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Ballistic simulation on direct effects of small arms projectiles on human bone tissue

Abstract:

The article deals with an application of a model of part of lower limb (human thigh) in ballistic experiments focused on evaluation of wounding effects of small arms projectiles (SAP) on human body. SAP of different designs and ballistic parameters are used for the ballistic experiments. There is also shown the essential method of indirect identification applied on the physical model that substitutes a real body part of a hit man in the article. Design and creation of the physical model for ballistic experiments presume the use of both real biological tissue (pig's femur) and substitute tissue (ballistic gelatine). Ways of determination of basic properties of tissues are also described in the article. Experimentally obtained properties of the target material (pig's tissue and ballistic gelatine) are compared with properties of a human tissue. The ballistic experiment is focused on the research into direct effects of SAP on human femur. Additional aim of the work is the examination of human bone and muscle tissue substitutions and their behaviour during small arm projectile penetration; including a movement of small arms projectile after the penetration. All experimental results are compared with real wounds of human lower limb. Differences between SAP wounding effects on the physical model and real human tissues are discussed at the end of this article.

Keywords: Firing wounds, indirect identification method, small arms ammunition, ballistic system.

1. Introduction

There is relatively little information about the direct and non-indirect effects of small arms projectiles on bone tissues available in technical literature [1]. Only some information on the head firing wounds with bone involvement and different levels of tissue devastation is available. This information usually comes from car accidents and criminal activities.

The ballistic experiments focused on examination of both direct and non-direct effects of small arms projectiles on a femur were carried out and contributed to some human femur projectile injuries illustration. Indirect identification method in combination with new designs of physical models were used. Three ballistic systems of different ballistic performance (chosen pistol and rifle calibres of latest design) were used for the experiments. For purposes of the ballistic experiments the pig's femurs were used [6, 7].

Previously used experimental homogeneous blocks substituting the biological tissues were replaced by partially non-homogeneous physical models. Experimental substitution of real entity with this model is the basis for the indirect identification method.

2. Strenght and fractures properties of pig's compact bone tissue

For needs of this experiment bone tissue similar to the human one was searched for. This search resulted in the use of pig's bone tissue (femur). Flat bone samples were subjected to three-point bending test. The following strength properties were obtained: E [GPa] - Young's modulus, $R_{p0,2}$ [MPa] – a conventional yield stress and R_m [MPa] – a fracture stress [3, 9].

Tab. 1 shows initial pig's femur sample sizes of three givers. The parameters b_0, h_0, L_0 and S mean width, thickness, length and cross-section area of the samples [7].

Tab.1 Initial dimensions of flat samples of pig's femur

Sample number	b_0	h_0	L_0	S_0
	[mm]	[mm]	[mm]	[mm^2]

Sample 1	7.46	1.8	55.00	13.43
Sample 2	7.53	1.82	55.00	13.71
Sample 3	7.46	1.5	55.00	11.19

Initial dimensions of the flat samples from the compact pig's femur from three donors and used in the experiment are shown in the Tab. 1. Their shape with glued strain gauge and placement of the sample with width of support (l = 40 mm) in the universal press FP 10/1 HECKERT before measurement can be seen in Fig. 1.

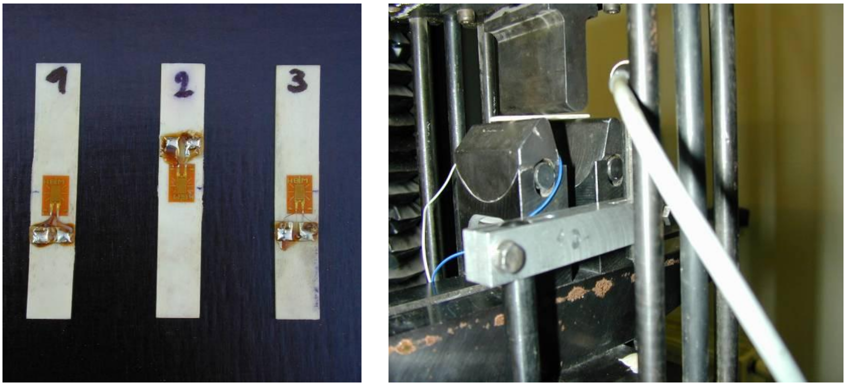

Fig. 1. 1 View on the flat samples of bone tissue (left) and loading of the sample on universal press (right)

Only two samples were tested because the sample number 2 was damaged during the installation of strain gauge. A constant test speed (v_Z = 6.10^{-4} s^{-1}) was used. Fig. 2 shows the dependence of stress on sample deflection. Bending tests were finished when the sample fracture occurred.

