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Experimental measurement of rifle dynamics during the range shooting of biathlon weapons

Andrey Koptyug*, Mats Ainegren

SportsTech Research Center, Mid Sweden University, Akademigatan 1, SE-831 25, Östersund, Sweden

Abstract

Some of the shooting training that biathletes implements takes place indoors, even in hotel rooms or at home, through so-called "dry firing" training. It involves imitating shooting at a target with real rifle but without ammunition, when the result is evaluated by various electronic devices counting the number of virtual hits. But dry firing cannot adequately represent real shooting, as it does not produce any rifle recoil, which significantly limits its value for the training. To reach a higher realism of the dry firing training a system mimicking the weapon recoil is therefore needed. Present research aims to overcome an existing lack of data on the dynamics of small caliber rifles recoil dynamics. Present paper describes first measurement results acquired in the controlled environment of the shooting range. Two types of experiments were carried out with firing freely suspended rifle and when backed with the force measurement device (load cell). Average recoil peak force values were reaching 5 kg, rising from zero for about 10-15 ms and keeping altogether for about 30-40 ms. Corresponding energy going into the recoil motion of the rifle is found to be about 390 J. The measured values provide an adequate input for designing the devices mimicking the biathlon weapon recoil in dry firing training.

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*Keywords:*B*iathlon, dry firing, gun recoil, athlete training*

1. Introduction

Biathlon is a form of competition combining cross-country skiing with rifle shooting, where the total time from start to finish determines the result [1]. Each time the athletes pass the shooting range, they have five bullets to shoot

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* Corresponding author. Tel.: +46-16 59 41; fax: +46 16 55 00.
E-mail address: andrei.koptioug@miun.se

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at as many targets. For each missed target the biathlete is punished with either one minute penalty time or an extra penalty loop to ski. The time athlete spends at the shooting range varies depending on the skills and weather conditions and is commonly under 1 minute. At highly competitive international events today an extra fraction of a second at finishing line can deprive athlete from the medal. Thus continuous training for the best shooting performance is an essential component of the overall training process.

Some of the shooting training that biathletes implements takes place indoors, even in hotel rooms or at home, through so-called "dry firing" training [2, 3]. Dry firing training involves imitating shooting at a target with real rifle but without ammunition. The result can be evaluated by various electronic devices counting the number of virtual hits.

One drawback of dry firing training is that it cannot correctly represent real shooting with the ammunition, which significantly limits its value for the training process. In particular such training does not represent the dynamics of the firing weapon. After a real shot is fired, the rifle and skier are influenced by a recoil force. The recoil disturbs the athlete's balance and affects the time to focus at the next target, and thus affects the precision of the next shot. Ideally the dry shooting training should mimic the real competition conditions as much as possible. Modern virtual reality systems can well reproduce visual and audio side of shooting. But it would be quite desirable if the rifle behaved similarly in dry firing as in real shooting. To reach a higher realism of the dry firing training a system mimicking the weapon recoil is therefore needed.

Though certain information on the recoil of the larger caliber weapons is available [4, 5] there is a definite lack of data on the biathlon rifles. Also many of the formulae suggested need rather hard to measure input parameters, for example such as the velocity and the mass of propellant gases [5]. Some of the training systems for the combat arms are using the systems that can mimic the recoil, but these are complex stationary mounted systems [6]. Unfortunately any heavy device mimicking the recoil added to a standard biathlon rifle will not be accepted by athletes as good training support option, which further adds to the system design challenges.

The purpose of present study was to investigate the dynamic behavior of the biathlon rifle during range shooting with ammunition. The corresponding experimental setup can also be used in the future to evaluate innovative features designed to mimic the recoil dynamics. Early pilot studies carried out in the field have outlined the difficulties of measuring small caliber rifle recoil dynamics. Shooting produces intense acoustic ringing and overloads sensitive accelerometers for significant time. Flexiforce sensors (by Tekscan) used to record the dynamics of the pressure between the rifle and the shoulder were not showing any consistent values and are very sensitive to the distortions through even little bending. Also athlete's hands and clothing produce significant damping strongly reducing the reproducibility of the measurements and reducing the pressure between the back of the rifle and the shoulder. Thus it was decided to design a laboratory setup to improve the recoil dynamics measurements.

