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The traumatic potential of a projectile shot from a sling

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ABSTRACT

Herein, we analyze the energy parameters of stones of various weights and shapes shot from a sling and based on this data evaluate its traumatic potential. Four police officers proficient in the use of a sling participated in the trials. The following projectile types, shot using an overhead technique at a target 100 m away were: round steel balls of different sizes and weights (24 mm, 57 g; 32 mm, 135 g; 38 mm, 227 g); different shaped stones weighing 100–150 g and 150–200 g and a golf ball (47 g). Our data indicated that projectiles shot from unconventional weapons such as a sling, have serious traumatic potential for unprotected individuals and can cause blunt trauma of moderate to critical severity such as fractures of the trunk, limb, and facial skull bone, depending on the weight and shape of the projectile and the distance from the source of danger. Asymmetrically shaped projectiles weighing more than 100 g were the most dangerous. Projectiles weighing more than 100 g can cause bone fractures of the trunk and limbs at distances of up to 60 m from the target and may cause serious head injuries to an unprotected person (Abbreviated Injury Scale 4–5) at distances up to 200 m from the target. Due to the traumatic potential of projectiles shot from a sling, the police must wear full riot gear and keep at a distance of at least 60 m from the source of danger in order to avoid serious injury. Furthermore, given the potential for serious head injuries, wearing a helmet with a visor is mandatory at distances up to 200 m from the source of danger.

1. Introduction

Interest in the damaging effects of flying projectiles (foreign objects shot from a sling or thrown by hand) on the human body has increased due to the increasing use of this unconventional weapon by offenders and participants in various types of demonstrations against the agents of law enforcement authorities. According to Israel Police data, in 2007–2008, 6477 people sustained injuries of various types in the above circumstances, 737 (11.4%) of them sustained head injuries. Law enforcement authorities face an important task—to protect police officers from the damaging effect of flying projectiles.

The traumatic potential of the unconventional weapons used by individuals opposing the police has not been sufficiently studied. This is also true with regard to evaluating the traumatic effects from projectiles shot from a sling. A number of studies have reported on the dangerous effects of a shot thrown from a sling, however, these studies have only evaluated the historical and sporting aspects of the sling [1–15]. These reports do not define the general criteria and predictors of the damaging effects of projectiles shot from a sling on protected and unprotected parts of the body. Specifically, what is missing is a definition of the potential damage that could help the police determine the level of police protection, choose adequate personal protective equipment, plan the logistics of police confrontation with crowds and assist police officers in the field avoid injury.

Herein, we attempt to analyze the energy parameters of stones of various weights and shapes shot from a sling and based on this data, evaluate its traumatic potential.

2. Material and methods

Four police officers proficient in using a sling participated in the trials. The following projectile types, shot using an overhead technique, at a target 100 m away (Fig. 1) were used: round steel