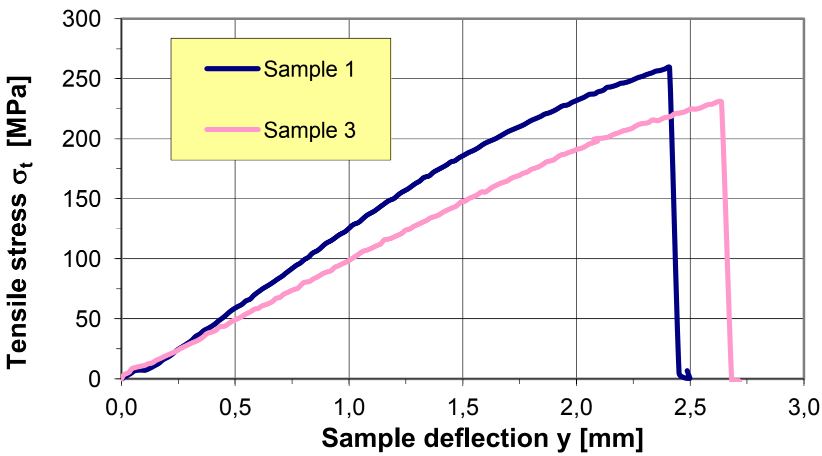

Fig. 2 Dependence of stress on the sample deflection

Modulus of elasticity E_1 was analytically obtained from sample deflection Δy [mm] and E_2 from strain gauge relative elongation $\Delta \varepsilon$ [μm.m^{-1}]. Tab. 2 presents E_1, E_2, $R_{p0,2}$ and R_m values of pig's femur bone [7].

Tab. 2 E_1, E_2, $R_{p0,2}$ and R_m Values of Pig's Femur Bone

Bone sample	ΔF	Δy	E_1	ΔF	$\Delta \varepsilon$	E_2	$R_{p0.2}$	R_m
	[N]	[mm]	[GPa]	[N]	[μm.m^{-1}]	[GPa]	[MPa]	[MPa]
Sample 1	34.4	1	24.5	34.4	3 486	23.3	244	259
Sample 2	-	-	-	-	-	-	-	-
Sample 3	28.7	1	18.6	28.7	5 512	17.96	217	230

3. Simulation of direct effects of small arms projectile on human femur

Verification of the physical model and determination of impact and exit velocities are the major aims of this experiment [7]. There were determined other partial aims for this experiment:

- verification of possibility to repeat obtained results and their archiving by means of X-ray photography;
- assessment of substitution of bone tissue behaviour and its response to projectile penetration through the physical model; including influence on motion of projectile after its exit from the model;
- on basis of evaluation of profiles of wound tracks created by used SAP predict their effects on human tissues.

3.1 Physical model form and ballistic characteristics

The physical model consisted of following parts:

- pig's femur;
- gelatine block - 80 % of water, cube shape – edge of length of 150 mm;
- plastic frame.

The physical model was placed at distance X = 4.5 m in front of ballistics barrel. Precise aiming of the weapon was realised by means of an optical muzzle sight because accurate hit of the bone and capture of the development of wound track were necessary. Projectile impact (v_d) and exit (v_v) velocities were measured by means of intelligent ballistics gate LS 04. Projectiles went through the physical model with a redundancy of kinetic energy [7]. Fig. 3 shows a scheme of ballistic station.

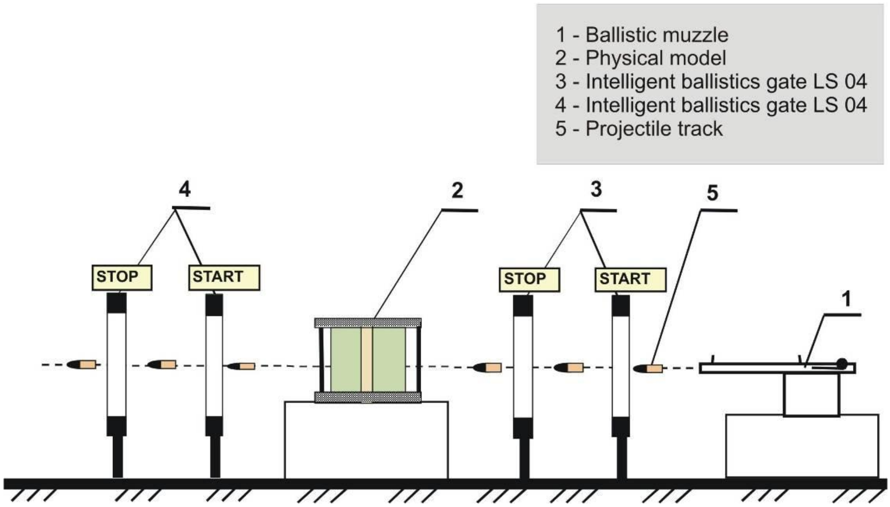

Fig. 3 Scheme of ballistic station

Ammunition used for the ballistic experiment:

- 9 mm Luger, fully jacketed projectile made by Sellier & Bellot. Initial velocity 390 m.s^{-1}, corresponding kinetic energy is E_0 = 570 J, and projectile weight is 7.5 g.
- 5.56x45, fully jacketed projectile SS 109 made by Sellier & Bellot. Initial velocity is 945 m.s^{-1}, corresponding kinetic energy is E_0 = 1786 J, and projectile weight is 4.0 g.
- 5.45x39, tombac covered mild steel core, projectile 7H6. Russian infantry small arms ammunition is used for assault rifle AK-74 and machine guns. Initial velocity is 880 m.s^{-1}, corresponding kinetic energy is E_0 = 1336 J, and projectile weight is 3.42 g.

The two basic effects were predicted: a complicated wound caused by the slow pistol projectile and complicated wounds caused by the rifle projectile with massive devastation of bones and soft tissues.

3.2 Small Arms Ammunition Calibre 9 mm Luger (S&B)

The projectile impacted into frontal part of the gelatine block, penetrated steadily, except the bone and left the block with velocity v_v = 66.1 m.s^{-1}. The energy transferred into the block was equal to E_{TR} = 529 J. The wound track was close and very narrow and kept original direction of projectile motion. Small temporary cavity was created. The projectile was caught slightly deformed but integral and without loss of weight.

Limited penetrating capability, in case of presence of the bone in trajectory of projectile, was proved by these ballistic experiments. The 9 mm Luger projectile lost a large portion of its kinetic energy (97 %). X-ray pictures were acquired after ballistic tests, see Fig. 4, and show the wound track containing large number of bone fragments [6, 7]

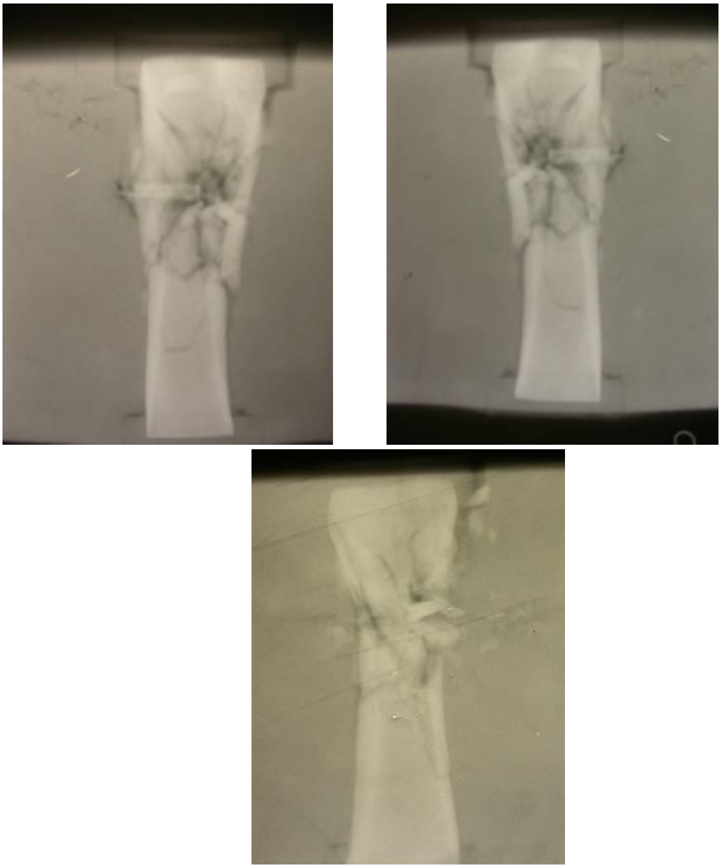

Fig. 4 X-ray pictures of disturbed femur in gelatine block

Non-complicated firing wound (only soft tissues are hit) will change into complicated firing wound in case of presence of bone. X-ray pictures show limited fracture of femur caused by penetrating projectile and large number of small bone fragments.

3.3 Rifle projectile SS 109 micro-calibre 5.56x45

Fully jacketed projectile (SS 109) calibre of 5.56x45 is a very powerful modern rifle projectile and is used e.g. for automatic assault rifle M16 A2 with progressive barrel bore and steeper rifling (6.97”) that provides good stability and a high penetrating capability. The projectile of calibre 5.56x45 hit the frontal part of the gelatine block at velocity v_2 = 938.1 m.s^{-1}. Beginning of the wound track was close and very narrow. Blast effect occurred after impact on the bone. This blast caused a massive damage to the bone as well as the gelatine block. Upper parts of the frame were also damaged and fixing screws were bended. Bottom part of the frame was not damaged. Fig. 5 shows destroyed gelatine model containing bone fragments after impact of the projectile SS 109 [6].

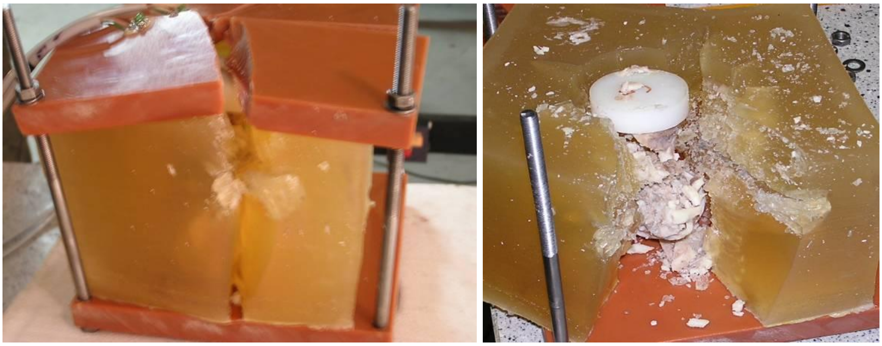

Fig. 5 Damaged gelatine model with bone fragments after impact of rifle projectile SS 109 of calibre 5.56x45

It is very likely that after an impact of projectile on a leg (including tissue), a huge devastation of both soft and bone tissues will occur. In case of this test, the entire length of 90 mm of femur was totally damaged.

All fragments were located in the wound track (temporary cavity). A significant effect of temporary cavity on tissues devastations is evident and was reinforced by the presence of liquids (bone marrow) inside of femur substitution. This fact caused an increase in effect of blast after impact of projectile on the femur [7].

3.4 Rifle projectile 7H6 micro-calibre 5.45x39

The rifle micro-calibre projectile (7H6) has a lower kinetic energy than SS 109 but has a comparable performance as the rifle projectile SS 109. Projectile 5.45x39 impacted on the frontal part of gelatine block at velocity v_2 = 902.2 m.s^{-1} and hit the bone during penetration through the test block. Wounding effects of the projectile 7H6 on both soft and bone tissues are similar to effects caused by impact of the projectile SS 109. Huge volume of temporary cavity caused also radial cracks. The temporary cavity filled more than 50 % of gelatine block [7]. Many bone fragments were found in the place of bone attachment after frame disassembles. Moreover a small part of bone fragments were forced out of the gelatine and were found on the floor. Influence of the temporary cavity and projectile design caused huge devastation of all tissues comparable to damages caused by the projectile SS 109. Fig. 6 shows damaged gelatine model with bone fragments after impact of the rifle projectile 7H6.

Fig. 6 Damaged gelatine model with bone fragments after impact of rifle projectile 7H6 of micro-calibre round 5.56x45

4. Conclusions

A conducted ballistic experiment simulating direct wounding effects of SAP on lower part of the limb (thigh) with tight bone involvement, carried out by the method of indirect identification on the physical model proved full capability of the proposed model to quantify response of bone and soft tissues on dynamic acting of investigated projectiles and their mutual comparison [4]. The arrangement of physical model (including the frame) and used biological substitutes proved full functionality.

From the comparison of results of firing experiment it is obvious that bigger devastation of hit bone tissues was caused by the rifle projectiles than by the pistol one. The rifle projectiles have twice or three times higher impact of kinetic energy than the pistol one. In the range of lacerated soft tissues this ratio is even more significant in favour of micro-calibre rifle ammunition [3].

A certain disadvantage of the ballistic experiment focused on the direct effects of SAP on thigh bone was a relatively small number of fired samples by a small group of small calibre projectiles in limited range of impact velocities [9]. Despite that, the results unambiguously confirmed a significant effect of the temporary cavity on the volume of destroyed bone tissue and the overall seriousness of firing wounds in case of hit of limb bones.

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