.4	969	726
1	10	132	1.82	6.958	0.059	24	115	489	76.6	959	745

Shot Number SHN	Foot Forces Left Differenc [N] LVD	Right Vertical Before [N] RVB	Right Vertical After [N] RVA	Right Vertical Differenc [N] RVD	Left Horizontal Before [N] LHB	Left Horizontal After [N] LHA	Left Horizontal Differenc [N] LHD	Right Horizontal Before [N] RHB	Right Horizontal After [N] RHA	Right Horizontal Differenc [N] RHD	Right Elbow [degrees] REL
1	-251	437	671	234	-21	-32	-11	20	32	12	123
2	-194	430	576	146	-21	-36	-15	20	35	15	126
3	-206	405	589	184	-32	-40	-8	29	41	12	122
4	-264	365	578	213	-19	-32	-13	21	34	13	127
5	-222	329	524	195	-16	-33	-17	17	34	17	125
6	-232	369	559	190	-20	-34	-14	19	37	18	125
7	-257	360	575	215	-18	-29	-11	18	30	12	126
8	-235	385	585	200	-21	-31	-10	22	30	8	124
9	-243	390	562	172	-20	-28	-8	19	29	10	130
10	-214	396	534	138	-16	-29	-13	17	28	11	127

Shot Number SHN	Left Elbow [degrees] LEL	Shoulder to line of fire Before [degrees] SLOFB	Shoulder to line of fire After [degrees] SLOFA	Shoulder to line of fire Differenc [degrees] SLOFD	Barrel Lift [degrees] BL	Left Hand Position [m] LHP	Feet Distance Apart [m] FDA	Mass Center Displ. [m] MCD	Recoil Energy [J] RE	Recoil Force [N] RF
1	80	29	25	4	1	0.232	0.372	0.066	10.9	181.5
2	88	29	25	4	1	0.223	0.372	0.046	13.1	222.5
3	76	29	25	4	1	0.264	0.372	0.053	17.4	290.0
4	91	29	25	4	1	0.239	0.372	0.064	17.1	290.4
5	94	29	25	4	1	0.233	0.372	0.056	17.8	302.3
6	95	27	23	4	1	0.248	0.372	0.056	17.5	307.7
7	93	29	25	4	1	0.224	0.372	0.063	23.6	400.2
8	89	29	25	4	1	0.229	0.372	0.059	21.5	363.8
9	97	32	28	4	1	0.215	0.372	0.056	16.5	289.9
10	95	29	25	4	1	0.228	0.372	0.047	17.1	289.9

Table B2

Kinetic and Kinematic Data for Subject Number 2

Subject Number SN	Shot Number SHN	Mass [kg] MASS	Height [m] HEIGHT	Impulse [Ns] IMP	Recoil Distance [m] RD	Impulse Duration [ms] IT	Preload [N] PRE	Peak Recoil Load [N] PRL	Grip force [N] GRIP	Foot Forces Left Vertical Before [N] LVB	Foot Forces Left Vertical After [N] LVA
2	1	82	1.72	6.855	0.093	31	128	438	80.0	497	237
2	2	82	1.72	6.886	0.088	30	160	458	96.6	481	308
2	3	82	1.72	5.928	0.088	30	158	492	105.9	472	215
2	4	82	1.72	6.615	0.088	27	131	478	100.7	474	280
2	5	82	1.72	6.654	0.094	31	169	438	101.1	469	292
2	6	82	1.72	6.753	0.088	29	176	480	104.9	465	240
2	7	82	1.72	7.190	0.088	31	169	441	100.3	468	213
2	8	82	1.72	6.687	0.079	29	198	449	110.8	465	300
2	9	82	1.72	6.967	0.088	29	173	450	106.4	463	253
2	10	82	1.72	8.322	0.088	30	140	459	89.6	468	308

Shot Number SHN	Foot Forces: Left Differenc [N] LVD	Right Vertical Before [N] RVB	Right Vertical After [N] RVA	Right Vertical Differenc [N] RVD	Left Horizontal Before [N] LHB	Left Horizontal After [N] LHA	Left Horizontal Differenc [N] LHD	Right Horizontal Before [N] RHB	Right Horizontal After [N] RHA	Right Horizontal Differenc [N] RHD	Right Elbow [degrees] REL
1	-260	378	610	232	-17	-19	-2	17	31	14	112
2	-173	394	572	178	-16	-2	14	15	23	8	114
3	-257	401	587	186	-13	-31	-18	16	27	11	121
4	-194	392	539	147	-15	-15	0	16	21	5	115
5	-177	392	548	156	-14	-16	-2	16	21	5	119
6	-225	398	562	164	-17	-17	0	14	22	8	120
7	-255	392	544	152	-18	-6	12	17	23	6	118
8	-165	395	524	129	-16	0	16	17	20	3	123
9	-210	395	551	156	-17	0	17	20	22	2	114
10	-160	401	558	157	-17	-5	12	18	21	3	119

Shot Number SHN	Left Elbow [degrees] LEL	Shoulder to line of fire Before [degrees] SLOFB	Shoulder to line of fire After [degrees] SLOFA	Shoulder to line of fire Differenc [degrees] SLOFD	Barrel Lift [degrees] BL	Left Hand Position [m] LHP	Feet Distance Apart [m] FDA	Mass Center Displ. [m] MCD	Recoil Energy [J] RE	Recoil Force [N] RF
1	91	17	15	2	1	0.331	0.324	0.093	20.6	221.1
2	92	22	20	2	1	0.329	0.324	0.065	20.2	229.5
3	96	22	20	2	1	0.345	0.324	0.088	17.4	197.6
4	89	22	20	2	1	0.359	0.324	0.067	21.6	245.0
5	94	21	19	2	1	0.364	0.324	0.064	20.2	214.6
6	95	22	20	2	1	0.348	0.324	0.078	20.5	232.9
7	95	22	20	2	1	0.333	0.324	0.085	20.4	231.9
8	83	29	26	3	1	0.312	0.324	0.057	18.2	230.6
9	94	22	20	2	1	0.322	0.324	0.073	21.1	240.2
10	93	22	20	2	1	0.317	0.324	0.059	24.4	277.4

Table B3

Kinetic and Kinematic Data for Subject Number 3

Subject Number SN	Shot Number SHN	Mass [kg] MASS	Height [m] HEIGHT	Impulse [Ns] IMP	Recoil Distance [m] RD	Impulse Duration [ms] IT	Preload [N] PRE	Peak Recoil Load [N] PRL	Grip force [N] GRIP	Foot Forces Left Vertical Before [N] LVB	Foot Forces Left Vertical After [N] LVA
3	1	78	1.73	7.559	0.165	30	136	346	84.6	477	343
3	2	78	1.73	7.304	0.165	31	106	303	94.4	516	332
3	3	78	1.73	8.249	0.165	30	101	397	63.8	507	441
3	4	78	1.73	7.826	0.160	30	109	354	102.3	489	346
3	5	78	1.73	7.827	0.165	30	109	353	101.1	559	461
3	6	78	1.73	9.033	0.149	31	105	339	90.9	596	489
3	7	78	1.73	7.571	0.165	28	84	374	75.9	590	513
3	8	78	1.73	7.584	0.165	30	110	339	103.2	598	519
3	9	78	1.73	7.702	0.165	30	125	384	122.6	538	425
3	10	78	1.73	7.604	0.186	28	108	345	85.3	593	513

Shot Number	Foot Forces										Right Elbow
	Left	Right Vertical			Left Horizontal			Right Horizontal			
	Differenc [N]	Before [N]	After [N]	Differenc [N]	Before [N]	After [N]	Differenc [N]	Before [N]	After [N]	Differenc [N]	[degrees]
SHN	LVD	RVB	RVA	RVD	LHB	LHA	LHD	RHB	RHA	RHD	REL
1	-134	348	483	135	-14	-24	-10	15	18	3	150
2	-184	303	509	206	-10	-30	-20	8	25	17	145
3	-66	322	429	107	-11	-13	-2	11	12	1	147
4	-143	335	500	165	-11	-26	-15	10	27	17	165
5	-98	259	398	139	-9	-12	-3	10	17	7	150
6	-107	235	426	191	-6	-16	-10	6	19	13	135
7	-77	243	372	129	-9	-14	-5	5	10	5	145
8	-79	233	395	162	-8	-14	-6	8	12	4	150
9	-113	288	478	190	-14	-16	-2	14	26	12	156
10	-80	226	395	169	-10	-16	-6	10	16	6	148