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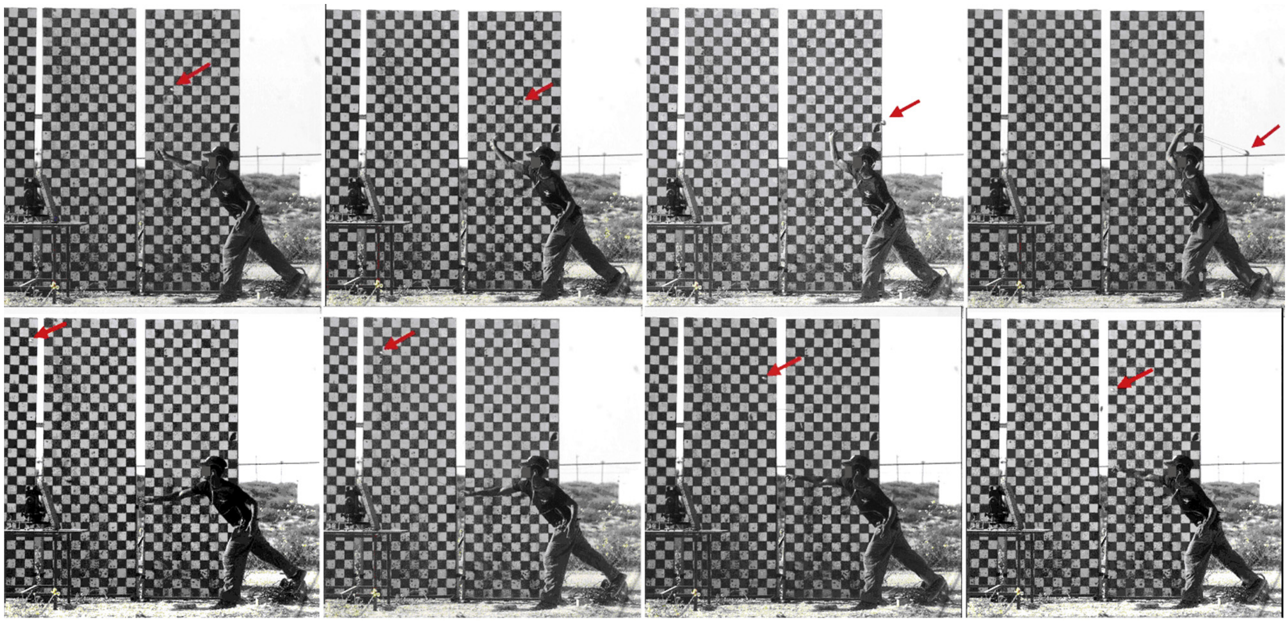

Fig. 1. Sling-shoot setup.

balls of different sizes and weights (24 mm, 57 g; 32 mm, 135 g; 38 mm, 227 g); different shaped stones weighing 100–150 g and 150–200 g and a golf ball (47 g).

All projectiles were weighed, measured and photographed. Each shot at the target was recorded, including the throwing distance and type of projectile used (steel ball/stone/golf ball). The velocity of stones and other projectiles was determined using radar (Weibel Equipment A/S, GP-80 Copenhagen, Denmark) and a high-velocity video camera (Vision-VR511 294V51CG).

2.1. Predictors of injury

The severity criteria of injuries caused by thrown stones have not been specifically studied by ballistic specialists. However, if stones are regarded as projectiles, a number of criteria used in assessing the severity of ballistic and non-ballistic trauma apply to the injuries caused by stones. Impact force is most frequently employed as a predictor of non-penetrating injuries of the human body (bone fractures and tissue damage): Peak Force = $m \times v/\Delta t$, where m = mass; v = velocity and Δt = impact time.

Furthermore, the following parameters were used as predictors of penetrating trauma: energy and specific kinetic energy: projectile energy ($E = 0.5m \times v2$ [J]) and specific kinetic energy (projectile energy density)—$SE = 0.5m \times v2/S$ [J/m2]. The blunt trauma criterion (BC) was used for blunt trauma [16,17].

2.2. Specific energy as a predictor

The specific kinetic energy of the projectile (E/impact area-J/cm^2) is widely used in evaluating the traumatic potential of lethal and less than lethal ballistic weapons as a predictor of penetration into the soft tissues of the human body [18–21]. Savran [22] demonstrated that a projectile hitting the middle of the chest with a specific kinetic energy of 6–8 J/cm^2 causes abrasions; 14–17 J/cm^2—superficial wounds; 32–36 J/cm^2—non-penetrating chest wounds with fractures of the sternum; 54–60 J/cm^2—penetrating injuries of the chest; and 134–145 J/cm^2—penetrating wounds of the chest with damage to the posterior chest wall. Later, a number of studies [23–27] that evaluated the values of the specific kinetic energy of less than lethal weapons presented the traumatic potential in terms of Abbreviated Injury Scale (AIS).

2.3. BC as a predictor

BC, designed by Sturdivan [17,22,23], is a criterion in which the severity of the injury is determined by acceleration value and impact duration and is often used for assessing the severity of blunt trauma. In our calculations of this criterion, we used the algorithm and model anthropometric parameters of the human body and head used by Sturdivan [23] and Frank et al. [28]. Borovsky & Belkin [27] applied the ($AIS = 1.33 \times BC + 0.60$) equation obtained from Bir & Viano [16] to convert BC values into AIS levels.

