CRESST REPORT 756

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DEVELOPMENT OF SENSOR-BASED MEASURES OF RIFLE MARKSMANSHIP SKILL AND PERFORMANCE

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National Center for Research on Evaluation, Standards, and Student Testing

Graduate School of Education & Information Studies
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DEVELOPMENT OF SENSOR-BASED MEASURES OF RIFLE MARKSMANSHIP SKILL AND PERFORMANCE[1]

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Abstract

Measures of rifle marksmanship skill and performance were developed using a prototype instrumented laser-based training system. Measures of performance were derived from laser strikes on a video-projected target. Measures of rifle marksmanship skill—breath control, trigger control, and muzzle wobble—were developed from shooters' breathing and trigger squeeze patterns. Existing marksmanship instructional materials and expert shooters' breath and trigger control profiles guided the development of the skill measures. A shooter's breath control was described as where and how long into the respiratory cycle the trigger broke. A shooter's trigger control was described as the duration of the trigger squeeze. A shooter's muzzle was described as the total acceleration during the two seconds prior to the shot. The use of sensor-based measures provides insight into exactly how a shooter is executing two of the three skills considered to be the fundamentals of rifle marksmanship.

Introduction

One of the most remarkable achievements in modern marksmanship training and weaponry is in developing a shooter's skill to routinely hit a 19-inch circular area at 500 yards in the prone position. What makes this achievement even more remarkable is that virtually any deviation of the rifle from the center line will result in a miss. A rifle muzzle deflection of 1/16 inch from the center line will result in the bullet strike being off by over 2 feet at 500 yards. Adding to this complexity are uncontrollable factors such as wind velocity, gravity, and ammunition ballistics. Variations in the amount of propellant across bullets result in 10-inch shot groups at 300 yards for skilled shooters (U.S. Army, 2003).

These examples do not take into account factors associated with the shooter—perhaps the most variable component. Normal breathing in the standing position can displace the rifle muzzle 1/2 inch from inhale to exhale, while changes due to heart pulse can also displace the muzzle a fraction of an inch. If a shooter's sight alignment is off by a fraction of an inch, the shooter is unlikely to hit the target. Fatigue decreases performance by causing shaking, wobble, or other instabilities; flinching or bucking due to recoil or reaction to the report

[1]We would like to thank the staff at Camp Pendleton WTBN. We would also like to thank Joanne Michiuye from UCLA/CRESST for her help with the preparation of this manuscript and with data collection.

causes the shooter to jerk the rifle, as does yanking the trigger. Exacerbating position instability is the emotional state of the shooter—anxiety can increase the heart and breathing rates.

Thus, accurately and consistently hitting a target is a complex interaction of physical and mental processes immediately before, during, and immediately after the weapon fires. Effective shooting is the simultaneous coordination between breathing; gross-motor control of positioning the hands, elbows, legs, feet, and cheek; fine-motor control of the trigger finger with respect to the trigger; and the processing of perceptual cues related to the target, the front sight, and the rear sight. The coordination is intended to minimize muzzle movement by controlling body movement, particularly important while under the stress of high-stakes qualification.

Measurement of Rifle Marksmanship Skills

In this study, we focused on developing techniques to measure two of the three fundamentals of rifle marksmanship, breath control and trigger control, and to measure overall steadiness (U.S. Army, 2003; USMC, 2001). We focused on these skill components because of the importance of these measures—simple as they are—to the consistency of shot placement. For training purposes, breath and trigger control are typically unobservable to the coach. Thus, the development of a sensing system to measure these skills would be potentially valuable as a training aid for both the coach (for diagnosing shooter skills) and the shooter (as augmented feedback on their performance). In an earlier design study, Chung, Dionne, and Elmore (2006) developed a prototype system that used sensors to measure breath control, trigger control, flinch, and rifle steadiness. We adopted and expanded their approach to develop shot group precision, breath control, trigger control, and muzzle wobble.

The following section provides a systems-level view of how the various sensing components, data processing, data files, and data extraction components interact. The next section describes the development of measures of trigger control, breath control, and steadiness. For each measure, we describe the methodology and data processing used to extract the skill measure from the raw sensor data. The last section describes a pilot test of the system with marksmanship experts. We present experts' trigger control and breath control profiles. We conclude with a brief discussion of the implications of this work.

Sensing Apparatus

Most of the equipment and software were built or customized in our lab. A laptop with Intel® Core™ 2 Duo and 2 gigabytes of memory running Microsoft™ Windows XP was used for data collection. Data collections were performed in a room that was minimum 300

inches (8.33 yards, 7.62 meters) in length and wide enough to accommodate equipment and several people. Participants included novice and expert rifle marksmen.

The sensing apparatus consisted of a LaserShot rifle simulation system (LaserShot, 2008). The rifle trainer approximates the size and mass, about 8 pounds, of an M4 rifle. The LaserShot weapon contains a CO_2 gas recoil system that simulated the kick of the weapon. The weapon came fitted with an infrared laser inserted into the muzzle of the rifle. The internal circuitry that triggered the laser was tapped for the trigger break signal. The rifle was also instrumented, in house, with a force pressure sensor on the trigger to measure trigger squeeze and a 3-axis accelerometer on the muzzle to measure wobble. External to the weapon was a pressure cuff to measure shooter respiration. The system diagram in Figure 1 shows the relation among sensors, data processing components, and output data files.