Shot Number	Left Elbow	Shoulder to line of fire			Barrel Lift	Left Hand Position	Feet Distance Apart	Mass Center Displ.	Recoil Energy	Recoil Force
	[degrees]	Before [degrees]	After [degrees]	Differenc [degrees]	[degrees]	[m]	[m]	[m]	[J]	[N]
SHN	LEL	SLOFB	SLOFA	SLOFD	BL	LHP	FDA	MCD	RE	RF
1	54	34	20	14	16	0.294	0.295	0.048	41.6	252.0
2	58	34	20	14	16	0.284	0.295	0.069	38.9	235.6
3	49	34	20	14	16	0.291	0.295	0.031	45.4	275.0
4	59	30	17	13	16	0.308	0.295	0.054	41.7	260.9
5	48	34	20	14	16	0.289	0.295	0.043	43.0	260.9
6	46	35	21	14	15	0.267	0.295	0.054	43.4	291.4
7	51	34	20	14	15	0.278	0.295	0.038	44.6	270.4
8	54	34	20	14	15	0.269	0.295	0.045	41.7	252.8
9	59	34	20	14	15	0.285	0.295	0.053	42.4	256.7
10	53	36	21	15	17	0.286	0.295	0.047	50.5	271.6

Table B4

Kinetic and Kinematic Data for Subject Number 4

Subject Number [SN]	Shot Number [SHN]	Mass [kg] MASS	Height [m] HEIGHT	Impulse [Ns] IMP	Recoil Distance [m] RD	Impulse Duration [ms] IT	Preload [N] PRE	Peak Recoil Load [N] PRL	Grip force [N] GRIP	Foot Forces Left Vertical Before [N] LVB	Foot Forces Left Vertical After [N] LVA
4	1	117	1.87	7.677	0.122	35	61	358	31.3	594	402
4	2	117	1.87	7.676	0.122	35	61	356	41.3	599	353
4	3	117	1.87	7.735	0.135	34	54	355	32.1	508	333
4	4	117	1.87	7.190	0.122	35	45	322	36.9	594	399
4	5	117	1.87	7.744	0.122	37	39	355	26.2	535	324
4	6	117	1.87	7.666	0.115	34	61	383	57.9	606	425
4	7	117	1.87	7.669	0.122	32	73	384	37.8	584	421
4	8	117	1.87	7.891	0.122	34	73	355	46.7	585	384
4	9	117	1.87	7.584	0.117	34	81	377	59.0	490	285
4	10	117	1.87	7.931	0.122	36	65	332	43.5	529	365

Shot Number	Foot Forces Left Differenc [N]	Right Vertical Before [N]	Right Vertical After [N]	Right Vertical Differenc [N]	Left Horizontal Before [N]	Left Horizontal After [N]	Left Horizontal Differenc [N]	Right Horizontal Before [N]	Right Horizontal After [N]	Right Horizontal Differenc [N]	Right Elbow [degrees]
SHN	LVD	RVB	RVA	RVD	LHB	LHA	LHD	RHB	RHA	RHD	REL
1	-192	618	937	319	-40	-42	-2	42	32	-10	103
2	-246	617	926	309	-35	-41	-6	37	25	-12	104
3	-175	706	887	181	-30	-36	-6	31	13	-18	100
4	-195	631	869	238	-41	-43	-2	44	37	-7	101
5	-211	686	911	225	-38	-38	0	37	23	-14	102
6	-181	603	838	235	-40	-42	-2	40	36	-4	101
7	-163	624	788	164	-40	-42	-2	41	41	0	102
8	-201	635	846	211	-41	-44	-3	42	37	-5	107
9	-205	728	935	207	-34	-39	-5	31	24	-7	109
10	-164	691	887	196	-41	-44	-3	39	38	-1	100

Shot Number	Left Elbow [degrees]	Shoulder to line of fire Before [degrees]	Shoulder to line of fire After [degrees]	Shoulder to line of fire Differenc [degrees]	Barrel Lift [degrees]	Left Hand Position [m]	Feet Distance Apart [m]	Mass Center Displ. [m]	Recoil Energy [J]	Recoil Force [N]
SHN	LEL	SLOFB	SLOFA	SLOFD	BL	LHP	FDA	MCD	RE	RF
1	18	22	14	8	6	0.211	0.390	0.074	26.8	219.3
2	17	22	14	8	6	0.214	0.390	0.084	26.8	219.3
3	17	22	17	5	6	0.218	0.390	0.057	30.7	227.5
4	17	22	14	8	6	0.198	0.390	0.066	25.1	205.4
5	19	22	14	8	6	0.208	0.390	0.069	25.5	209.3
6	18	19	11	8	5	0.202	0.390	0.064	25.9	225.5
7	18	22	14	8	5	0.213	0.390	0.053	29.2	239.7
8	19	22	14	8	5	0.209	0.390	0.065	28.3	232.1
9	20	26	15	11	7	0.204	0.390	0.066	26.1	223.1
10	17	22	14	8	7	0.202	0.390	0.055	26.9	220.3

Table B5

Kinetic and Kinematic Data for Subject Number 5

Subject Number SN	Shot Number SHN	Mass [kg] MASS	Height [m] HEIGHT	Impulse [Ns] IMP	Recoil Distance [m] RD	Impulse Duration [ms] IT	Preload [N] PRE	Peak Recoil Load [N] PRL	Grip force [N] GRIP	Foot Forces Left Vertical Before [N] LVB	Foot Forces Left Vertical After [N] LVA
5	1	73	1.72	7.687	0.101	33	75	412	31.5	399	117
5	2	73	1.72	8.160	0.102	33	72	396	36.5	433	178
5	3	73	1.72	8.066	0.099	33	81	351	33.5	417	144
5	4	73	1.72	7.581	0.102	33	76	373	27.5	458	245
5	5	73	1.72	8.351	0.102	33	75	424	28.9	434	205
5	6	73	1.72	7.777	0.104	36	72	302	28.5	428	220
5	7	73	1.72	8.202	0.102	34	81	360	19.5	410	160
5	8	73	1.72	7.998	0.102	34	76	374	23.9	391	168
5	9	73	1.72	8.170	0.103	34	78	379	13.7	409	179
5	10	73	1.72	7.999	0.102	34	76	375	21.0	411	207

Shot Number SHN	Foot Forces Left Differenc [N] LVD	Right Vertical Before [N] RVB	Right Vertical After [N] RVA	Right Vertical Differenc [N] RVD	Left Horizontal Before [N] LHB	Left Horizontal After [N] LHA	Left Horizontal Differenc [N] LHD	Right Horizontal Before [N] RHB	Right Horizontal After [N] RHA	Right Horizontal Differenc [N] RHD	Right Elbow [degrees] REL
1	-282	377	726	349	-21	-21	0	20	25	5	147
2	-255	353	726	373	-20	-31	-11	23	34	11	150
3	-273	363	744	381	-21	-38	-17	20	32	12	153
4	-213	330	586	256	-20	-48	-28	20	34	14	145
5	-229	339	586	247	-22	-43	-21	21	50	29	149
6	-208	350	593	243	-21	-44	-23	21	48	27	150
7	-250	363	643	280	-19	-24	-5	19	32	13	145
8	-223	380	698	318	-16	-23	-7	17	31	14	149
9	-230	381	686	305	-18	-21	-3	18	28	10	142
10	-204	371	723	352	-15	-16	-1	14	29	15	147

