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Comparing the Performance of the Biathlon Rifles with Wooden and Titanium Frames †

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Abstract: The present paper describes preliminary results of studies carried out using a new measurement setup and a biathlon rifle with two different interchangeable stocks: a commercial, mainly wooden one and one additively manufactured from titanium alloy and a polymer PA 2200, employing lightweight, 3D lattice architecture. A finite element analysis of the predicted mechanical properties of new design elements was carried out prior to the manufacturing. Experiments were carried out using a novel setup for the assessment of athlete and rifle performance in biathlon shooting. Data acquisition was carried out at the rates of few kilosamples per second, using a combination of an airbag-based rifle butt pressure sensor, a trigger loading sensor, strap load cell, and two tri-axis MEMS sensors—an accelerometer and a gyroscope. All tests indicate that a rifle stock additively manufactured from titanium alloy could provide better recoil damping compared to the commercial, mainly wooden one. Together with the high capacity of additive manufacturing technologies in equipment individualization, this may provide additional possibilities for the improvement of sports rifle construction and help athletes achieve better results in competitions.

Keywords: biathlon rifle; shooting dynamics; recoil; sensors; additive manufacturing

1. Introduction

Biathlon is an Olympic sport combining sharp shooting and cross-country skiing. Success in this discipline depends on the interaction of multiple factors, including the performance of athletes and equipment. The shooting technique of biathletes is strongly influenced by different psychophysiological factors, postural balance, triggering technique, rifle performance and stability [1–4]. During the competitions, multiple precision shots should be performed in a fast sequence, so steady postural balance and fast rifle stability recovery after each shot is a critical element for biathlete performance—for example, it was shown that combining special tension release and specialized shooting training could significantly improve an athlete's shooting results [5]. Recoil is a major factor causing additional rifle motion during and after each shot, so technologies for measuring the firing impulse at the shoulder and rifle position disturbances have been successfully developed for both larger caliber weapons [6] and biathlon rifles [7]. To date, major studies have aimed to develop training procedures that provide better rifle stabilization during shooting and faster stability recovery after each shot. At the same time, certain advances can be achieved by improving rifle technology. Biathlon rifle construction has continuously improved, and the application of additive manufacturing (commonly referred to as 3D printing) to the design and manufacturing of its critical components adds a new dimension to this process. Additive manufacturing can simultaneously allow for unprecedented freedom of equipment individualization, weight reduction, weight distribution and for the manipulation of component properties, including acoustic damping and impulse energy absorption. Modern additive manufacturing (AM) technology in metal allows for the lightweight manufacture of lattice constructions with excellent, designed-by-purpose mechanical properties [8]. In particular, titanium alloys and AM components have a superior strength-to-weight ratio. However, it is not obvious how additively manufactured parts of the biathlon rifle assembly would affect the equipment and the athlete's shooting performance. The present paper describes the preliminary results of the first assessment carried out using a novel measurement setup and a biathlon rifle with two different interchangeable stocks: a commercial, mainly wooden one and a novel one additively manufactured from titanium alloy Ti64 and PA 2200 polymer, employing a lightweight, 3D lattice architecture.

2. Materials and Methods

An unmodified caliber 5.6 mm ANSCHÜTZ 1827 F biathlon rifle system (barrel, bridge and triggering part) was tested together with a commercial, mainly wooden, individualized stock by Erkki Antila, Finland (Figure 1a) and an alternative one, additively manufactured from titanium alloy Ti64 and PA 2200 polymer (Figure 1b). The titanium alloy-based stock, together with its plastic elements, is 155 g lighter than the original, mainly wooden one. It is not a dramatic change if one takes into account that the overall weight of the rifle with all additional elements, the belt and straps, together the with ammunition athlete carries during the competition, is about 4 kg. All new parts are designed using lightweight, 3D lattice structures partially surrounded by solid periphery layers.