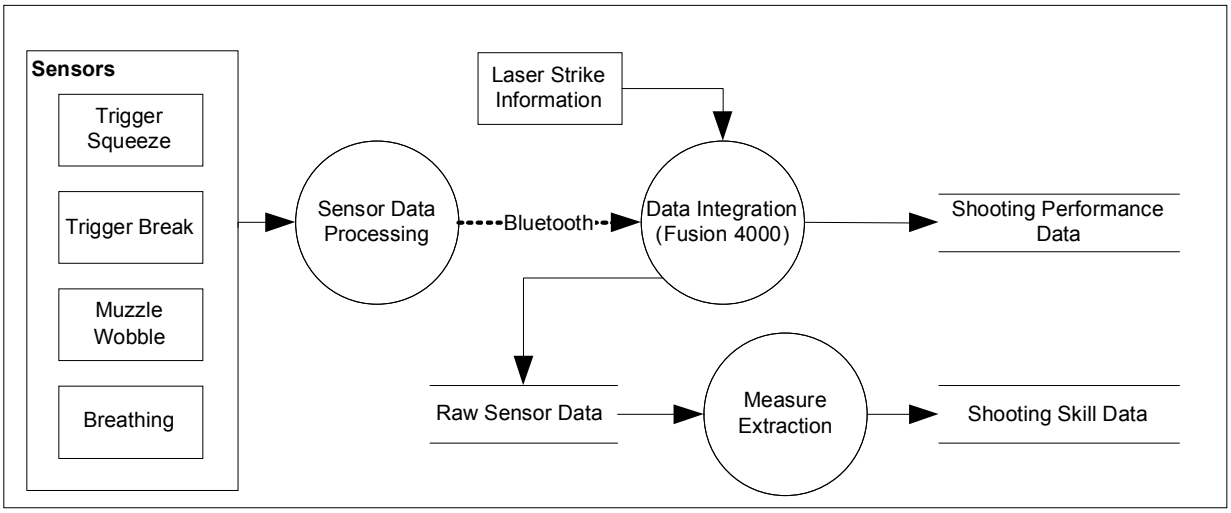

Figure 1. LaserShot rifle simulation; system data flow diagram.

Data flow. The sensor data processing unit was designed in-house and contains circuitry related to the sensor signals (e.g., signal conditioning, amplifiers) and a microcontroller. The microcontroller sampled the sensor signals at a rate of 128 samples/sec with a 10-bit resolution. The sensor data (i.e., each sample of each sensor) were packaged into a data frame and sent via Bluetooth to a data integration laptop.

To determine shooting performance, the rifle's built-in infrared laser, accompanying infrared camera, and digital projector were used. The LaserShot simulation system included an infrared detecting camera and a digital projector. The LaserShot system included software to calibrate the camera onto the digitally projected screen area. Once calibrated and enabled, the infrared detecting camera generates a mouse-click at the location of where it detected an

infrared signal. A data integration program, Fusion 4000, was developed to display a target and to collect shot performance data based on mouse-click location.

Fully developed in-house, Fusion 4000 is a combination of earlier data collection applications and was intended to streamline the data collection process. Setting up the targeting system to collect shooting performance and also to interface with the microcontroller to collect sensor data is possible with this program. Data collection within a single application enabled proper synchronization and logging of the data.

The sensor data and shooting performance data are stored in two separate files. The sensor data log file stores all the raw data from the microprocessor plus bookkeeping and shot markers. The shot performance data log stores shot locations in raw pixel coordinates as well as converted "at the range" coordinates. Fusion 4000 also enabled the instantaneous calculation of shot performance measures at the completion of each trial. The shot performance data log contains measures such as the coordinates of the shot group center, how far each shot is to its shot group center, and the mean distance of all shots in a shot group to the shot group center.

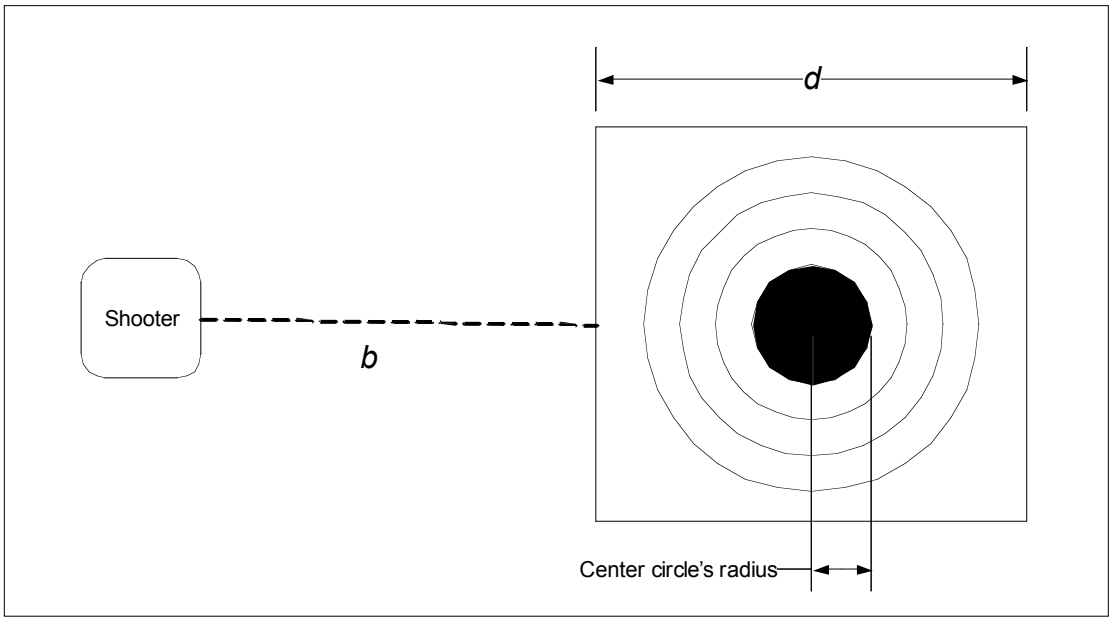

Figure 2. Target.

$$\text{center circle's radius} = \frac{abc}{2de} \qquad \text{(Eq. 1)}$$

where

a = Distance, in inches, from the shooter's eye to the LCD-projected target

b = Diameter, in inches, of the **range** target's center circle

c = Width, in inches, of the LCD-projected image

d = Shooting distance, in inches, that is being simulated. This is the simulated distance.