Shot Number SHN	Left Elbow [degrees] LEL	Shoulder to line of fire Before [degrees] SLOFB	Shoulder to line of fire After [degrees] SLOFA	Shoulder to line of fire Differenc [degrees] SLOFD	Barrel Lift [degrees] BL	Left Hand Position [m] LHP	Feet Distance Apart [m] FDA	Mass Center Displ. [m] MCD	Recoil Energy [J] RE	Recoil Force [N] RF
1	21	24	19	5	4	0.164	0.422	0.158	23.5	232.9
2	20	24	19	5	4	0.170	0.422	0.149	25.2	247.3
3	20	24	19	5	4	0.171	0.422	0.157	24.2	244.4
4	22	24	19	5	4	0.164	0.422	0.121	23.4	229.7
5	21	24	19	5	4	0.166	0.422	0.127	25.8	253.1
6	20	25	20	5	1	0.158	0.422	0.118	22.5	216.0
7	21	24	19	5	1	0.167	0.422	0.140	24.6	241.2
8	20	24	19	5	1	0.163	0.422	0.132	24.0	235.2
9	22	23	18	5	3	0.165	0.422	0.131	24.8	240.3
10	21	24	19	5	3	0.160	0.422	0.128	24.0	235.3

Table B6

Kinetic and Kinematic Data for Subject Number 6

Subject Number	Shot Number	Mass	Height	Impulse	Recoil Distance	Impulse Duration	Preload	Peak Recoil Load	Grip force	Foot Forces Left Vertical Before	Foot Forces Left Vertical After
		[kg]	[m]	[Ns]	[m]	[ms]	[N]	[N]	[N]	[N]	[N]
SN	SHN	MASS	HEIGHT	IMP	RD	IT	PRE	PRL	GRIP	LVB	LVA
6	1	73	1.73	7.048	0.117	33	100	400	36.3	424	197
6	2	73	1.73	6.840	0.117	33	84	372	48.5	442	244
6	3	73	1.73	7.012	0.129	35	77	363	46.7	445	239
6	4	73	1.73	7.049	0.117	33	100	400	86.6	439	264
6	5	73	1.73	6.624	0.117	32	118	441	50.2	461	282
6	6	73	1.73	6.571	0.119	36	86	431	67.4	440	264
6	7	73	1.73	7.471	0.117	34	113	419	89.8	461	279
6	8	73	1.73	7.130	0.117	33	101	401	63.3	479	320
6	9	73	1.73	7.048	0.104	33	100	400	59.3	494	301
6	10	73	1.73	7.690	0.117	31	120	470	70.2	490	325

Shot Number	Foot Forces Left Differenc	Right Vertical Before	Right Vertical After	Right Vertical Differenc	Left Horizontal Before	Left Horizontal After	Left Horizontal Differenc	Right Horizontal Before	Right Horizontal After	Right Horizontal Differenc	Right Elbow
	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[degrees]
SHN	LVD	RVB	RVA	RVD	LHB	LHA	LHD	RHB	RHA	RHD	REL
1	-227	362	543	181	-21	-24	-3	21	23	2	116
2	-198	343	503	160	-25	-26	-1	26	29	3	117
3	-206	329	506	177	-27	-27	0	25	29	4	115
4	-175	347	509	162	-28	-32	-4	26	27	1	115
5	-179	315	472	157	-22	-29	-7	21	23	2	116
6	-176	334	458	124	-23	-27	-4	23	23	0	115
7	-182	326	450	124	-20	-28	-8	22	31	9	116
8	-159	305	400	95	-16	-25	-9	18	22	4	115
9	-193	286	460	174	-21	-29	-8	23	34	11	117
10	-165	298	472	174	-20	-27	-7	23	29	6	117

Shot Number	Left Elbow	Shoulder to line of fire Before	Shoulder to line of fire After	Shoulder to line of fire Differenc	Barrel Lift	Left Hand Position	Feet Distance Apart	Mass Center Displ.	Recoil Energy	Recoil Force
	[degrees]	[degrees]	[degrees]	[degrees]	[degrees]	[m]	[m]	[m]	[J]	[N]
SHN	LEL	SLOFB	SLOFA	SLOFD	BL	LHP	FDA	MCD	RE	RF
1	42	29	24	5	3	0.198	0.370	0.101	25.0	213.6
2	44	29	24	5	3	0.211	0.370	0.087	24.3	207.3
3	50	28	22	6	3	0.218	0.370	0.094	25.8	200.3
4	49	29	24	5	3	0.182	0.370	0.080	25.0	213.6
5	45	29	24	5	3	0.187	0.370	0.081	24.2	207.0
6	39	31	25	6	2	0.197	0.370	0.075	21.7	182.5
7	40	29	24	5	2	0.216	0.370	0.075	25.7	219.7
8	43	29	24	5	2	0.202	0.370	0.062	25.3	216.1
9	41	29	25	4	2	0.183	0.370	0.088	22.2	213.6
10	42	29	24	5	2	0.196	0.370	0.079	29.0	248.1

Table B7

Kinetic and Kinematic Data for Subject Number 7

Subject Number	Shot Number	Mass	Height	Impulse	Recoil Distance	Impulse Duration	Preload	Peak Recoil Load	Grip force	Foot Forces Left Vertical Before	Foot Forces Left Vertical After
		[kg]	[m]	[Ns]	[m]	[ms]	[N]	[N]	[N]	[N]	[N]
SN	SHN	MASS	HEIGHT	IMP	RD	IT	PRE	PRL	GRIP	LVB	LVA
7	1	89	1.7	7.696	0.095	33	125	426	65.4	484	252
7	2	89	1.7	8.169	0.096	33	124	358	54.0	449	304
7	3	89	1.7	8.390	0.098	33	96	363	49.9	449	272
7	4	89	1.7	8.217	0.096	34	92	339	46.7	456	253
7	5	89	1.7	8.971	0.096	34	87	372	42.8	470	264
7	6	89	1.7	8.760	0.095	33	83	375	38.7	481	261
7	7	89	1.7	7.551	0.096	33	94	360	30.1	495	274
7	8	89	1.7	8.586	0.096	33	93	366	35.6	471	311
7	9	89	1.7	8.923	0.094	34	89	441	39.9	420	224
7	10	89	1.7	9.057	0.096	34	86	454	43.5	493	263

Shot Number	Foot Forces Left Differenc	Right Vertical Before	Right Vertical After	Right Vertical Differenc	Left Horizontal Before	Left Horizontal After	Left Horizontal Differenc	Right Horizontal Before	Right Horizontal After	Right Horizontal Differenc	Right Elbow
	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[degrees]
SHN	LVD	RVB	RVA	RVD	LHB	LHA	LHD	RHB	RHA	RHD	REL
1	-232	454	703	249	-47	-49	-2	46	52	6	140
2	-145	483	712	229	-46	-51	-5	47	47	0	138
3	-177	480	649	169	-45	-45	0	45	45	0	140
4	-203	472	738	266	-44	-46	-2	45	49	4	139
5	-206	460	721	261	-41	-45	-4	44	47	3	137
6	-220	458	671	213	-45	-47	-2	47	49	2	146
7	-221	446	646	200	-40	-50	-10	40	40	0	142
8	-160	458	695	237	-39	-41	-2	36	34	-2	139
9	-196	512	751	239	-37	-39	-2	34	28	-6	131
10	-230	445	668	223	-35	-39	-4	36	36	0	138

Shot Number	Left Elbow	Shoulder to line of fire Before	Shoulder to line of fire After	Shoulder to line of fire Differenc	Barrel Lift	Left Hand Position	Feet Distance Apart	Mass Center Displ.	Recoil Energy	Recoil Force
	[degrees]	[degrees]	[degrees]	[degrees]	[degrees]	[m]	[m]	[m]	[J]	[N]
SHN	LEL	SLOFB	SLOFA	SLOFD	BL	LHP	FDA	MCD	RE	RF
1	48	31	28	3	5	0.264	0.375	0.095	22.2	233.2
2	50	31	28	3	5	0.289	0.375	0.069	23.8	247.5
3	51	34	31	3	5	0.279	0.375	0.071	24.9	254.2
4	48	31	28	3	5	0.280	0.375	0.089	23.2	241.7
5	49	31	28	3	5	0.276	0.375	0.089	25.3	263.9
6	47	31	27	4	5	0.264	0.375	0.087	25.2	265.5
7	50	31	28	3	5	0.266	0.375	0.086	22.0	228.8
8	51	31	28	3	5	0.283	0.375	0.074	25.0	260.2
9	49	29	26	3	1	0.295	0.375	0.083	24.7	262.4
10	48	31	28	3	1	0.270	0.375	0.091	25.6	266.4