In the present study, we have employed a newly developed measurement setup with the pressure monitor applied to the butt plate of the rifle, a three-axis accelerometer and three-axis gyroscope placed at the rifle stock, a modified standard trigger with an incorporated strain gauge and dedicated load cell in the strap. The present studies were simultaneously used to assess the performance of the new measurement setup. Figure 2 illustrates the placement of all sensors with the biathlon rifle. The three-axis microelectromechanical system (MEMS) accelerometer MMA7341LT by NXP with an analogue output is set to the sensitivity of ±11g. Two MEMS analogue output gyroscopes, LY330 ALH (yaw rate) and LPR430AL (pitch and roll), both by ST Microelectronics, mounted on a small printed board together, provide a tri-axis sensor with a sensitivity of ±300 dps in each rotation direction. The accelerometer and gyroscopes are placed on the gunstock opposite the bridge (Figure 2c).

(a)

(b)

Figure 1. (**a**) Original ANSCHÜTZ 1827 F biathlon rifle with individualized, mainly wooden stock and (**b**) its modification with additively manufactured stock and PA 2200polymer elements (in blue color).

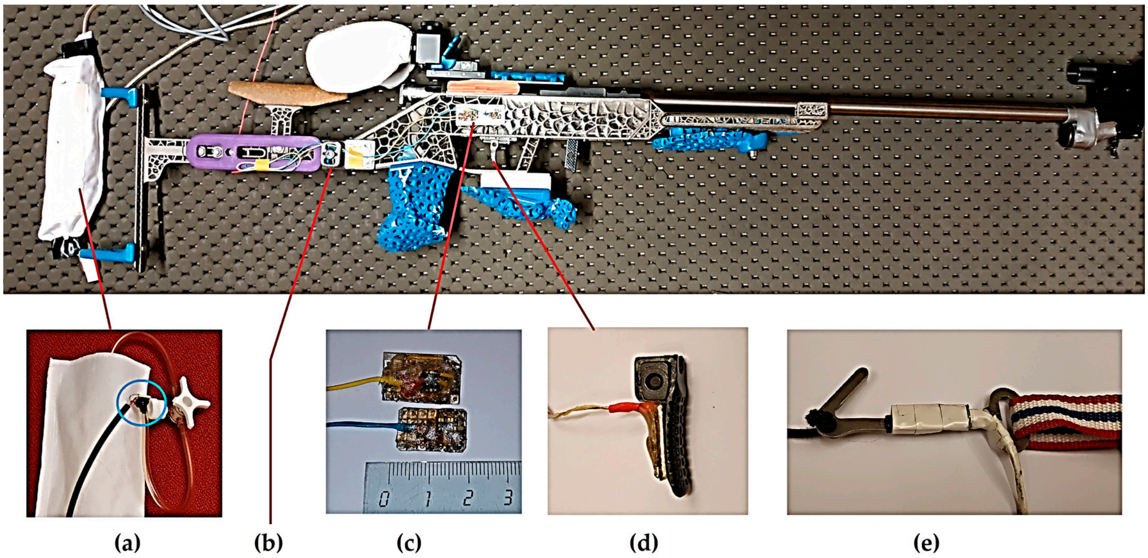

Figure 2. Placement of the sensors: (**a**) pressure sensing airbag; (**b**) signal cable fixation bracket; (**c**) accelerometer and gyroscope boards; (**d**) modified trigger unit; (**e**) load sensitive belt hook.

The standard commercial trigger is modified—its backside is made thinner and a strain gauge BF120-3AA (sensing area 3 × 2.6 mm) is glued to it. A small homemade board of the same width as the trigger accommodates the bridge resistors and amplifier (Figure 2d). Three trigger assemblies were manufactured and tested with similar good results. Trigger sensor calibration is performed together with the gun, applying a force in the same way as the athlete's finger. The corresponding sensitivity of the tested trigger sensors after the amplification is about 1V for a 500 g loading force. A special small load cell with a dedicated amplifier for measuring strap tension was manufactured (Figure 2e). Its sensitivity after amplification is about 1 V for 1.4 kg force. Earlier experience with employing thin film pressure sensors glued to the butt of the rifle pointed out some serious deficiencies. It appeared that the distribution of the pressure between the rifle butt and athlete's shoulder significantly varied between shots, even for the same athlete. Moreover, a few thin film sensors were not producing reliable measurement data. Thus, we employed a new approach similar to the one used in blood pressure monitors with an air-filled bag. A similar soft airbag is placed over the butt of the rifle, fixed to it with double sticky tape (Figure 2a). Its pressure is monitored by the ABPLLNN600MGAA3 sensor by Honeywell (highlighted in Figure 2a), with an analogue output and a built-in amplifier. The resultant sensitivity of pressure measurement is about 58 mBar/V. Data acquisition was carried out with the sampling of all channels up to 5000 times per second using the USB-6210 data acquisition module by National Instruments under the LabVIEW software.