The target (Figure 2) was digitally projected to simulate a target 20 inches wide on a 200-yard (7200-inch, 182.88-meter) shooting range. Since data collections were performed in a room at least 8.3 yards (~300 inches) long, the digitally projected image of the target had to be scaled. Equation 1 was derived using similar triangles to scale the target. The actual calculation and scaling were performed by Fusion 4000. In order for Fusion 4000 to scale the target correctly, first, we had to make sure that the projected screen area was very close to being square. This was determined by taking measurements of the top and bottom of the image projected on screen. Next, we measured and recorded the center width of the projected screen. Lastly, we measured and recorded the distance of the projection screen to the location of the shooter. We entered these values along with the desired "at the range" measurements into the software. The "at the range" measurements are values, in inches, of how far we are simulating the shooter to be shooting from as well as the diameter of the center circle, 8 inches, of the target at the firing range. The software also calculates and uses the projected screen's pixel resolution in the calculation.

Shot performance is scaled to "at range" conditions using a similar equation for determining the radius of the digitally projected target.

$$\textit{correction coefficient} = de/ab \qquad \text{(Eq. 2)}$$

Equation 2 shows the correction coefficient needed to transform pixel values into physical dimensions at the "at range" distance. Equation 2 uses the same values as Equation 1. This correction coefficient is multiplied against the pixel location of the detected shot.

Development of Measures

This section describes the measures that were developed and subsequently used to model expert skill performance (Nagashima, Chung, Espinosa, Berka, & Baker, 2009). The measures are summarized in Table 1. MATLAB™ on a desktop with an Intel® Core™ 2 Duo processor and 3 gigabytes of memory running Microsoft™ Windows XP was used to

post-process data. The computations for each measure involve analyzing sensor data shot by shot and trial by trial.

Table 1

Description of Measures

Measure	Unit	Description
Shot group precision	in	The mean distance of shots from the shot group center.
Trigger control-onset	sec	The time since the start of the trial, when the trigger was initially pulled.
Trigger control-duration	sec	The amount of time that the trigger was being pulled.
Steadiness	–	The mean value of the wobble data two seconds prior to trigger break.
Breath control-duration	sec	The amount of time between respiration maxima (peaks) surrounding a trigger break.
Breath control-location	–	The proportion of the trigger break's location between the two respiration maxima (peaks).

Figure 3 shows the general steps taken to derive measures from the sensor data. First, all sensor data were cleaned. Cleaning the data involved removing sensor data artifacts caused by the microprocessor or computer processing of microprocessor data, removing trials with less than five shots, and synchronizing any trials that had missing shots in the sensor data. Some of the cleaning was done manually. After cleaning, the data were imported into a database. Each shot was identified by a unique shooter ID as well as a trial number. At the start of each trial iteration, the trial data were pulled from the database and the process shown in Figure 3 was followed. At the end of the trial iteration, the measures were appended to a comma-delimited file.

Smoothing was done using triangular smoothing with a quarter-second window prior to running the algorithms to compute the measures. This was chosen empirically after reviewing multiple trials.

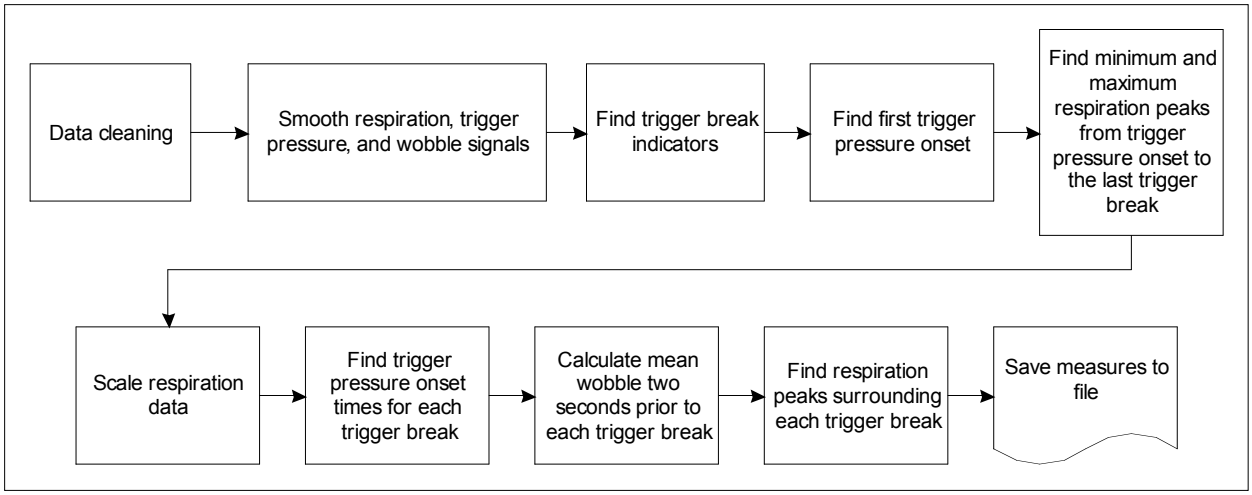

Figure 3. Process performed for every trial.

Shooting Performance Measure

Shooting performance was captured by shot group precision, which reflects how well a shooter can *consistently* apply the fundamentals of rifle marksmanship. Such measures have been found to correlate with shooting performance (Taylor, Dyer, & Osborne, 1986). Johnson (2001) defined precision as dispersion of shots within a shot group (D_{SG}) as shown in Table 2. Higher values of D_{SG} indicate greater dispersion of shots within a trial and poorer performance.