Table B8

Kinetic and Kinematic Data for Subject Number 8

Subject Number [] SN	Shot Number [] SHN	Mass [kg] MASS	Height [m] HEIGHT	Impulse [Ns] IMP	Recoil Distance [m] RD	Impulse Duration [ms] IT	Preload [N] PRE	Peak Recoil Load [N] PRL	Grip force [N] GRIP	Foot Forces Left Vertical Before [N] LVB	Foot Forces Left Vertical After [N] LVA
8	1	109	1.89	7.872	0.061	30	108	363	50.2	748	529
8	2	109	1.89	8.893	0.061	31	110	397	66.1	775	535
8	3	109	1.89	8.302	0.062	30	96	380	56.1	776	428
8	4	109	1.89	8.212	0.061	29	90	386	53.3	766	522
8	5	109	1.89	8.671	0.061	32	81	373	55.9	774	561
8	6	109	1.89	8.351	0.063	31	94	369	46.3	783	574
8	7	109	1.89	7.651	0.061	28	97	368	60.4	782	561
8	8	109	1.89	7.943	0.061	31	101	401	56.5	775	542
8	9	109	1.89	8.318	0.058	30	88	352	44.4	793	567
8	10	109	1.89	8.804	0.061	30	98	408	51.7	872	641

Shot Number SHN	Foot Forces Left Differenc [N] LVD	Right Vertical Before [N] RVB	Right Vertical After [N] RVA	Right Vertical Differenc [N] RVD	Left Horizontal Before [N] LHB	Left Horizontal After [N] LHA	Left Horizontal Differenc [N] LHD	Right Horizontal Before [N] RHB	Right Horizontal After [N] RHA	Right Horizontal Differenc [N] RHD	Right Elbow [degrees] REL
1	-219	390	573	183	-37	-56	-19	40	33	-7	125
2	-240	362	556	194	-33	-46	-13	34	49	15	127
3	-348	352	655	303	-39	-55	-16	40	51	11	120
4	-244	363	566	203	-35	-58	-23	40	54	14	122
5	-213	355	526	171	-37	-55	-18	39	56	17	125
6	-209	361	566	205	-25	-42	-17	26	41	15	129
7	-221	355	591	236	-25	-43	-18	24	47	23	129
8	-233	360	578	218	-32	-55	-23	30	54	24	128
9	-226	333	528	195	-30	-49	-19	31	52	21	130
10	-231	257	460	203	-20	-39	-19	21	40	19	126

Shot Number SHN	Left Elbow [degrees] LEL	Shoulder to line of fire Before [degrees] SLOFB	Shoulder to line of fire After [degrees] SLOFA	Shoulder to line of fire Differenc [degrees] SLOFD	Barrel Lift [degrees] BL	Left Hand Position [m] LHP	Feet Distance Apart [m] FDA	Mass Center Displ. [m] MCD	Recoil Energy [J] RE	Recoil Force [N] RF
1	72	31	29	2	0	0.314	0.398	0.071	16.0	262.4
2	75	31	29	2	0	0.316	0.398	0.076	17.5	286.9
3	74	33	32	1	0	0.317	0.398	0.117	17.2	276.7
4	68	31	29	2	0	0.313	0.398	0.079	17.3	283.2
5	65	31	29	2	0	0.336	0.398	0.068	16.5	271.0
6	63	33	29	4	0	0.313	0.398	0.072	17.0	269.4
7	70	31	29	2	0	0.316	0.398	0.080	16.7	273.3
8	75	31	29	2	0	0.325	0.398	0.079	15.6	256.2
9	78	27	26	1	0	0.333	0.398	0.074	16.1	277.3
10	74	31	29	2	0	0.320	0.398	0.076	17.9	293.5

Table B9

Kinetic and Kinematic Data for Subject Number 9

Subject Number	Shot Number	Mass	Height	Impulse	Recoil Distance	Impulse Duration	Preload	Peak Recoil Load	Grip force	Foot Forces Left Vertical Before	Foot Forces Left Vertical After
		[kg]	[m]	[Ns]	[m]	[ms]	[N]	[N]	[N]	[N]	[N]
SN	SHN	MASS	HEIGHT	IMP	RD	IT	PRE	PRL	GRIP	LVB	LVA
9	1	105	1.85	7.313	0.091	32	108	388	87.2	608	417
9	2	105	1.85	7.159	0.088	32	80	334	45.6	598	437
9	3	105	1.85	7.430	0.091	33	68	320	56.9	599	436
9	4	105	1.85	8.940	0.091	34	54	315	38.1	548	372
9	5	105	1.85	8.189	0.100	33	60	293	54.5	586	417
9	6	105	1.85	8.548	0.091	34	44	303	29.9	594	437
9	7	105	1.85	8.223	0.083	35	41	289	49.2	577	412
9	8	105	1.85	7.743	0.091	34	48	303	31.9	599	439
9	9	105	1.85	7.778	0.091	35	51	397	49.3	606	417
9	10	105	1.85	8.324	0.091	33	48	308	51.2	609	439

Shot Number	Foot Forces Left Differenc	Right Vertical Before	Right Vertical After	Right Vertical Differenc	Left Horizontal Before	Left Horizontal After	Left Horizontal Differenc	Right Horizontal Before	Right Horizontal After	Right Horizontal Differenc	Right Elbow
	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[N]	[degrees]
SHN	LVD	RVB	RVA	RVD	LHB	LHA	LHD	RHB	RHA	RHD	REL
1	-191	483	734	251	-31	-31	0	33	20	-13	97
2	-161	501	671	170	-35	-36	-1	35	31	-4	96
3	-163	486	648	162	-31	-33	-2	34	37	3	100
4	-176	535	729	194	-32	-35	-3	33	34	1	97
5	-169	500	681	181	-32	-34	-2	31	34	3	100
6	-157	492	661	169	-34	-34	0	32	37	5	99
7	-165	510	731	221	-33	-33	0	32	32	0	98
8	-160	500	658	158	-34	-34	0	34	32	-2	98
9	-189	494	679	185	-31	-32	-1	32	34	2	97
10	-170	488	679	191	-30	-32	-2	32	26	-6	99

Shot Number	Left Elbow	Shoulder to line of fire Before	Shoulder to line of fire After	Shoulder to line of fire Differenc	Barrel Lift	Left Hand Position	Feet Distance Apart	Mass Center Displ.	Recoil Energy	Recoil Force
	[degrees]	[degrees]	[degrees]	[degrees]	[degrees]	[m]	[m]	[m]	[J]	[N]
SHN	LEL	SLOFB	SLOFA	SLOFD	BL	LHP	FDA	MCD	RE	RF
1	41	26	22	4	3	0.266	0.374	0.073	20.8	228.5
2	42	28	22	6	3	0.260	0.374	0.056	19.7	223.7
3	40	26	22	4	4	0.269	0.374	0.056	20.5	225.2
4	41	26	22	4	4	0.269	0.374	0.063	23.9	262.9
5	40	24	21	3	4	0.267	0.374	0.060	24.8	248.2
6	42	26	22	4	4	0.266	0.374	0.056	22.9	251.4
7	41	25	24	1	4	0.270	0.374	0.064	19.5	234.9
8	43	26	22	4	4	0.267	0.374	0.054	20.7	227.7
9	40	26	22	4	4	0.259	0.374	0.064	20.2	222.2
10	41	26	22	4	4	0.265	0.374	0.061	23.0	252.2