Shooting experiments for the recoil impulse investigation on the rifle with different gunstocks were carried out by the authors at the same range in both standing and prone positions in accordance with the World Health Organization Declaration of Helsinki. A series of five shots were performed for each rifle stock in each shooting position, with the simultaneous video recording and monitoring of the shooting precision. Data processing and storage was performed following the EU General Data Protection Regulation.

3. Results and Discussion

The performed experiments have shown that the most valuable information for the assessment of athlete and rifle performance in shooting is provided jointly by the pressure sensor, modified trigger, strap load cell and accelerometer. Figure 3 presents the typical time evolution for the signals from the pressure sensor and one of the acceleration sensor components for shooting in standing and prone positions.

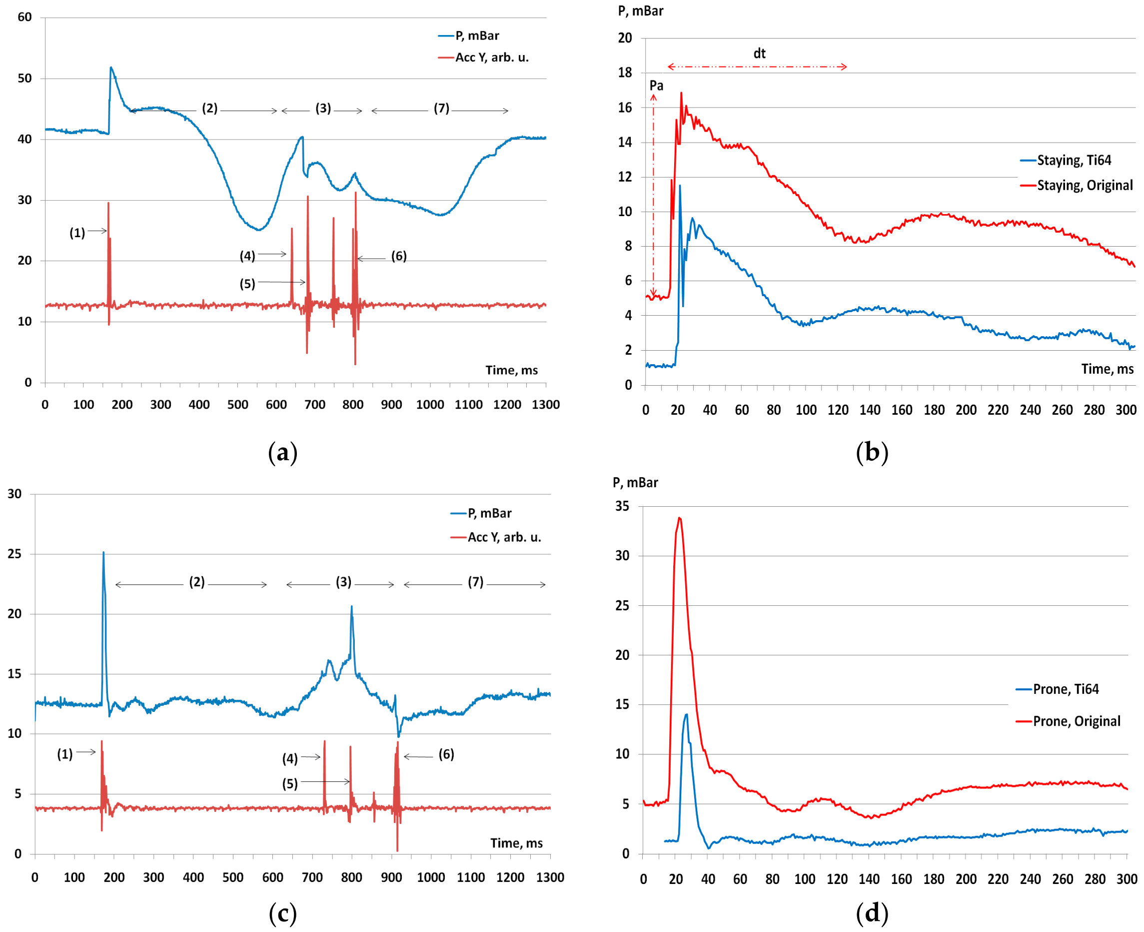

Figure 3. Typical signal traces recorded from pressure sensor and accelerometer (Y component) during shooting in standing (**a**,**b**) and prone (**c**,**d**) positions. Plots in figures (**a**) and (**c**) reflect true pressure values, including steady state before and after the shot, but the accelerometer signal is scaled for better event identification. Plots in figures (**b**) and (**d**) reflect the pressure changes, but are offset for a better comparison.