Table 2

Shot Group Precision Measures (modified from Johnson, 2001)

Measure	Symbol	Formula	Interpretation
Center of shot group	SG_x	$\frac{\sum_{i=1}^{N} x_i}{N}$	Center of *N* shots, *x* coordinate.
	SG_y	$\frac{\sum_{i=1}^{N} y_i}{N}$	Center of *N* shots, *y* coordinate.
Distance of each shot to the center of the shot group	d_{SG}	$\sqrt{(x_i - SG_x)^2 + (y_i - SG_y)^2}$	
Mean distance of *N* shots to the center of the shot group	D_{SG}	$\frac{\sum_{i=1}^{N} d_{SG_i}}{N}$	This is the measure of precision and reflects the mean dispersion across all shots with respect to the center of the shot group.

Note. N = number of shots. x_i and y_i = location of *i*th shot.

Breath Control Measures

Respiration location at trigger break. Firing while breathing can cause rounds to disperse vertically on the target due to the muzzle being displaced as the lungs expand and contract during the breathing cycle. To determine where the breath was located during the shot, the minimum and maximum values of the respiration data were determined. The minimum and maximum values were identified by analyzing the respiration data starting from the first trigger squeeze onset to the last trigger break in the trial. Finding the trigger squeeze onset is described in the next section. A simple peak detection algorithm was used to find the extrema. An example of this is shown in Figure 4. The delimited region specifies the range of breath data examined.

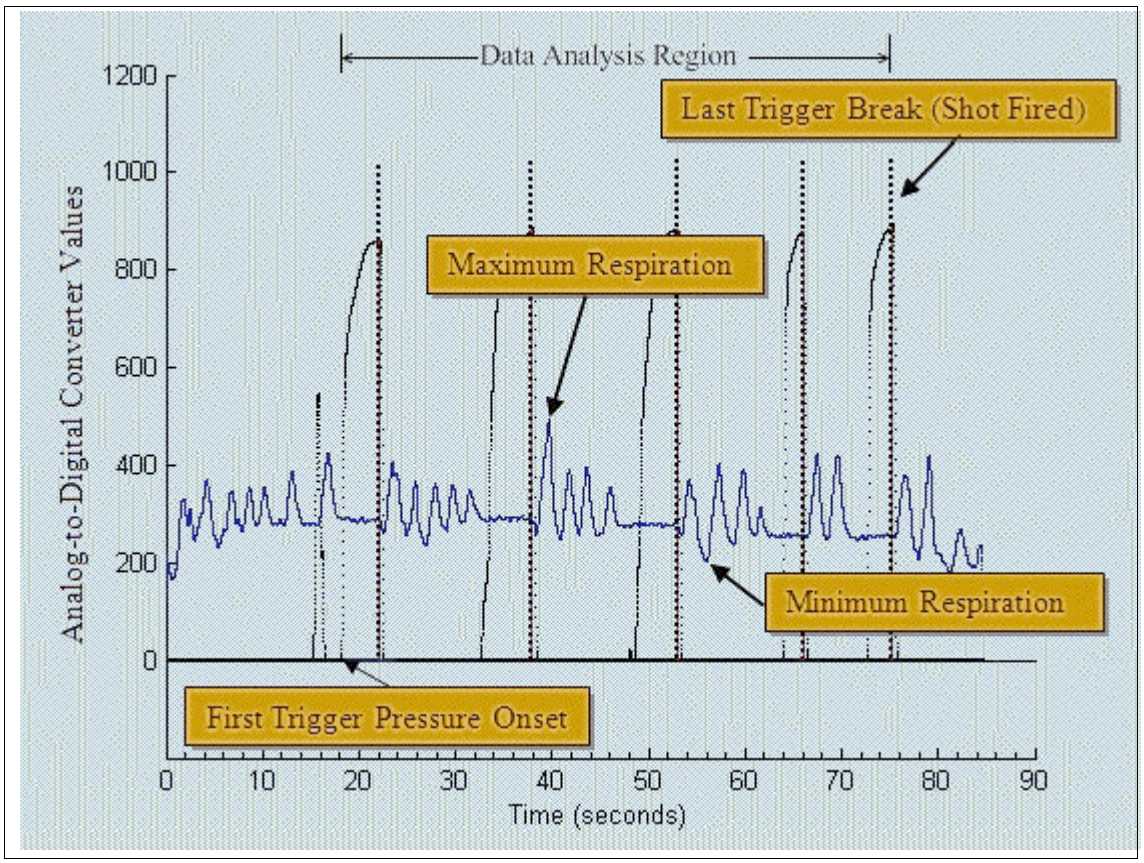

Figure 4. Example of trigger squeeze, respiration, and shot markers.

Once the minimum and maximum respiration values were found, the respiration data were scaled to lie between 0 and 1 on the *y*-axis as shown in Figure 5. The equation used to scale the data is given as: [(*Respiration Data – minimum*)/(*maximum – minimum*)].