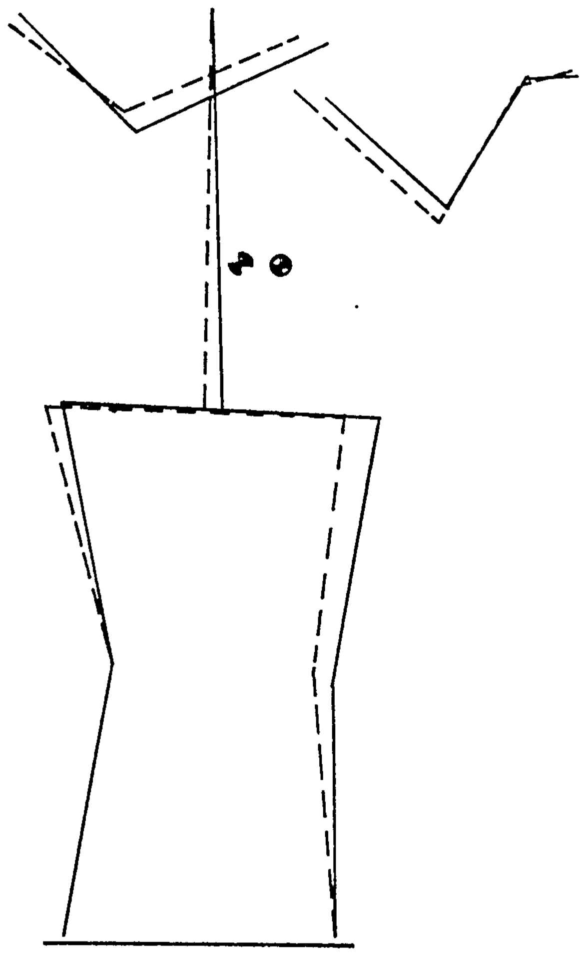


Figure B1: *Typical shooting posture of subject number 1*

◉	*Centre of mass before shooting*
◈	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
---	*Limb and trunk positions after shooting*

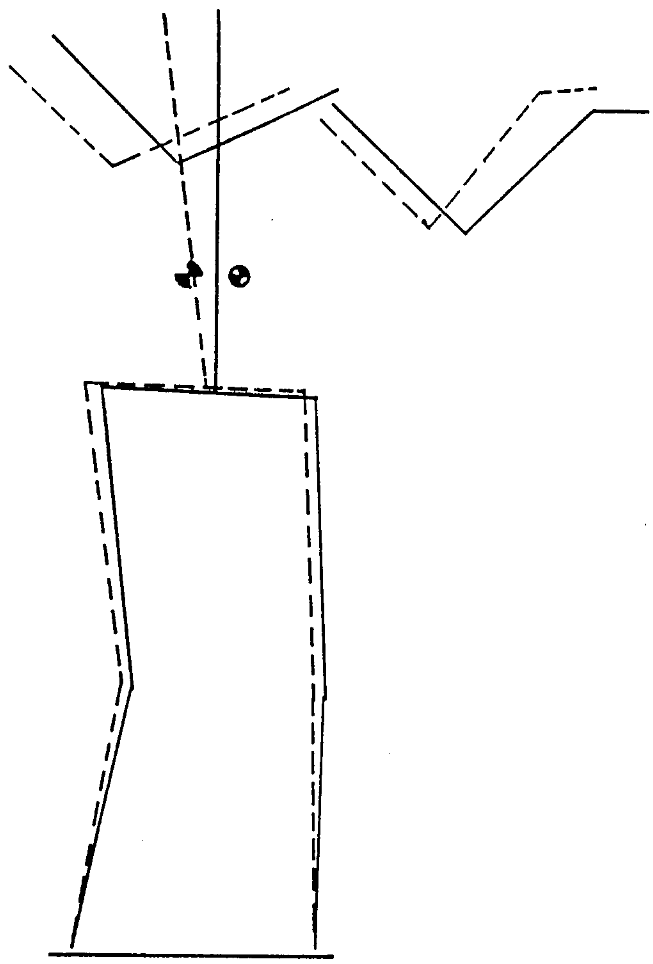


Figure B2: *Typical shooting posture of subject number 2*

◕ *Centre of mass before shooting*

✦ *Centre of mass after shooting*

—— *Limb and trunk positions before shooting*

--- *Limb and trunk positions after shooting*

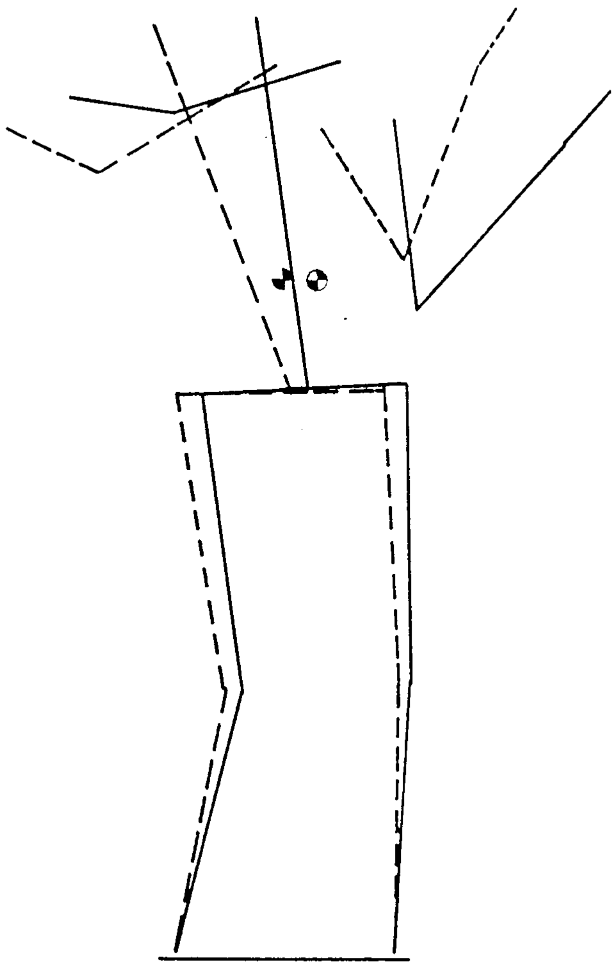


Figure B3: *Typical shooting posture of subject number 3*

◕	*Centre of mass before shooting*
◔	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
---	*Limb and trunk positions after shooting*

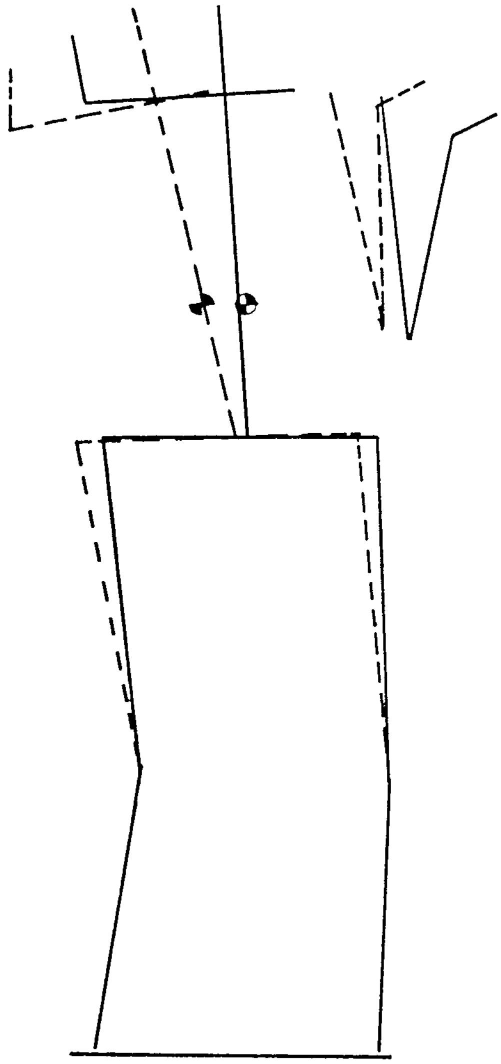


Figure B4: Typical shooting posture of subject number 4

◕	*Centre of mass before shooting*
◆	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
- - -	*Limb and trunk positions after shooting*