Recognition of the characteristic events during shooting and following recharging is relatively straightforward (Figure 3a,b). A strong accelerometer signal and pressure peak during the shot (1) are followed by the recoil impulse and gun position recovery motion (2). Recharging (3) is characterized by the initial increase in the rifle butt pressure with two peaks when the bridge is opened (4) and reaches the limiting position at the back (5). It is followed by a decreasing rifle butt pressure during the forward motion, and the 'click' of the closing bridge (6). After this, the athlete can stabilize the gun for the following shot (7).

To assess the recoil impulse, three parameters were chosen: rifle butt pressure change during the shot (Pa, Figure 3b), duration of the recoil event (dt, Figure 3b) and pressure change integral Pa(t)*dt during the recoil event, reflecting the recoil impulse energy. Figure 4 presents a comparison of the butt pressure peak values Pa (a) and pressure change integral Pa(t)*dt during the recoil event, (b) averaged for all performed shots. For the shots in a standing position, peak pressure values for the rifle with the Ti64 stock are higher. However, the "recoil impulse integral" values are lower, reflecting the subjective feeling of the user by indicating smaller recoil impulse disturbance with the Ti alloy stock. This could be explained by the stronger transfer of the acoustic vibrations by the Ti64 stock during first milliseconds after the shot, but stronger mechanical damping of the slower motion in the following two–three hundred milliseconds (Figure 3b). In the prone position, both the peak pressure and "recoil impulse integrals" values are lower for the rifle with the Ti stock.

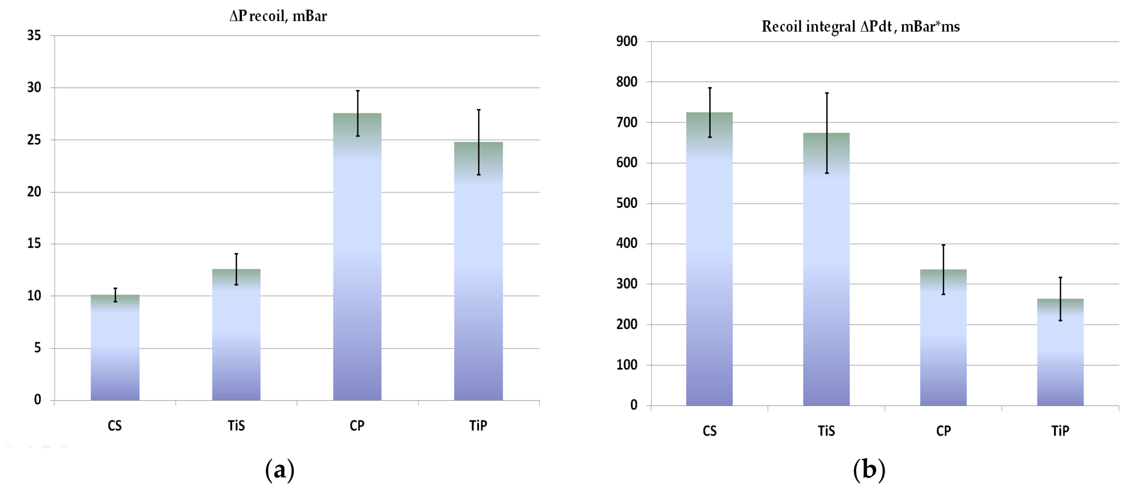

Figure 4. (**a**) Butt pressure peak values Pa, and (**b**) pressure change integral Pa(t)*dt during the recoil event averaged for all performed shots. Standing position: original commercial stock (CS), stock made from Ti alloy (TiS); prone position: original commercial stock (CP), stock made from Ti alloy (TiP).