2.4. Statistical analysis

All results are expressed as means ± SD. The analysis included descriptive statistics, correlation analysis and one-way analysis of variance (ANOVA). Posteriori multiple comparisons of means were applied by the Tukey honest significant difference (HSD) test. The P-values indicated the post hoc significance levels for the respective pairs of means. A P-value <0.05 was considered significant. The aforementioned calculations were performed using the STATISTICA package.

3. Results and discussion

The average fluctuations of velocity and energy of the projectiles over the thrown distance are shown in Table 1. The data were limited to 60 m—the distance at which it was possible to adequately determine the velocity of the projectile over its trajectory using recording devices. It is worth mentioning that almost all the projectiles shot at the target, located 100 m away, successfully covered this distance. Several stones were found at a distance of 128 m (the distances of these projectiles were determined using a distance-measuring device).

An analysis of the data in Table 1 shows that the average muzzle velocity values ($V_{0\,m}$) of projectiles shot from a sling are comparable with the velocities demonstrated by Richardson

Table 1
Velocity and energy of projectiles shot from a sling at different distances (n = 12).

Distance (meters)	Velocity (m/s)			Energy (J)		
	Means ± SD	Min	Max	Means	Min	Max
Steel ball—57 g						
0	34.0 ± 3.8	27.5	41.2	33.2 ± 7.5	21.6	48.4
20	29.7 ± 3.8	24.5	36.0	25.6 ± 6.7	17.1	36.9
40	27.5 ± 4.1	22.6	33.8	21.9 ± 6.6	14.6	32.6
60	26.8 ± 3.7	21.3	32.9	20.8 ± 5.8	12.9	30.8
Steel ball—135 g						
0	28.4 ± 5.9	20.9	37.4	56.5 ± 7.5	29.5	94.4
20	26.0 ± 5.1	19.7	34.6	47.1 ± 8.4	26.2	80.8
40	25.6 ± 4.8	18.8	33.8	45.7 ± 7.1	23.9	77.1
60	25.0 ± 3.6	20.0	31.2	51.9 ± 9.1	32.1	65.7
Steel ball—227 g						
0	26.5 ± 5.2	20.4	35.2	82.6 ± 12.5	47.2	140.6
20	24.2 ± 4.3	19.4	29.9	68.6 ± 10.1	42.7	101.5
40	23.1 ± 4.4	17.6	28.6	62.5 ± 8.2	35.2	92.8
60	23.0 ± 3.8	17.0	28.4	81.5 ± 10.5	61.6	91.5
Stone—100–150 g						
0	29.9 ± 1.3	29.5	30.3	57.3 ± 8.7	51.3	63.3
20	28.8 ± 0.9	27.7	29.8	53.2 ± 7.8	45.3	61.3
40	27.3 ± 1.1	26.1	28.5	48.1 ± 7.8	40.2	56.0
60	26.3 ± 0.9	25.3	27.1	45.5 ± 6.8	37.8	50.7
Stone—150–200 g						
0	30.4 ± 0.6	29.8	30.8	81.0 ± 7.7	73.3	88.6
20	28.6 ± 1.3	26.6	29.9	71.6 ± 9.4	58.4	82.9
40	26.5 ± 1.3	24.6	28.0	61.7 ± 8.2	49.9	71.6
60	25.4 ± 1.2	22.6	26.0	52.3 ± 5.1	42.1	59.7
Golf ball—47 g						
0	35.7 ± 2.2	31.8	50.5	30.1 ± 2.2.	23.3	58.7
20	27.9 ± 1.0	27.8	36.0	17.9 ± 2.4	16.4	23.6
40	27.8 ± 0.9	26.7	32.0	11.1 ± 0.3	10.8	11.5
60	22.0 ± 1.2	21.7	22.4	8.4 ± 0.4	8.0	8.8

[29,30]. The maximum velocity (V_{0max}) values were similar to Dohrenwend [31] and Skov's calculations [14,15].

Overall, in the final phase of the throw, $V_{60\,m}$ (60 m), the velocity of the steel balls and stones shot from a sling dropped by 11.9–21.2% (Table 2). These data were also similar to the theoretical tolerances in Dohrenwend's study [31] of projectiles shot from a sling and Widder et al's data [24] obtained during the tests of non-lethal 40 mm diameter projectiles.

3.1. Force as a predictor

Data on air velocity and weight of projectiles shot from a hand sling (Table 1) was sufficient to assess the moment of impact (m × v) but inadequate to assess the impact force. As this parameter was not corroborated in the present study, we scrutinized publications dealing with the evaluation of blunt trauma caused by less than lethal or non-lethal ballistic weapons [16,19,21,22]. We found that the ballistic and velocity characteristics of impactors are comparable to those of the projectiles we analyzed. The tests were performed on universally recognized ballistic models (in particular, non-preserved corpses), with

Table 3
Predictors of impact force in trauma caused by projectiles shot from a sling.[a]

Distance (meters)	Force (Newton)			Force (Newton)		
	Mean	Min	Max	Means	Min	Max
	Steel ball—57 g			Stone—100–150 g		
0	1935 ± 219	1568	2348	3831 ± 495	3481	4181
20	1694 ± 219	1397	2052	3690 ± 436	3269	4112
40	1565 ± 235	1288	1927	3506 ± 441	3080	3933
60	1525 ± 213	1214	1875	3456 ± 411	2985	3740
	Steel ball—135 g			Stone—150–200 g		
0	3926 ± 748	2822	5049	5319 ± 430	4917	5772
20	3517 ± 675	2660	4671	4996 ± 469	4389	5584
40	3458 ± 652	2638	4563	4640 ± 433	4059	5189
60	3430 ± 344	2643	4212	4269 ± 385	3729	4738
	Steel ball—227 g			Golf ball—47 g		
0	6016 ± 1189	4631	7990	1642 ± 287	1463	2323
20	5499 ± 982	4404	6787	1281 ± 81	1228	1472
40	5240 ± 996	3995	6492	1011 ± 14	998	1030
60	5100 ± 560	4000	6447	878 ± 21	860	902

[a] Time of impact is 1 ms.

appropriate instrumentation recording the required impact parameters, including the time of impact.

According to Bir and Viano [16] and Bir et al. [19], the total time of impact in blunt trauma of the thorax (chest) at 40.1 ± 3.5 m/s average velocity of the impactor, does not exceed 2.4 ms and the maximum peak force (maximum time to peak force) is approximately 0.4 ms. In Shen et al's [32] study assessing blunt abdominal trauma, the total time of impact reached 1.5 ms, and the maximum time to peak force was 0.5–0.6 ms. Several studies [33–36] have evaluated blunt trauma to various parts of the skull at 0.8–1.0 ms total time of impact and 0.6–0.4 ms peak force.

Taking into consideration the above data, we calculated the parameters of the impact of projectiles shot from a sling at the time of impact of 1 ms (Table 3). For overall assessment of the traumatic potential, we used the empirical gradation of impact force of blunt objects most commonly used in Russian forensics [37,38]: 160.0 N – considered a small impact force; 160.0 N–1.96 kN – a significant impact force; 1.96–4.9 kN – a high impact force and over 4.9 kN – a very high impact force.

Since practical assessment of the traumatic potential of a projectile is based on the worst-case scenario, in this context, judging by the majority of the impact force values (Table 3), projectiles shot from a sling from a distance of 60 m can cause damage typical of high and very high forces. Projectiles weighing 57 g and golf balls can cause only a small or significant trauma at close range (20 m).

The literature on the use of impact force as a predictor of fracture severity is fairly extensive and focuses on the impact tolerance of various bones. For the long bones of the upper limb, particularly the humerus, impact force limits are different for men and women, ranging from 1.71 to 2.71 kN [38]. For lower limb bones, in particular the femur, these values range from 2.58 to 3.9 kN and for the sternum—3.5 kN [39].

The boundaries of impact force causing fractures of the skull have been studied in more detail in the literature. These

Table 2
Velocity decrease (means ± SD) of projectiles shot from a sling over a distance of 60 m ($V_{0\,m}$–$V_{60\,m}$).

Projectile	Steel ball			Stone		Golf ball
Weight (g)	57	135	227	100-150	150-200	47
Velocity decrease (%)	21.2 ± 2.6	11.9 ± 3.3	13.2 ± 2.8	12.2 ± 3.0	17.2 ± 3.8	38.4 ± 10.5

m/s—meters per second.

characteristics are discussed separately for cranial vault bones [11,33,35] and the facial skull [40]. These authors present the initial human bone tolerance level—the force that can cause fractures. On average, for blunt trauma to the bones of the cranium, the initial human bone tolerance level for female victims is 2 kN, and for male victims—2.6 kN [32,40,41]. For the bones of the facial skull, as reported by Viano et al. [21] and Kennedy and Duma [25], the initial human bone tolerance level was defined by the following values: frontal bone—2.6 kN; zygomatic bone—1.36 kN; nasal bone—0.34 kN; upper jaw—1.15 kN; and lower jaw—1.78 kN.

Based on the above data, it can be argued that the impact force of stones weighing 50 g or more, shot from a sling (not only from up close but also at a distance of 40–60 m from the target), represent a significant threat to the head, torso, and limbs of a person wearing no protective gear (Table 3).

3.2. Specific energy as a predictor

In our tests, calculation of the specific energy of projectiles presented certain difficulties due to the nature of the linear-volumetric characteristics and shapes of the projectiles. For steel and golf balls shot from a sling, the contact surface area (impact area) was calculated simply as a function of the diameter of the projectile. The data in Table 4 show that the maximum values of the specific energy for blunt trauma with steel balls shot from a sling do not exceed 12.4 J/cm^2, which is a level of exposure usually causing superficial skin damage [17,18].

For stone projectiles, the contact surface upon impact depends on factors such as shape and the probability of hitting a target with a larger or smaller surface (Table 4). In particular, when considering the traumatic potential of an irregularly-shaped stone shot from a sling whose air velocity we managed to determine over its flight distance of 128 m (Fig. 2, Table 5), we observed that depending on the area of the surface that hits the target, the specific energy may increase many times over, which can cause very serious injury, especially when the stone hits the head. At the same time, regardless of the contact surface dimension, the peak impact force of the projectile ranged from 4.9 kN at V_0 to 3.9 kN at $V_{128\,m}$.

3.3. BC as a predictor

The data presented in Tables 6 and 7 confirm the statement that the risk of trauma caused by stones thrown by hand at close range

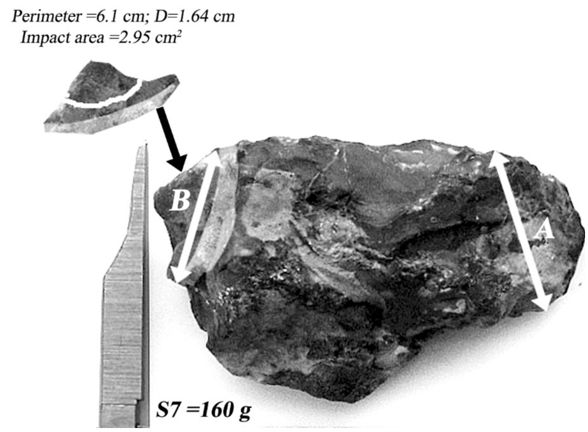

Fig. 2. Asymmetrical stone shot from a sling, recorded at a distance of 128 m (linear dimensions of the projectile: length 1.8 cm, width 5.1 cm, thickness 4.0–3.2 cm). The figure shows sections of the surfaces of potential impact (perimeter A: 14.5 cm, diameter = 4.6 cm; perimeter B: 6.1 cm, diameter = 1.9 cm).

(60 m) can be critical (AIS 5—critical) and can pose a risk of serious head injury (AIS 4—severe) at a considerable distance (over 120 m) from the source of danger.

Table 8 presents the theoretical calculations of the predictors of injury from a steel ball weighing 135 g, which, in our tests, was found at a distance of 201 m from the point of origin. These data show that the impact force of a projectile shot from a sling at the distance of 201 m, reaches 3.5 kN, while the severity of blunt trauma reaches AIS 3 level for the body and AIS 5 for the head. Taking into account that in 19% of the cases in our tests, the velocity values of a projectile shot from a sling ranged from 38 to 50 m/s; projectiles shot at this velocity carry a significant traumatic potential, even at distances of up to 200 m from the point of origin. Depending on the weight of the projectile, the injury can be classified as having a strong or very strong impact, thus leading to

Table 4
Specific kinetic energy of steel balls of different diameters shot from a sling.

Distance (meters)	Impact area (cm^2)	Specific kinetic energy (J/cm^2)		
		Mean	Min	Max
	Steel ball—150 g (D = 24 mm)			
0	4.52	7.35 ± 1.66	4.77	10.7
20	4.52	5.65 ± 1.48	3.78	8.17
40	4.52	4.85 ± 1.47	3.22	7.2
60	4.52	4.59 ± 1.29	2.86	6.82
	Steel ball—135 g (D = 32 mm)			
0	8.04	7.34 ± 2.75	3.67	11.74
20	8.04	5.89 ± 2.26	3.26	10.05
40	8.04	5.69 ± 2.13	2.97	9.59
60	8.04	6.46 ± 1.13	3.99	8.17
	Steel ball—227 g (D = 38 mm)			
0	11.34	7.28 ± 2.86	4.17	12.4
20	11.34	6.05 ± 2.12	3.77	8.95
40	11.34	5.51 ± 2.05	3.1	8.19
60	11.34	7.19 ± 0.92	5.43	8.07

Table 5
Estimated ballistic parameters of an asymmetrical stone (weight 160 g) shot from a sling at various distances.

Distance (m)	Velocity (m/s)	Energy (J)	Specific E (J/cm^2)[a]	Specific E— (J/cm^2)[b]
0	30.8	75.9	4.5	27.1
10	29.9	71.5	4.3	25.5
20	29.0	67.3	4.0	24.0
30	28.0	62.7	3.8	22.4
40	27.0	58.3	3.5	20.8
50	26.0	54.1	3.2	19.3
60	25.1	50.4	3.0	18.0
100	24.9	49.6	3.0	17.7
128	24.3	47.2	2.8	16.9

[a] Impact area –16.7 cm^2 (line B—Fig. 2).
[b] Impact area –2.8 cm^2 (line A—Fig. 2).

Table 6
Blunt trauma criterion and AIS values for a steel ball (weight = 227 g, diameter = 38 mm) shot from a sling.

Distance (meters)	Velocity (m/s)	Energy[a] (J)	Chest		Head	
			BC	AIS	BC	AIS
0	35.2	140.6	1.584	3	3.222	5
20	29.9	101.5	1.258	2	2.895	4
40	28.6	92.8	1.169	2	2.806	4
60	28.4	91.5	1.155	2	2.792	4

m/s—meters per second; BC—blunt trauma criterion; AIS—Abbreviated Injury Scale.
[a] Energy calculations were based on real size, weight, and speed of the projectile (as it was measured by the radar) in different parts of the trajectory.

Table 7
Blunt trauma criterion and AIS values for asymmetrical stone (weight 160 g) (Fig. 2) shot from a sling, at various distances from the point of origin.

Distance (meters)	Velocity (m/s)	Energy (J)	Impact diameter = 4.6 cm				Impact diameter = 1.9 cm			
			Chest		Head		Chest		Head	
			BC	AIS	BC	AIS	BC	AIS	BC	AIS
0	30.8	75.9	0.776	2	2.464	4	1.650	3	3.146	5
10	29.9	71.5	0.717	2	2.404	4	1.591	3	3.087	5
20	29.0	67.3	0.656	1	2.343	4	1.530	3	3.026	5
30	28.0	62.7	0.586	1	2.273	4	1.460	3	2.956	5
40	27.0	58.3	0.513	1	2.200	4	1.387	2	2.883	4
50	26.0	54.1	0.438	1	2.125	3	1.311	2	2.808	4
60	25.1	50.4	0.367	1	2.054	3	1.241	2	2.737	4
100	24.9	49.6	0.351	1	2.038	3	1.225	2	2.721	4
128	24.3	47.2	0.302	1	1.990	3	1.176	2	2.672	4

m/s—meters per second; BC—blunt trauma criterion; AIS—Abbreviated Injury Scale.

Table 8
Estimated ballistic parameters of a steel ball shot from a sling at maximum range (according to the simulation data—up to distance 200 m).

Weight (g)	V_{term} (m/s)	Energy (J)	Specific E (J/cm^2)	Force (N)	BC (Chest)		BC (Head)	
135	39.5	105.3	13.1	5333	1.467	AIS = 3	3.028	AIS = 5

V_{term}—calculated terminal velocity of the projectile shot from a sling, considering the initial velocity V_0 equal 50 m/s.

fractures of the ribs, individual bones of the limbs, facial bones, and the cranium.

3.4. Personal protection equipment

The data presented may have practical importance for law enforcement authorities when encountering riots, as any injury, even a slight one, can affect the quality of performance of official duties. Offenders who use improvised projectiles during riots are unconstrained by any rules or restrictions. These projectiles can connect with a head or any other part of the body, therefore, the police must use riot helmets and face shields for head protection and riot gear (protective clothing and equipment for use in violent situations) to protect their trunk and extremities.

According to standard requirements, helmets must withstand a peak force of up to 16 kN and face shields up to 6.6 kN. Levels of protection of the body from blunt trauma to soft tissues of the human body range from 4 kN to 8 kN, depending on the area of the trunk protected, according to the BS 7971 standard and up to 10 kN according to the Home Office Scientific Development Branch (HOSDB) standard. It is worth mentioning that testing of protectors for different parts of the body and limbs has been performed at kinetic energies of 15 J and 30 J for the BS 7971 standard [42] and up to 40 J for the HOSDB Blunt Trauma Protector Standard for UK Police [43]. These energies are significantly lower than the actual energy of stones and other makeshift projectiles shot from a sling; consequently, a projectile hitting the protective equipment with its smallest contact surface can cause damage. In general, the protective equipment discussed can quite successfully withstand the traumatic potential of stones shot from a sling.

4. Conclusions

The data presented demonstrate that projectiles shot from unconventional weapons such as a sling have serious traumatic potential for unprotected human beings and can cause fractures of the trunk, limb and facial skull bone, causing blunt trauma of moderate to critical severity, depending on the weight and shape of the projectile and on the distance from the source of danger. Asymmetrically shaped projectiles weighing more than 100 g are the most dangerous.

Projectiles weighing more than 100 g can cause bone fractures of the trunk and limbs at distances of up to 60 m from the target and may cause serious head injuries to an unprotected person: AIS 4–5 at distances >100 m from the target, up to 200 m.

According to the data presented on the traumatic danger of projectiles shot from a sling, the police must wear full riot gear and keep a distance of at least 60 m from the source of danger to avoid serious injury. In addition, given the potential for serious head injuries, wearing a helmet with a visor is mandatory at distances up to 200 m from the source of danger.

Conflict of interest

None.

Author contributions

Igor Borovsky: study design, data analysis, interpretation of the data, approval of final draft.

Zvi Lankovsky: study design, interpretation of the data, approval of final draft.

Leonid Kalichman: interpretation of the data, drafting of the manuscript.

Victor Belkin: study design, data analysis, interpretation of the data, drafting of the manuscript.

All authors have approved the final article.

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