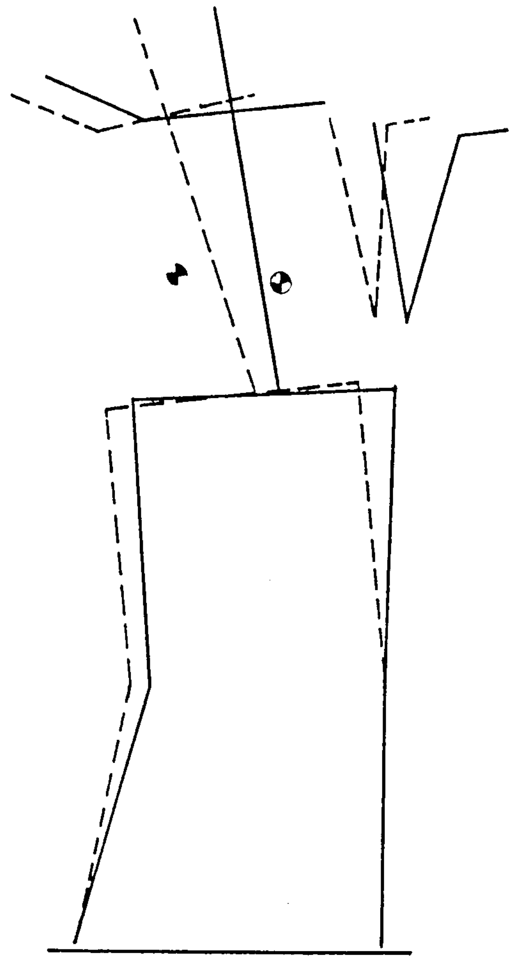


Figure B5: Typical shooting posture of subject number 5

◕	*Centre of mass before shooting*
◕	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
---	*Limb and trunk positions after shooting*

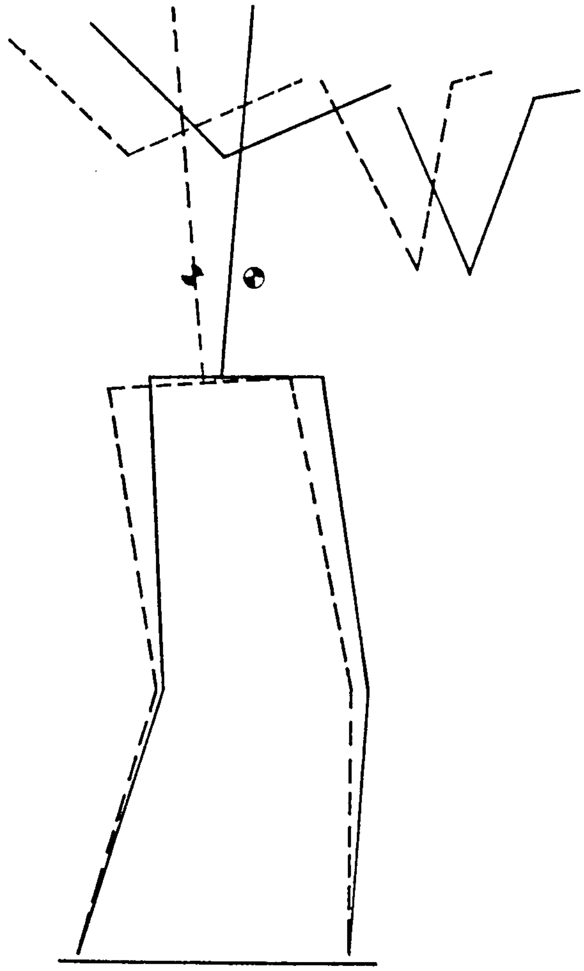


Figure B6: *Typical shooting posture of subject number 6*

●	*Centre of mass before shooting*
◆	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
---	*Limb and trunk positions after shooting*

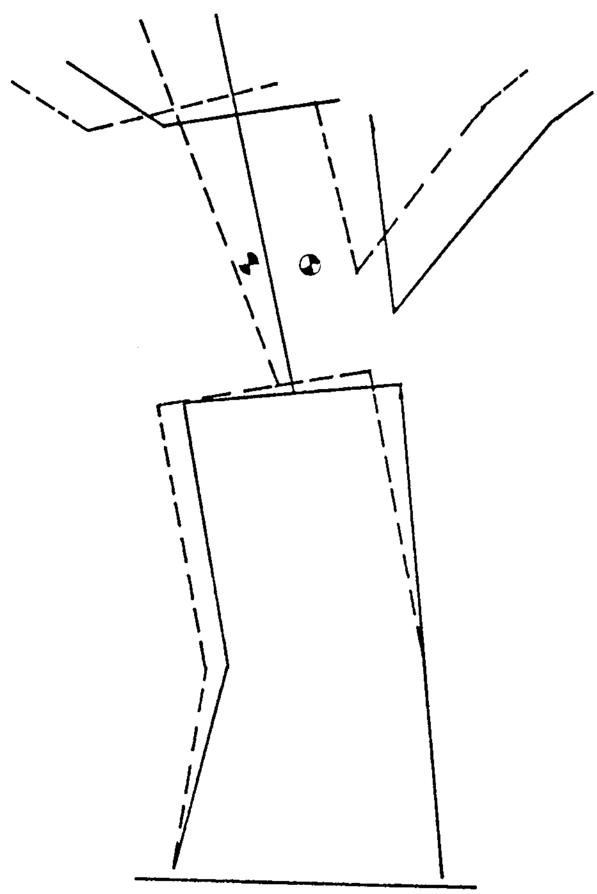


Figure B7: *Typical shooting posture of subject number 7*

◕	*Centre of mass before shooting*
◕	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
- - -	*Limb and trunk positions after shooting*

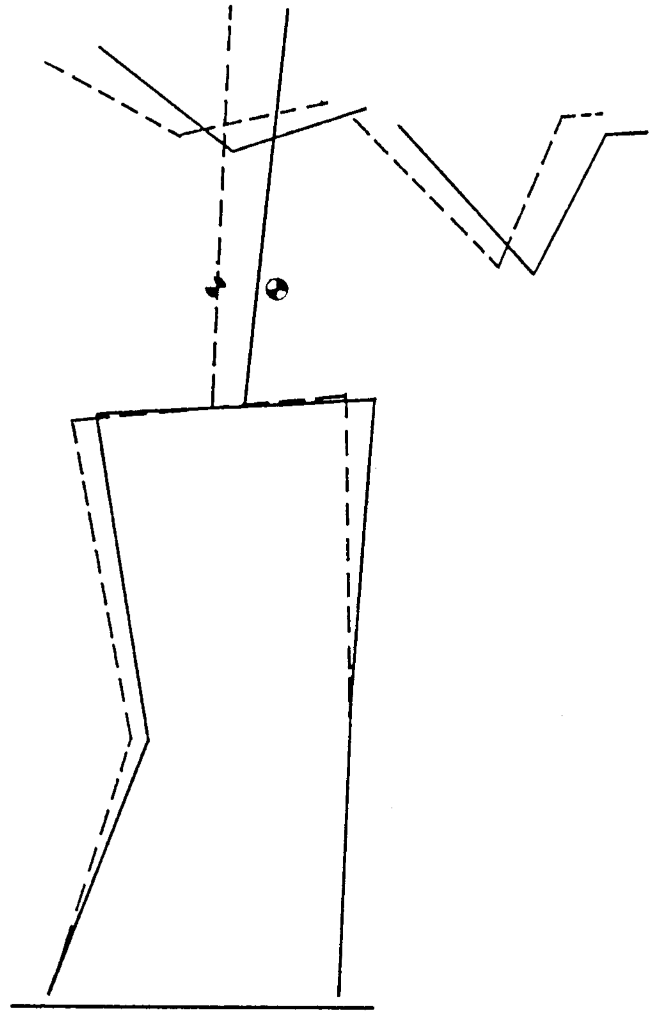


Figure B8: *Typical shooting posture of subject number 8*

◕	*Centre of mass before shooting*
◕	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
---	*Limb and trunk positions after shooting*