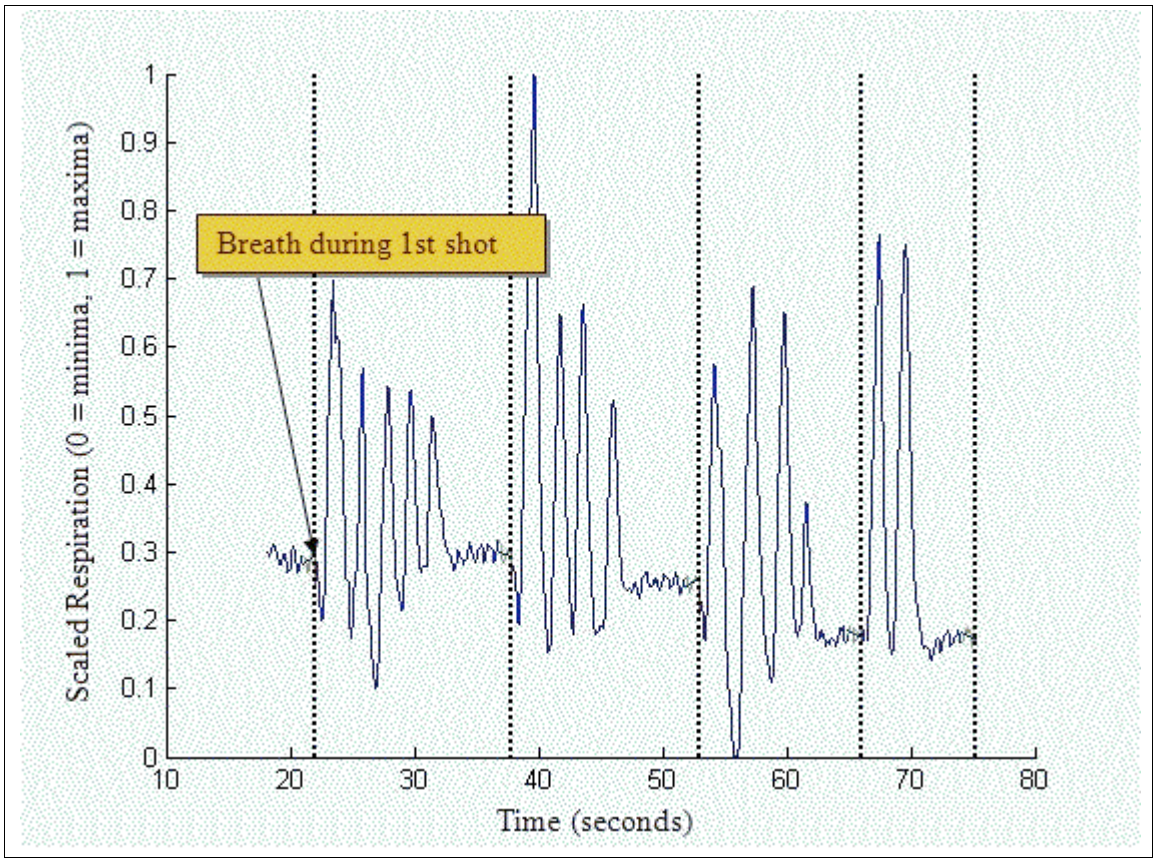

Figure 5. Scaled respiration data with trigger break markers.

After scaling the respiration data, the location of the shooter's breath is found by taking the point that corresponds to when the shot was fired. Figure 5 points out the location of the shooter's breath when the first shot was fired.

Breath duration. The algorithm used to determine the breath duration uses the scaled respiration data (as shown in Figure 5). The algorithm works by locating the maximum peak to the left and right of a trigger break. The locations of the peaks represent start and end times for a single respiratory cycle. Figure 6 points out the peak values that are used to determine the breath duration of shot number two. The algorithm also detects cases when peaks cannot be found. There are two special checks for the first and last trigger break to account for incomplete breath data or for cases when a peak cannot be found. Whenever peaks cannot be found, the default breath duration will be set to 0.

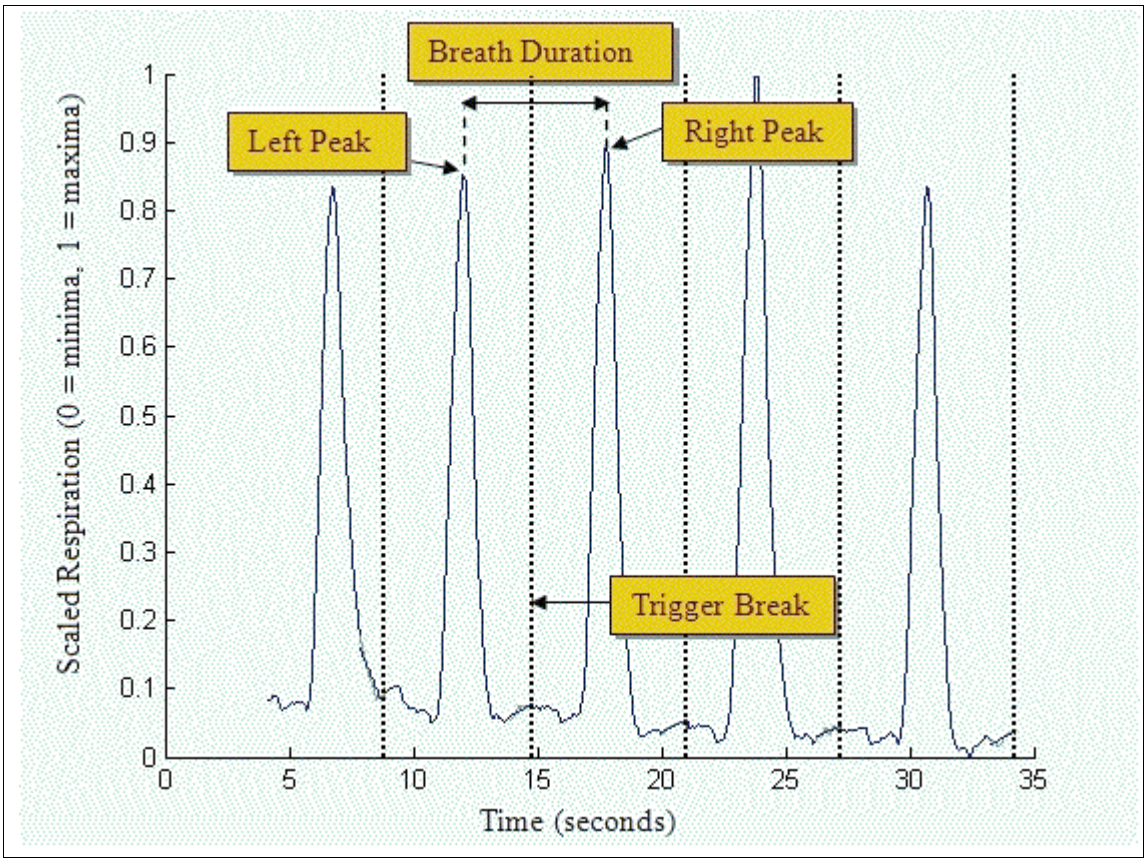

Figure 6. Breath duration (focused on second trigger break).