It is also clear that recoil pressure to the butt of the rifle with both stock types is different when shooting in standing or prone positions. This could be explained by the stronger damping action of the athlete's hands and body during the standing position shots. In the prone rifle position, handling is significantly more 'rigid', which is clearly reflected by much smaller changes in the quasi-static pressure values before and after the shot (Figure 3a,c). In the standing position, the peak recoil pressure is smaller, but it results in the longer duration of the increased pressure between the rifle butt and the shoulder.

Interestingly, the variation in the measured recoil parameters within each shooting series is not very significant, with a considerably larger spread of these values between the series (Figure 5). There is also a certain tendency for the peak recoil pressure to decrease between the rifle butt and the shoulder for each consecutive shot in the standing position, while in the prone position it is not pronounced (Figure 5b). One feasible explanation is that trained expert shooters tend to improve the rifle position recovery after each consecutive shot, continuously adjusting for the recoil impulse. Such an effect would be more pronounced when shooting in the prone position, when the relatively rigid trusses formed by the elbows touching the ground and a rifle strap help to ensure much more stable rifle positioning.

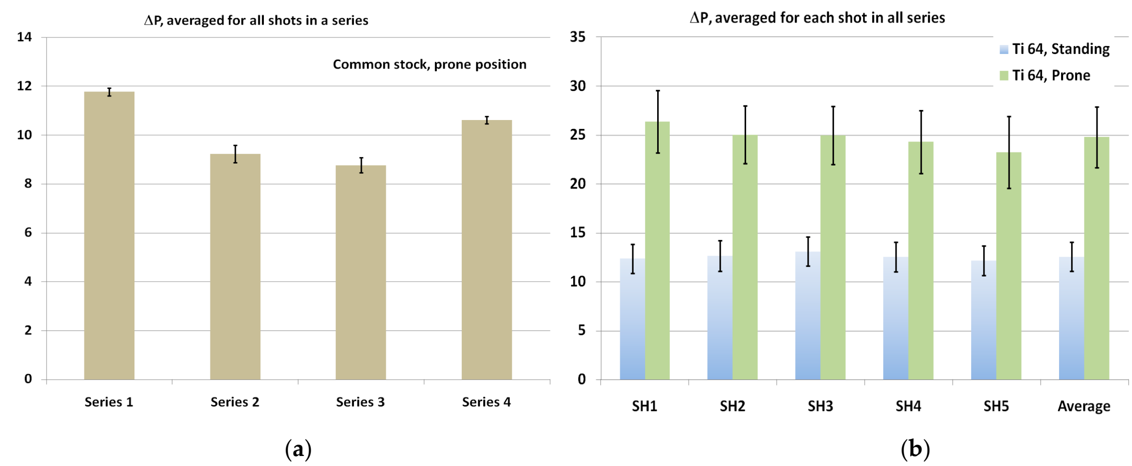

Figure 5. (**a**) Variation in the peak pressure between four different representative series, averaged for all shots in the series: prone position shooting, original commercial rifle stock. (**b**) Variation in the peak pressure between consecutive shots: shots one to five in the series ('SH1'—'SH5'), values are averaged for all series; values averaged for all shots in all series ('Average'); Ti alloy stock, standing and prone position shooting.

4. Conclusions

An assessment of the recoil properties of a biathlon rifle with two different interchangeable stocks (a commercial, mainly wooden one and one additively manufactured from titanium alloy Ti64 and PA 2200 polymer, employing a lightweight, 3D lattice architecture) was performed using a new multi-sensor measurement setup. Preliminary experiments with this setup indicate that the combination of an airbag-based rifle butt pressure sensor, trigger loading sensor, strap load cell and tri-axis accelerometer is adequate for the assessment of athlete and rifle performance in biathlon shooting. The airbag-type pressure sensor appears to be relatively non-obtrusive, and provides an adequate assessment of the gun's recoil intensity. Signals from the loading-sensitive trigger and accelerometer can provide precision timing of the rifle dynamics throughout the entire shooting series. The new gunstock design not only helps to achieve a lighter weight, but can also decrease the recoil impulse, and improve the rifle stability recovery after the shot. High-capacity additive manufacturing technologies in equipment individualization, together with our measurement setup, open additional possibilities for the improvement of sports rifle construction, and may help athletes to achieve better results in competitions.

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