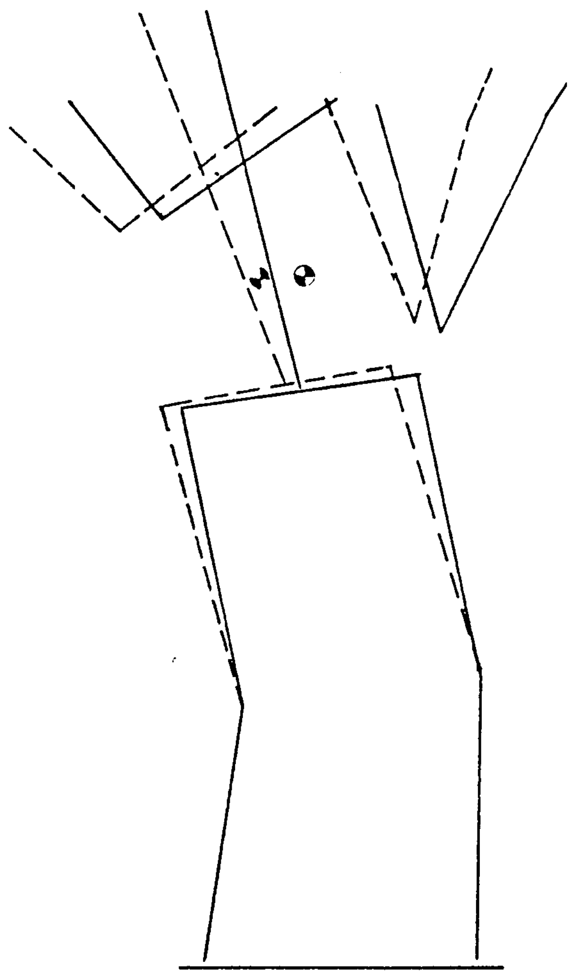


Figure B9: Typical shooting posture of subject number 9

◕	*Centre of mass before shooting*
◕	*Centre of mass after shooting*
——	*Limb and trunk positions before shooting*
- - -	*Limb and trunk positions after shooting*

B.1.3.1 Recoil energy

Table B10

Analysis of variance of recoil energy for 10 shots fired

Source of variance	*Sum of squares*	*df*	*Mean Square*	*F-ratio*
Between groups	*4982.2780*	*8*	*622.78475*	*140.069*
Within groups	*360.1470*	*81*	*4.44626*	
Total	*5342.4250*	*89*		

df=degrees of freedom

B.1.3.2 Preload, impulse duration and recoil force

Table B11

Analysis of variance of preload force for 10 shots fired by each of the 9 subjects

Source of variance	*Sum of squares*	*df*	*Mean Square*	*F-ratio*
Between groups	*75427.800*	*8*	*9428.4750*	*46.018*
Within groups	*16595.800*	*81*	*204.8864*	
Total	*92023.600*	*89*		

Table B12

Analysis of variance of impulse time for 10 shots fired by each of the subjects

Source of variance	*Sum of squares*	*df*	*Mean Square*	*F-ratio*
Between groups	*862.75556*	*8*	*107.84444*	*53.135*
Within groups	*164.40000*	*81*	*2.02963*	
Total	*1027.1556*	*89*		

Table B13

Analysis of variance of recoil force for 10 shots fired by each of the subjects

Source of variance	*Sum of squares*	*df*	*Mean Square*	*F-ratio*
Between groups	*54799.306*	*8*	*6849.9133*	*11.244*
Within groups	*49346.852*	*81*	*609.2204*	
Total	*104146.16*	*89*		

Linear regression analysis for impulse duration and preload force for each subject is presented in Table B14 to Table B22, and for all the subjects together in Table B23.

Linear regression analysis for recoil force and preload force for each subject is presented in Table B24 to Table B32, and for all the subjects together in Table B33.

Table B14

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 1 and analysis of variance of the model

Y-intercept	29.5306
Standard error of Y-intercept	14.0541
X-Coefficient (slope)	- 0.046313
Standard error of X-coefficient	0.121824
Correlation coefficient	- 0.13321
R-Squared (percent)	1.77

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	1.3060273	1	1.3060273	0.1445241
Error	72.293973	8	9.036747	
Total	73.6	9		

Table B15

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 2 and analysis of variance of the model

Y-intercept	29.4541
Standard error of Y-intercept	3.26938
X-Coefficient (slope)	1.53503E-3
Standard error of X-coefficient	0.0202393
Correlation coefficient	0.0268053
R-Squared (percent)	.07

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	.0101312	1	.0101312	.0057523
Error	14.089869	8	1.761234	
Total	14.100000	9		

Table B16

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 3 and analysis of variance of the model

Y-intercept	26.8684
Standard error of Y-intercept	2.7318
X-Coefficient (slope)	0.026822
Standard error of X-coefficient	0.0248176
Correlation coefficient	0.356937
R-Squared (percent)	12.74

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	1.2230810	1	1.2230810	1.1680485
Error	8.3769190	8	1.0471149	
Total	9.6000000	9		

Table B17

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 4 and analysis of variance of the model

Y-intercept	38.7001
Standard error of Y-intercept	1.78407
X-Coefficient (slope)	-0.0668856
Standard error of X-coefficient	0.0285428
Correlation coefficient	-0.637984
R-Squared (percent)	40.70

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	6.6751826	1	6.6751826	5.4912559
Error	9.7248174	8	1.2156022	
Total	16.400000	9		

Table B18

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 5 and analysis of variance of the model

Y-intercept	39.2671
Standard error of Y-intercept	7.95823
X-Coefficient (slope)	-0.0730594
Standard error of X-coefficient	0.10436
Correlation coefficient	-0.240262
R-Squared (percent)	5.77

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	.4675799	1	.4675799	.4900987
Error	7.6324201	8	.9540525	
Total	8.1000000	9		

Table B19

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 6 and analysis of variance of the model

Y-intercept	40.3706
Standard error of Y-intercept	2.42957
X-Coefficient (slope)	-0.0707771
Standard error of X-coefficient	0.0240947
Correlation coefficient	-0.720348
R-Squared (percent)	51.89

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	9.3921222	1	9.3921222	8.6286211
Error	8.7078778	8	1.0884847	
Total	18.100000	9		

Table B20

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 7 and analysis of variance of the model

Y-intercept	34.9922
Standard error of Y-intercept	1.04103
X-Coefficient (slope)	-0.0164311
Standard error of X-coefficient	0.0106282
Correlation coefficient	-0.47962
R-Squared (percent)	23.00

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	.5520857	1	.5520857	2.3900921
Error	1.8479143	8	.2309893	
Total	2.4000000	9		

Table B21

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 8 and analysis of variance of the model

Y-intercept	31.5243
Standard error of Y-intercept	4.38021
X-Coefficient (slope)	-0.0137516
Standard error of X-coefficient	0.0453148
Correlation coefficient	-0.10668
R-Squared (percent)	1.14

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	.1320155	1	.1320155	.0920932
Error	11.467985	8	1.433498	
Total	11.600000	9		

Table B22

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for subject number 9 and analysis of variance of the model

Y-intercept	36.0258
Standard error of Y-intercept	0.711025
X-Coefficient (slope)	-0.0419569
Standard error of X-coefficient	0.0112381
Correlation coefficient	-0.797087
R-Squared (percent)	63.53

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	6.671153	1	6.671153	13.938717
Error	3.8288474	8	.4786059	
Total	10.500000	9		

Table B23

Linear regression analysis for the model Y=a+bX of impulse duration in [ms] and preload force in [N] for all the subjects together and analysis of variance of the model

Y-intercept	37.7042
Standard error of Y-intercept	3.25645
X-Coefficient (slope)	-0.0650419
Standard error of X-coefficient	0.0320885
Correlation coefficient	-0.608156
R-Squared (percent)	36.99

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	31.90933	1	31.90933	4.10853
Error	54.36622	7	7.76660	
Total	86.27555	8		

Table B24

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 1 and analysis of variance of the model

Y-intercept	209.347
Standard error of Y-intercept	304.38
X-Coefficient (slope)	0.733914
Standard error of X-coefficient	2.63843
Correlation coefficient	0.0978735
R-Squared (percent)	.96

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	327.97132	1	327.97132	.07737
Error	33909.845	8	4238.731	
Total	34237.816	9		

Table B25

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 2 and analysis of variance of the model

Y-intercept	267.747
Standard error of Y-intercept	52.9669
X-Coefficient (slope)	-0.222639
Standard error of X-coefficient	0.327895
Correlation coefficient	-0.233429
R-Squared (percent)	5.45