Shot percent in breath. This calculation relies on the breath duration in conjunction with the trigger break time. Shot percent in breath represents a ratio relating the time of the trigger break to the breath duration. For trigger break at time T_{TB}, breath duration right peak at time T_{RP}, and breath duration left peak at time T_{LP}, the shot percent in breath is defined as $\frac{T_{TB}-T_{LP}}{T_{RP}-T_{LP}}$. This translates roughly to the time of trigger break divided by time between two inhales. This value represents the relative location of a trigger break within the respiratory cycle.

Trigger Control Measures

Proper trigger control during slow fire is important because yanking the trigger will cause the weapon to sway laterally.

Trigger squeeze onset. The trigger squeeze onset value was recognized using a sliding window technique. The algorithm works backwards from the trigger break using a 0.25-second sliding window until the average of the data falls below 2 as shown in Figure 7. The count value of 2 was chosen empirically after examining trigger squeeze data visually for

many trials. Inherent noise from the data signal prevented absolute indications of no activity. Figure 7 demonstrates the algorithm. The dark rectangle in the middle of the figure represents the 0.25-second sliding window. When the sliding window calculates a mean below 2, the location of the right border, or trailing edge, of the sliding window is identified as the trigger pull onset.

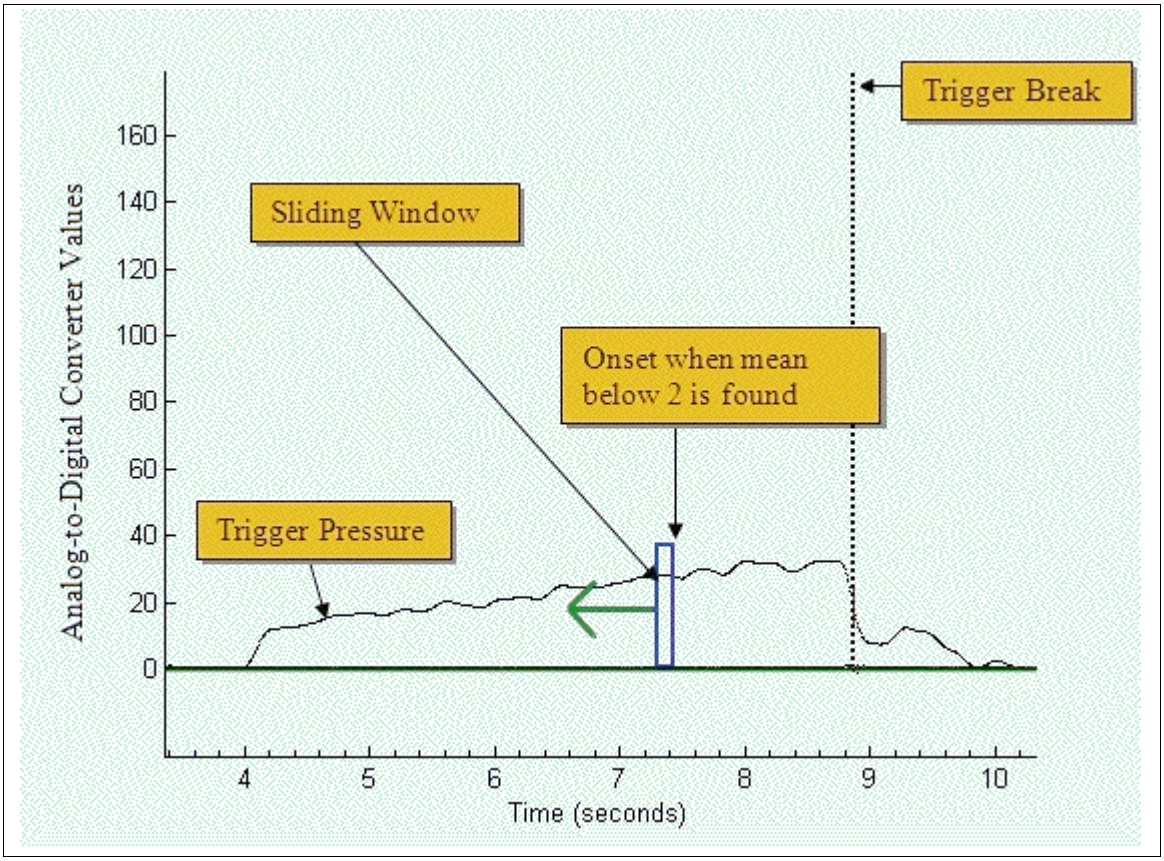

Figure 7. Trigger pull onset algorithm.

Two safety checks were used in the algorithm to ensure accurate identification of trigger pull onset. If the sliding window has reached the beginning of the trial and fails to identify a mean less than 2, the onset is set to the beginning of the trial at time 0. Second, if the sliding window has reached the previous trigger break and fails to find a mean less than 2, the onset is set to the data point after the previous trigger break.

Trigger squeeze duration. Once the trigger squeeze onset was established, duration was calculated. The knowns at this point are the trigger break time, T, and the trigger squeeze onset, P. Thus, trigger squeeze duration is simply $T - P$.

Steadiness

Muzzle wobble. The wobble is simply the mean of the acceleration's magnitude data two seconds prior to trigger break. For trigger break at time T, the range of data used was [T – 2 seconds, T]. The accelerometer used was a 3-axis accelerometer. Magnitude was calculated as the Euclidean norm.

Pilot Study: Experts' Breath and Trigger Control Profiles

We tested the sensing apparatus with rifle marksmanship coaches currently serving in the armed forces. The purpose of the study was to test the feasibility of the system and to gather skill data—trigger control, breath control, and steadiness—from acknowledged experts. The skill data would then be used to establish performance ranges for each measure, which could then be used to compare novice performance. Shot group precision data were not collected.

Sample. Thirteen expert marksmanship coaches were recruited to provide reference performance data. Our sample of expert shooters have on average 5 years of armed forces experience, come from infantry units, frequently fire a rifle as part of their armed forces duties, and rarely fire a rifle for recreation. All experts completed the marksmanship coaches course and all experts are currently full-time marksmanship coaches. Twelve of the 13 experts qualified "expert" in their most recent armed forces qualification, and the average qualification score for the sample is 231 (SD = 6.6), with a range of 219–240 (the score range for "expert" is 220–250).

Task. Using the instruments described below, sensor data were collected from expert marksmen. Shots were taken in the kneeling position, with five shots constituting a single trial. Five trials worth of data were collected.

Trigger control. To determine the range of trigger squeeze durations, experts' trigger squeeze data were examined. The scaling procedure began with first scaling all the trigger squeeze data so that they all have the same value at the time of the trigger break. This was done by multiplying each trigger squeeze, i, by 300 / $m(i)$ where $m(i)$ is the value of each trigger squeeze at the time of the trigger break. The value 300 was chosen empirically. Next, we dropped the shots that either had extremely low values (possibly caused by the touch pad's loss of sensitivity) or extremely high values (possibly caused by a glitch). Finally, we eliminated trigger squeezes that had spiked only at the trigger break, again possibly due to the sensor's loss of sensitivity. After filtering out extreme trigger squeeze profiles, about 100 expert trigger squeezes remained. Figure 8 shows the set of trigger squeezes, sorted by trigger squeeze onset time. The longest trigger squeeze is shown at the top of the plot

(approximately 11 seconds) and the shortest trigger squeeze is shown at the bottom of the plot (approximately 1 second). The axis perpendicular to the plane represents the magnitude of the pressure on the trigger sensor.

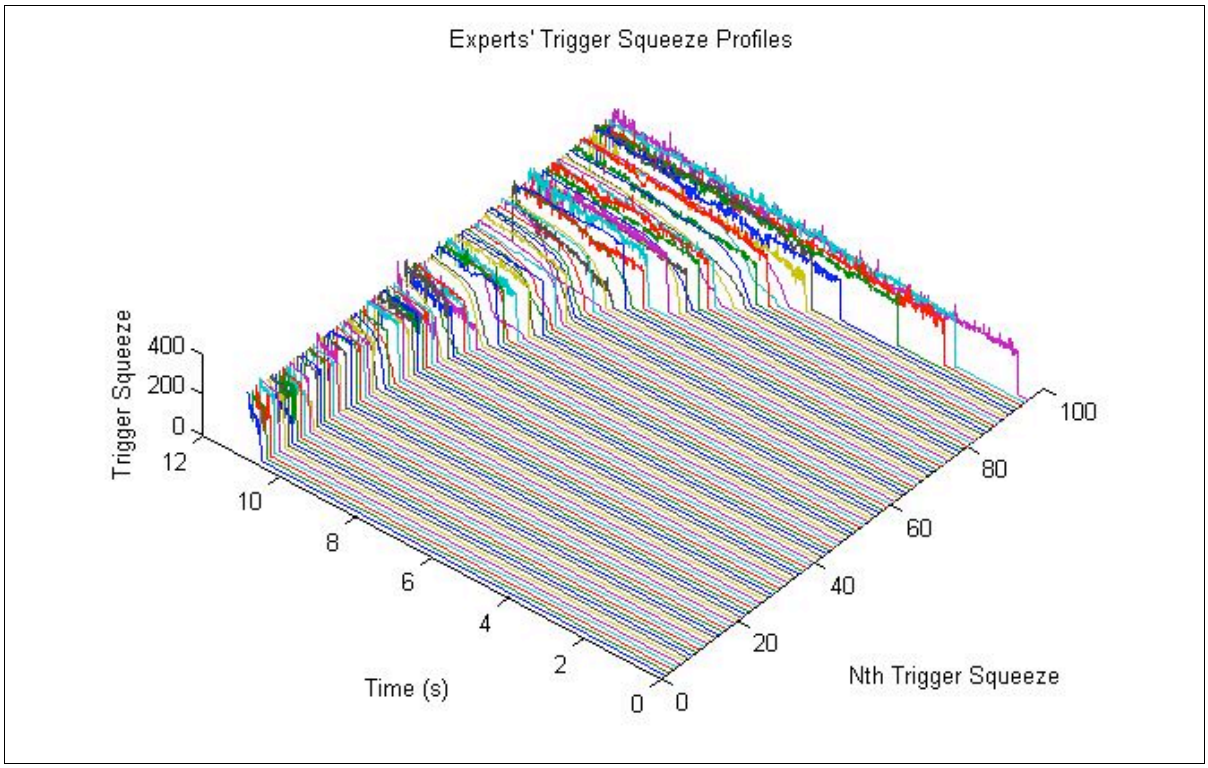

Figure 8. Trigger control sensor.

Breath and trigger control. Another view of experts' trigger control is seen in Figure 9 (bottom set of signals). Figure 9 shows an overlay of experts' breathing and trigger squeeze signals. Note the extremely high consistency in experts' breathing—*always* firing during the natural respiratory pause.

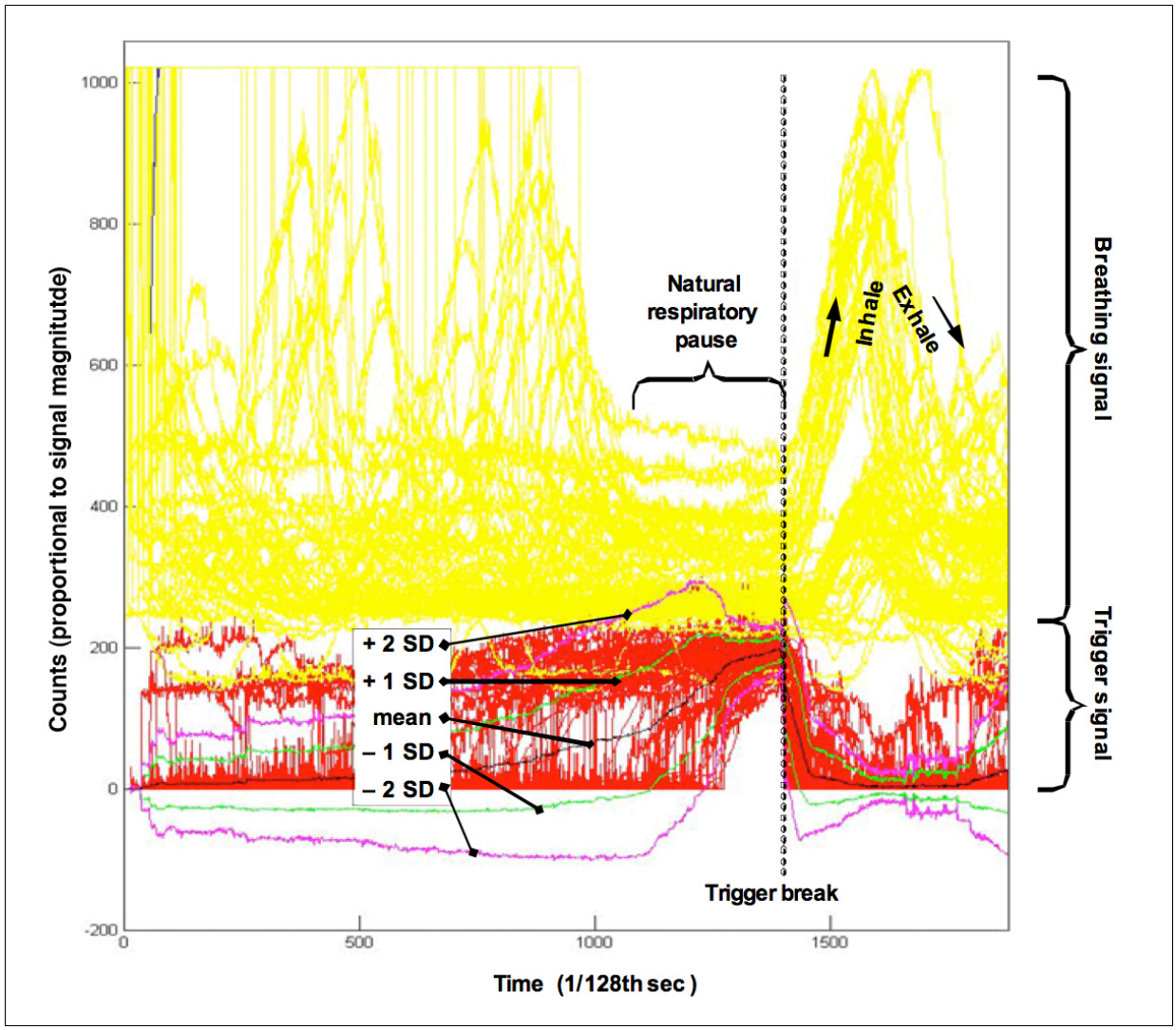

Figure 9. Overlay of experts' breath and trigger sensor signals, aligned to trigger break.

Discussion. Qualitatively, experts' breath control and trigger control appear consistent with existing relevant marksmanship instructional materials (USMC, 2001). That is, proper breath control is firing during the natural respiratory pause, and proper trigger control involves squeezing rather than jerking the trigger. The regularity of experts' breath and trigger control sensor signals suggested to us several measures that might discriminate between experts and novices, and guided the development of the specific measures. For example, for breath control we focused on measuring when in the breathing cycle the shot was taken and the duration between inhales. For trigger control, we focused on the start of the trigger squeeze and duration of the trigger squeeze. Taken together, we expected these measures to provide sufficient information to describe novices' breath control and trigger control.

Discussion

The analysis of expert data helped to determine the criteria for thresholds and patterns in developing the algorithms used to calculate the measures of skill performance. By examining both individual and aggregate data signals, we were able to determine and differentiate, empirically, common patterns consistent across all experts from patterns resulting from individual variability. This led to the examination of specific aspects of combined signals, for example, during the experts' respiration cycle, when do they generally start squeezing the trigger? The exploration of data signals helped us to isolate interesting features of overall performance. This was first done visually and then statistically to determine significance.

In a study to evaluate the likelihood of determining expert performance, the measures presented in this article were examined individually and simultaneously (Nagashima et al., 2009). The measures, as they are described above, appear capable of capturing differences in skill performance between experts and novices. However, defining marksmanship skill based only on these dimensions of psychomotor performance alone misrepresents the complex nature of the task. There is accumulating evidence that cognitive and affective factors play important roles in the development of marksmanship skills and performance (Chung, Delacruz, de Vries, Bewley, & Baker, 2006; Chung, Nagashima, Espinosa, Berka, & Baker, 2009; Chung, O'Neil, Delacruz, & Bewley, 2005). Sensor-based measures of marksmanship skill provide a direct and precise way to measure skill and will contribute to better understanding the psychomotor components of marksmanship.

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