2. Materials and Methods

The tests were performed in the shooting range using .22 caliber 1846 Fortner biathlon rifle by Anschütz and Lapua Polar Biathlon cartridges. The rifle (Fig 1) was in full competition configuration with a single cartridge in the bridge and an extra strap added for suspension near the rifle centre of gravity CG (arrow 'S' in Fig 1). Three extremely lightweight 3-axis accelerometers (LIS 334 by ST Semiconductors, ±6g full scale) were placed at the nozzle, near the center of gravity and near the back of the rifle (arrows 'A' in Fig 1). Light weight servo was used to trigger the shot (arrow 'E' in Fig 1). Rifle (R inset in Fig. 1) was suspended on two 0.2 mm Kevlar fishing lines set in triangular configuration in the plane normal to the rifle nozzle; the length of the wires was B= 1.0 m, distance between the suspension points was L= 1.2 m. The weight of the rifle with additional harness was 4034g, of the cartridge with the bullet- 3.3g (bullet separately- 2.6 g), of the accelerometers and triggering servo- 19g. Accelerometers and servo were connected to the control and measurement system using extremely lightweight and soft cables (home-made of 0.1 mm diameter enameled copper strands reinforced with a nylon tailor thread).

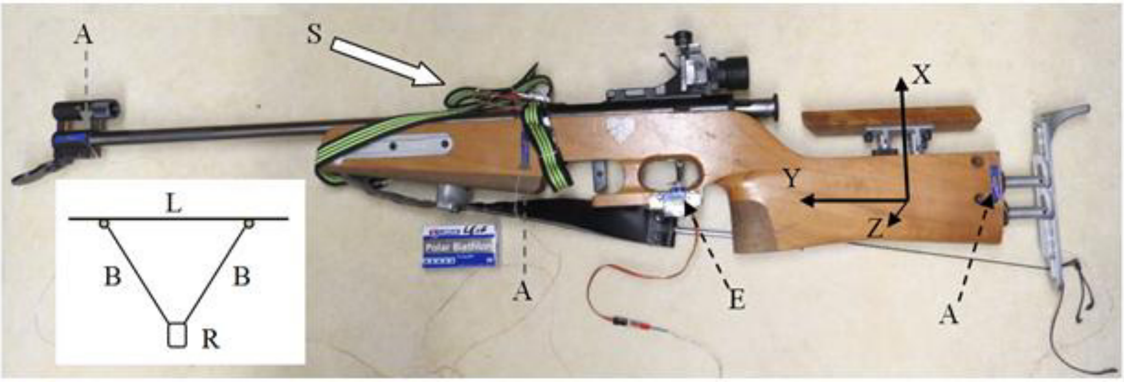

Fig. 1. Rifle with additional harness (S), accelerometers (A) and shooting servo (E). Inset is showing the suspension diagram.

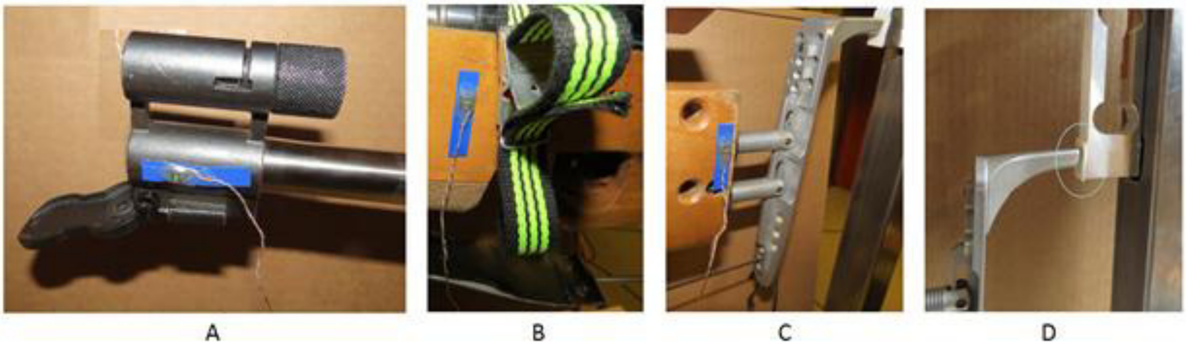

Fig. 2. Rifle with accelerometers at the nozzle (A), center of gravity (B) and back side (C), and connection with the load cell (C,D).

Two types of experiments were carried out: shooting with freely suspended rifle ("pendulum swing"), and shooting with suspended rifle backed by the load cell fixed to the solid frame ("force"). In "pendulum swing" experiments pendulum- like motion of the rifle after the shot was studied. In the second type experiments the dynamic force between the back of the rifle and solid obstacle during and after the shooting was recorded together with accelerometer signals. In both sets the shooting event was recorded by a video camera placed 1.8 m from the rifle and 3.6 m from the measuring tape on the opposite range wall. Load cell L6B-L-3kg-0.4B by Zemic Europe with the sensitivity 0.9±0.1 mV/V was used together with home-built preamplifier. Fig 2 illustrates the positioning of the accelerometers (A- C) and the load cell (C, D). Accelerometer axis assignment (also shown in Fig. 1) was as follows: Y axis is along the shooting direction; X-axis is 'up/down'; Z-axis is 'sideways' (in the rifle coordinate frame). Accelerometer and load cell signals were recorded using a USB-6211 NiDAQ module under the LabVIEW platform (both by National Instruments). For each type of experiments 10 shots were done recording at 7 kilosamples per second (ksps), and additional 5 shots - at10 ksps sampling to assure that sampling rate is not distorting the parameter values.

3. Results and discussion

Force measurement experiments produced quite consistent results. Fig. 3A shows a typical recording of the dynamic force signal. Peak force values were 5.2±0.7 kg, characteristic rise time and event duration were 12.4±5.7 and 29±10 ms correspondingly (values averaged for all measurements). Rise times of the force signal are very close to the duration it takes to reach the initial speed for the suspended rifle shooting (first 10 ms in the integrated accelerometer signals in Fig. 3B). No significant differences were observed with either 7 or 10 ksps sampling rates.

Load cell response is much faster than 0.1 ms (sampling time at maximum rate), as at two events the rifle had no initial contact with the load cell and produced significant ‘kick’ on the force cell, with the force signal rising time of one sampling step. With typical surface area of the back of rifles of 40 cm2 corresponding peak pressure values should be at the order of 125 g/cm2. Thus it is not surprising that early attempts to use Flexiforce thin film sensors to measure the pressure between the rifle and the shoulder were not successful as the particular sensors simply did not have enough sensitivity.

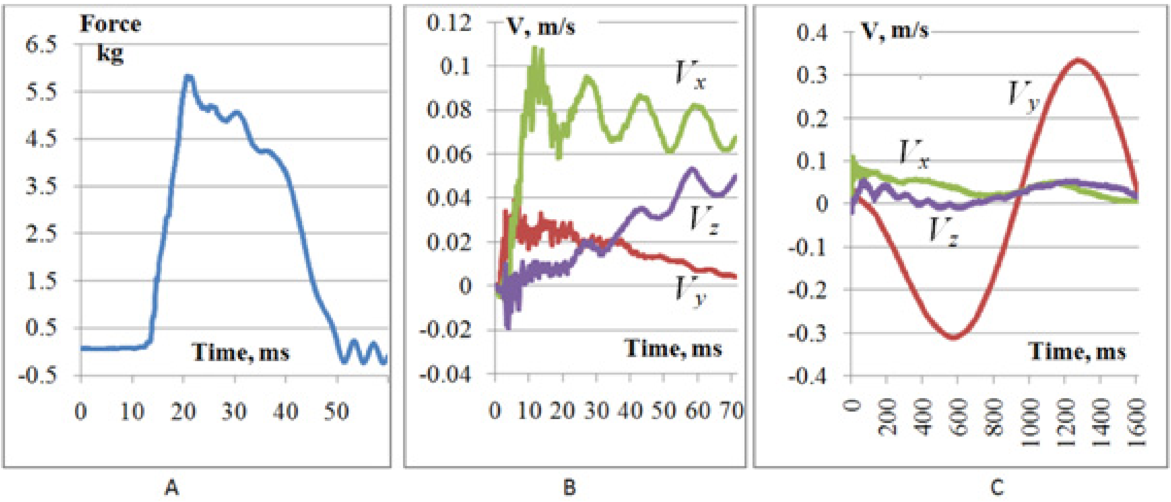

Fig. 3. Load cell signal (A) and rifle center of gravity velocity calculated from the CG acceleration signals (B,C). Both cases are single shooting events. Dynamics of all three components of velocity are presented at short (B) and long (C) time intervals.

Measuring rifle motion with MEMS accelerometers is rather complex. Shooting produces very strong acoustic reverberation in the rifle components, thus an early part of the rifle acceleration dynamics is masked by very intense 'ringing'. Used accelerometers are not good enough, and sampling rates available with present setup are not high enough to properly reproduce this event. In our experiments the peak acceleration values recorded during initial ringing produced by the shooting were reaching ±8 g, and the overall duration of the 'ringing' was reaching 50 ms. Surprisingly these times were noticeably different for three accelerometer positions used: 17±5 ms for the nozzle and center of gravity accelerometers and 25±4 ms for the back of the rifle one (values averaged for all measured data). Fig. 4 illustrates the shooting-induced acoustic reverberation signal (A) detected at shorter times, and low-pass filtered signal (B) detected on the longer time scale. Though there were no significant disturbance in Z- components of acceleration signals, both the nozzle and back side-mounted accelerometers were showing substantial oscillations in the 'up/down' direction X. Period of these oscillations is some different from the period of 'main' pendulum-like motion producing accelerations along the rifle (Y direction) as illustrated by Fig. 4 B. Most probably this is caused by the balance-type oscillations of the rifle swinging around the suspension point. Relative contribution of such vibrations was variable, which is most probably due to the slight differences in the initial balancing of the rifle.

The pendulum with relatively low dumping (as in our experiments) should have very similar swing velocities for the few first oscillation periods. Thus corresponding swing velocities of the pendulum motion of the rifle after the shooting can be used to assess the energy going directly into the rifle recoil motion, while not taking into account what is lost through the acoustics. Fig. 3 B and C illustrate typical results of the accelerometer signal integration (single shooting, accelerometer placed near the center of gravity) at both short (B) and long (C) time intervals. As illustrated by Fig 3 (B, C) accelerometers placed near the rifle center of gravity are mainly detecting the motion along the rifle (Y component), X- and Z- velocities are below 10% of these values. Accelerometers placed near the nozzle and back of the rifle record much stronger movement in X direction and some movement in Z direction (Fig. 4 B). Thus for assessing mechanical energy of the recoil module of the velocity vector was calculated in all cases.

To assess the disturbance of the initial rifle jolt produced by the shooting on the pendulum-like motion the time of corresponding "quarter periods" (between the points corresponding to zero and maximum rifle velocity) were calculated (see Table 1). These results clearly indicate that the disturbance is pronounced for a first quarter- to half-period of pendulum motion. Non-disturbed pendulum period is calculated to be 1.52±0.08s, which is some smaller than 1.8 s, a theoretical value for the ideal pendulum with the same arm length. Table 2 presents the values of the maximum rifle swing velocities (absolute values of the vector) for the first four half-periods of pendulum motion.

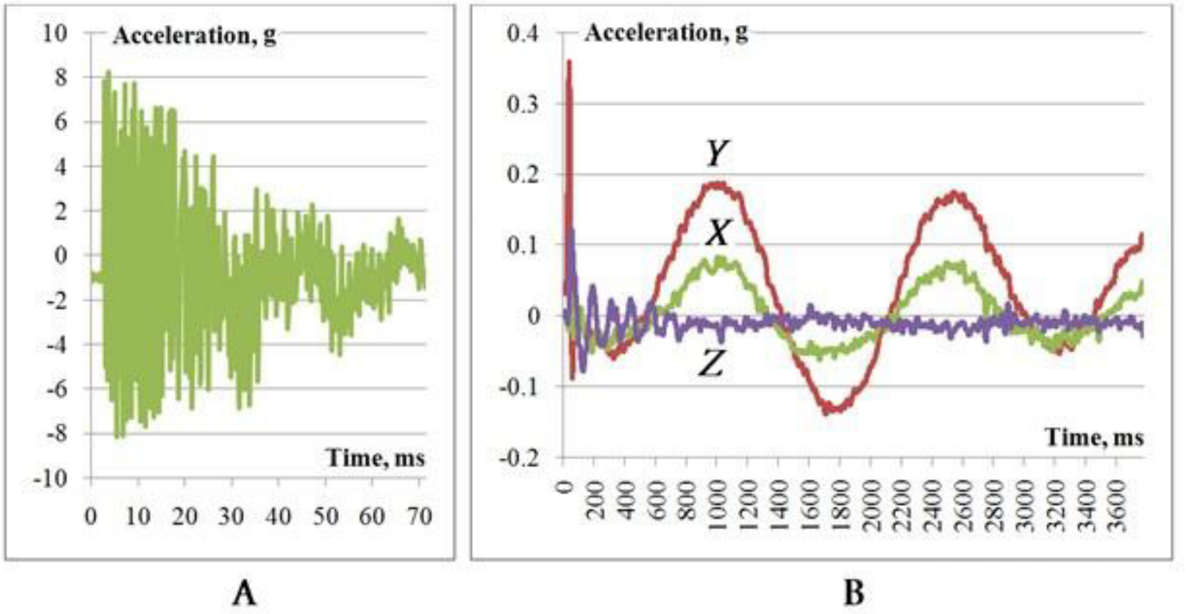

Fig. 4. Nozzle accelerometer signal at short (A, without filtering, X-component) and long (B, low-pass filtered, 50 Hz, all three components) time intervals.

These are also indicating the disturbance of the first pendulum swing, and most probably one should use the 'velocity 2' value for estimating the corresponding energy. Basing on above discussions corresponding value of 390 J calculated basing on the ‘velocity 2’ value should give a good estimate.

Table 1. Quarter- periods of the pendulum motion. Values are averaged from all recorded data.

time 0	time 1	time 2	time 3	time 4	time 5	average period
0.59±0.2 s	0.35±0.01 s	0.4±0.01 s	0.37±0.01 s	0.38±0.01 s	0.38±0.01 s	1.52 ±0.08 s

The estimate of the bullet exit velocity can be done basing on the momentum conservation law. Initial rifle speed after the shooting (10 ms, Fig. 3b) of about 0.09 m/s yields a bullet exit velocity about 140 m/s. It is reasonably close to 91.4 m/s, the bullet speed claimed by the manufacturer on the ammo box (329 km/h). But this estimate should be indeed excessive, as we did not take into account the mass and velocity of propellant gases and possible energy dissipation into the acoustic vibrations of the rifle after shooting.

Table 2. Rifle swing velocities for two consecutive pendulum periods.

velocity 1	velocity 2	velocity 3	velocity 4
0.32 ± 0.05 m/s	0.44 ± 0.07 m/s	0.39 ± 0.05 m/s	0.32 ± 0.06 m/s

4. Conclusions

Laboratory setup for studying recoil of the biathlon rifle produces much more reliable results as compared to the field experiments. When backed by the solid object the recoil force peaks at about 5 kg, rising from zero for about 10-15 ms and keeping altogether for about 30-40 ms. Assuming the uniform pressure distribution through the back of the rifle corresponding pressure peaks at just above 100 g/cm2. Load cell seems to be more adequate for such measurements as compared to the thin film pressure sensors (it is also much faster to respond). Shooting experiments with freely suspended rifle produced the estimate of recoil motion energy of about 400 J. Studying of the pendulum type rifle motion allows to minimize the influence of intense acoustic reverberation strongly disturbing MEMS accelerometers for up to 50 ms after the shooting. In actual shooting athlete's hands and clothing will change the recoil dynamics quite considerably as compared to the one observed in the laboratory setup.

The measured values provide an adequate input for designing the devices mimicking the biathlon weapon recoil in dry firing training. Developed setup will be also quite helpful for testing and validating of the designed recoil-mimicking devices.

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