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	213.12371	1	213.12371	.46104
Error	3698.1723	8	462.2715	
Total	3911.2960	9		

Table B26

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 3 and analysis of variance of the model

Y-intercept	309.546
Standard error of Y-intercept	39.9438
X-Coefficient (slope)	-0.428322
Standard error of X-coefficient	0.362878
Correlation coefficient	0.385125
R-Squared (percent)	14.83

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	311.89970	1	311.89970	1.39322
Error	1790.9613	8	223.8702	
Total	2102.8610	9		

Table B27

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 4 and analysis of variance of the model

Y-intercept	187.03
Standard error of Y-intercept	11.7712
X-Coefficient (slope)	0.572917
Standard error of X-coefficient	0.188323
Correlation coefficient	0.73237
R-Squared (percent)	53.64

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	489.75841	1	489.75841	9.25499
Error	423.34659	8	52.91832	
Total	913.10500	9		

Table B28

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 5 and analysis of variance of the model

Y-intercept	155.495
Standard error of Y-intercept	84.5424
X-Coefficient (slope)	1.07671
Standard error of X-coefficient	1.10864
Correlation coefficient	0.324758
R-Squared (percent)	10.55

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	101.55551	1	101.55551	.94322
Error	861.34849	8	107.66856	
Total	962.90400	9		

Table B29

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 6 and analysis of variance of the model

Y-intercept	132.592
Standard error of Y-intercept	29.1198
X-Coefficient (slope)	0.796672
Standard error of X-coefficient	0.288789
Correlation coefficient	0.698223
R-Squared (percent)	48.75

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	1189.9728	1	1189.9728	7.6102
Error	1250.9232	8	156.3654	
Total	2440.8960	9		

Table B30

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 7 and analysis of variance of the model

Y-intercept	305.027
Standard error of Y-intercept	25.6793
X-Coefficient (slope)	-0.543313
Standard error of X-coefficient	0.2622168
Correlation coefficient	-0.59103
R-Squared (percent)	34.93

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	603.63120	1	603.63120	4.29476
Error	1124.4048	8	140.5506	
Total	1728.0360	9		

B.1.3.2 Handgrip force

Table B34

Analysis of variance of handgrip force for 10 shots fired by each of 9 subjects

Source of variance	*Sum of squares*	*df*	*Mean Square*	*F-ratio*
Between groups	*46956.718*	*8*	*5869.5898*	*40.530*
Within groups	*11730.547*	*81*	*144.8216*	
Total	*58687.265*	*89*		

Table B35

Analysis of variance of left hand position distance for 10 shots fired by each of 9 subjects

Source of variance	*Sum of squares*	*df*	*Mean Square*	*F-ratio*
Between groups	*.2660622*	*8*	*.0332578*	*245.792*
Within groups	*.0109600*	*81*	*.0001353*	
Total	*.2770222*	*89*		

Table B36

Linear regression and analysis for the model Y=a+bX of grip force in [N] and left hand position distance in [m] for all the subjects together and analysis of variance of the model

Y-intercept	*-4.87348*
Standard error of Y-intercept	*32.692*
X-Coefficient (slope)	*256.861*
Standard error of X-coefficient	*125.647*
Correlation coefficient	*0.611421*
R-Squared (percent)	*37.38*

Analysis of variance

Source	*Sum of squares*	*df*	*Mean square*	*F-ratio*
Model	*1755.4118*	*1*	*1755.4118*	*4.1792*
Error	*2940.26*	*7*	*420.0371*	
Total	*4695.6718*	*8*		

B.1.3.4 Foot forces, rifle recoil, angular and linear displacements

A comparison of two samples procedure was used to determine whether the left horizontal foot force and the right horizontal foot force are of equal magnitude. The absolute values of the left and right foot forces were used in a Wilcoxon two-sample ranks test. The results are presented in Table B37.

Table B37

Result of ranks test for left and right horizontal foot forces before shooting

Number of positive differences	*29 avg. rank 35.6379*
Number of negative differences	*43 avg. rank 37.0814*
Large sample test statistic Z=	*1.57127*
Two-tailed probability of equaling or exceeding Z	*0.116119*
Total number of observations	*90 pairs*
Tied pairs ignored	*18*

The large sample test statistic and the probability values from Table B37 indicate no statistically significant difference between the medians of the left and right horizontal foot forces.

Table B38 presents the results of a simple regression analysis with the left horizontal foot force as dependent variable and right horizontal foot force before shooting as independent variable.

Table B38

Linear regression analysis for the model Y=a+bX of the left horizontal foot force before shooting in [N] and the right horizontal foot force before shooting in [N] for all the subjects together and analysis of variance of the model

Y-intercept	*-0.668392*
Standard error of Y-intercept	*0.455592*
X-Coefficient (slope)	*-0.963229*
Standard error of X-coefficient	*0.0161488*
Correlation coefficient	*-0.99*
R-Squared (percent)	*97.59*

Analysis of variance

Source	*Sum of squares*	*df*	*Mean square*	*F-ratio*
Model	*9869.0158*	*1*	*9869.0158*	*3557.7660*
Error	*244.10638*	*88*	*2.77394*	
Total	*10113.122*	*89*		

For 1 and 88 degrees of freedom F values greater than 6.93 and 3.95 are statistically significant for levels 0.01 and 0.05 respectively.

Table B31

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 8 and analysis of variance of the model

Y-intercept	280.462
Standard error of Y-intercept	43.2771
X-Coefficient (slope)	-0.0568257
Standard error of X-coefficient	0.447717
Correlation coefficient	-0.044829
R-Squared (percent)	.20

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	2.2542743	1	2.2542743	.0161095
Error	1119.4747	8	139.9343	
Total	1121.7290	9		

Table B32

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for subject number 9 and analysis of variance of the model

Y-intercept	254.422
Standard error of Y-intercept	14.6951
X-Coefficient (slope)	-0.27794
Standard error of X-coefficient	0.232262
Correlation coefficient	-0.389646
R-Squared (percent)	15.18

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	292.74825	1	292.74825	1.43200
Error	1635.4608	8	204.4326	
Total	1928.2090	9		

Table B33

Linear regression analysis for the model Y=a+bX of recoil force in [N] and preload force in [N] for all the subjects together and analysis of variance of the model

Y-intercept	229.196
Standard error of Y-intercept	31.906
X-Coefficient (slope)	0.185967
Standard error of X-coefficient	0.3144
Correlation coefficient	0.218179
R-Squared (percent)	4.76

Analysis of variance

Source	Sum of squares	df	Mean square	F-ratio
Model	206.85675	1	260.85675	0.34987
Error	5219.0739	7	745.5820	
Total	5425.93065	8		

Table B39

Stepwise selection result for recoil energy

Variables in the model		Variables not in the model	
Variable	F-ratio	Variable	F-ratio
LVD	23.58	RVD	0.84
MCD	35.13	RHD	1.93
FDA	10.68	LHD	0.43
SLOFD	15.30	REL	0.00
BL	22.59	LEL	1.46

Table B40

Regression results of the model for recoil energy

Independent variable	Coefficients	Standard error	R-squared
Constant	32.44839	3.80909	
LVD	0.04334	0.008926	0.9145
MCD	82.86430	13.981388	
FDA	-33.89685	10.371382	
SLOFD	0.67885	0.17356	
BL	0.76491	0.160937	

Table B41

Analysis of variance for the full regression model of recoil energy

Source	Sum of squares	df	Mean square	F-ratio
Model	4885.79	5	977.157	179.751
Error	456.639	84	5.43618	
Total	5342.429	89		

Table B42

Additional analysis of variance indicating the contribution to the total regression sum of squares that was attributable to each variable when it entered the regression

Source	Sum of squares	df	Mean square	F-ratio
LVD	2656.6633	1	2656.6633	488.70
MCD	384.7781	1	384.7781	70.78
FDA	514.3176	1	514.3176	94.61
SLOFD	1207.2245	1	1207.2245	222.07
BL	122.8021	1	122.8021	22.59
Total	4885.7856	5		

Notes: