EVALUATION AND TYPES OF ATTACKS WITH STABBING WEAPONS FOR THE DESIGN OF PROTECTIVE EQUIPMENT

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Abstract

Knife attacks have become a global problem in recent years, especially in countries where access to firearms is limited. However, the current situation is that the method of selection and characteristics of protective equipment about the physical attributes of stabbing attacks is not systematically determined. Attacks with stab weapons can be divided according to the weapon's grip, the angle of the attack, and its execution into six different attacks (e.g., underarm action stab, overarm action stab, etc.). Our work presents a survey of methods for capturing and then evaluating the physical parameters of point attacks in specific motion capture and analysis programs. In this work, kinematic analysis was used to analyze motion during a stabbing attack and to obtain data on the kinetic energy of the stab. The measurements were performed with the MoCap system - Vicon Nexus 2.70. The results of the study show that the average value for the straight stab and the underarm stab is almost the same (66.5–67.1 J), while the overarm stab reaches a much higher value (92.8 J). The study aims to determine the kinetic energy of types of attacks, for standards state the level of protection based on energy levels. The results could provide new insights into the current state of protective equipment and energy values in national/international standards.

Keywords

MoCap system, motion analysis, knife attack

Introduction

Knife attacks have become a global problem in recent years, particularly in countries where access to firearms is restricted. The advantage of cold weapons over guns is their availability and the fact that they are more easily concealed and do not require special training in their use. This advantage has contributed to the significant increase in these crimes in the last few years [1]. Despite the increased risk of this threat, the current problem is that the selection and characteristics of protective vests for the most common types of attack are not systematically established.

Parameters monitored in assessing the biomechanics of a knife attack include speed, energy, segment and knife momentum, applied force, and torque. Since all current standards define the impact energy that body armor must stop, this is the primary required measurement of impact energy [2]. Several methods can be used to analyze each parameter.

The first approach is to use Motion Capture (hereafter referred to as "MoCap") systems [2]. Among these systems used to study the biomechanics of stabbing is Vicon (Vicon, Oxford, UK) [2]. Other MoCap systems used in biomechanics include Qualisys (Qualysis, Gothenburg, Sweden), OptiTrack (Corvallis, Oregon, USA), and others [3]. These alternatives have also proven to be useful in the analysis of upper limb movement biomechanics [3]. MoCap systems are based on the principle of tracking infrared (passive/active) optical markers using a set of cameras [4]. Measurement using passive infrared markers is more convenient because it requires only independent, reflective markers on the skin/clothing of the subject. In contrast, active markers (standard infrared LEDs) require a connection to a battery via power cords [4]. Functional markers, however, compensate for this disadvantage with easier data processing, including the unmistakability of the markers when covered or nearby [4]. For systems that use passive markers (Vicon, Qualisys), despite several algorithms that automatically recognize the identity of the marker-based on it is likely trajectory, the data must be cleaned manually [5].

The second approach for measuring the strength of the attack is to use a specially developed knife to measure the power and speed of the attack [6]. The stab force is measured using strain gauges that are built into the handle of the blade [6]. The speed of attack is

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measured by accelerometers mounted on the back of the handle [6]. The aim of the attack is usually a standard target composed of several layers of Kevlar [6]. For example, a box containing plasticine can be used to simulate the conformation of the human body [6].

The third approach for measuring knife biomechanics is to measure the stab force via a dynamometer [1]. This device consists of a dashboard that is used for dynamic force measurement [1]. This method was used in a study by [1].

The above-mentioned approaches can also be combined [2]. For example, in the study by [2], the methods of a camera system for motion analysis and an instrumented knife for force measurement are combined.

This study aims to determine the kinetic energy of types of attacks using the MoCap system, for standards state the level of protection based on the energy levels. The results can provide new insights into the current state of protective equipment and energy values in national/international standards.

Methods

To calculate the total attack energy, it is first necessary to know the kinetic energy of the body segments ($E_{k,seg}$) [7]. The kinetic energy of the segments is calculated as the sum of the translational and rotational energy [7]. The translational energy of a segment is calculated from its mass and velocity and the rotational energy is calculated by knowing the moment of inertia and angular velocity of the segment. The mass of each segment is known from the biomechanical table, see Tab. 1 [8]. Other quantities such as segment velocities, segment moment of inertia, and segment angular velocity are determined by motion analysis software programs [7].

$$E_{k,seg} = \frac{1}{2}\sum[m_i(v_i - v)^2 + I_i\,(\omega_i - \omega)^2], \qquad (1)$$

where (m) is the segment's mass, (v) is the velocity, (I) is the moment of inertia and (ω) is angular velocity [7]. The total attack energy (E_k) is then obtained by summing the kinetic energies of all connected segments [7]. This energy is then converted to the strain energy (E_p) caused by the impact on the target object [7].

$$E_k = \sum E_{k,seg} \rightarrow E_p = \frac{1}{2}\,k\chi^2, \qquad (2)$$

where (k) is rigidity, (χ) is a change of object length [7]. The calculation of anthropometric data is given by the statistical results of previously published research [8]. As an example, we give the calculation of the weight of a body segment.

$$m_i = B_0 + B_1 \cdot m + B_2 \cdot w, \qquad (3)$$

where (m) is body weight in kilograms and (w) is body height in centimeters [8].

Table 1: Table for calculating the segment mass according to Zaciorsky and Selujanov. Reprinted from [8].

Segment	B_0 (kg)	B_1 (-)	B_2 (kg·cm^{-1})
Head	1.296	0.0171	0.0143
Upper Trunk	8.2144	0.1862	-0.0584
Mind Trunk	7.181	0.2234	-0.0663
Lower Trunk	-7.498	0.0976	0.04896
Thigh	-2.649	0.1463	0.0137
Shank	-1.592	0.03616	0.0121
Foot	-0.829	0.0077	0.0073
Upper arm	0.25	0.03013	-0.0027
Forearm	0.3185	0.01445	-0.00114
Hand	-0.1165	0.0036	0.00175

Measurement procedure

Six volunteer members of the security forces and armed forces were asked to perform three styles of stabbing with maximum effort: straight action stab, underarm action stab, overarm action stab. Subjects performed 5 stabs for each style, see Fig. 1. The group of volunteers consisted of 6 males, their body weights ranged from 75 kg to 98 kg, and their heights varied from 1.72 m to 1.90 m. Study approval was granted by the Ethics Committee of the Faculty of Biomedical Engineering of the Czech Technical University in Prague.

Reflective markers were placed on the proband according to the IOR Gait Full-Body Model on the corresponding anatomical points [9]. Based on the placement of the markers on the human body, selected body segments can then be defined. A total of 38 markers were placed on the subjects.

Fig. 1: Volunteer performing a knife attack.

Data processing

Motion measurements during the attack were made using 6 static and 1 portable Bonita 10 cameras at a sampling frequency 100 Hz (Vicon, Oxford, UK). The cameras capture images through an infrared filter. Each camera has stroboscopic infrared LEDs placed around its lens, emitting IR radiation that is reflected

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from reflective markers back to the camera lens, where it is then converted into a video signal [10]. If the images from two or more cameras are combined and the angle between the optical axes is 90°, it is possible to create 3D models from the analyzed points and calculate the basic kinematic parameters (trajectories, angle, velocity, acceleration, etc.) in the computer unit using Vicon Nexus 2.70 software (Vicon, Oxford, UK) [11].

To calculate the kinematics and kinetics of motion in this program, it was necessary to create the model as a series of rigid segments, see Fig. 2. To create the individual body segments, it was necessary to specify the appropriate mass and height of the proband. Subsequently, the mass of the proband's body segments was calculated using the biomechanical table to calculate the mass of the body segments [9].

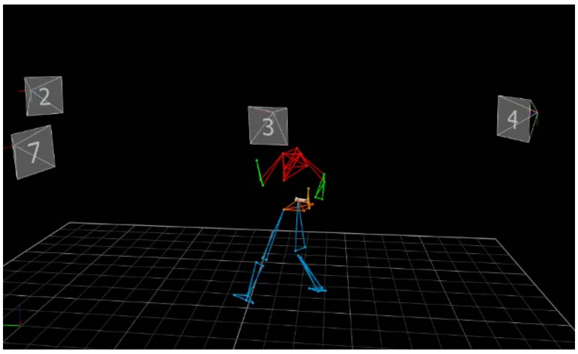

Fig. 2: Model of knife attacker in program Vicon Nexus 2.70.

Necessary results to determine the kinetic energy of each attack type were obtained in Matlab R2019a (MathWorks, Massachusetts, USA)

Results

The results for the different styles of stabs are shown in Table 2.

Table 2: Summary of results.

Attack type	Mean (J)	Maximum (J)	Total
Straight	66.5	100	
Overarm	92.8	126	75.5
Underarm	67.1	104	

Table 2 shows that the average value of the straight and underarm is almost the same (66.5–67.1 J), while the overarm reaches a much higher value (92.8 J). This is because the overarm action is an arcing stab, and the trajectory of the attacks is longer than the other two attacks. The physical relationship for calculating segment velocity shows that if the trajectory along which a body segment accelerates is longer, it will reach a higher velocity. This affects the kinetic energy of the body segment and consequently the total kinetic energy of the attack [12].

Recommended values for the physical properties of vests based on the most common stabbing attacks are as follows. The result of the measurements shows that the average value of the straight action stab and underarm action stab was around 66.5–67.1 J. These attacks are most often directed to the middle zone where the vital organs (heart, lungs) are located. The average value of the overarm stabbing action was higher, around 92.8 J. This attack is directed to the upper zone on the neck and head. The upper zone is difficult to protect as conventional vests usually do not provide good protection for the neck and shoulders. Neck protection is usually added in the form of a collar and shoulder strap. The mentioned protection zones have been marked on the body to show the degree of protection of the vest according to the type of attack and vital organs, see Fig. 3. Red indicates the highest level of protection, yellow the medium level of protection and green the lowest level of protection.

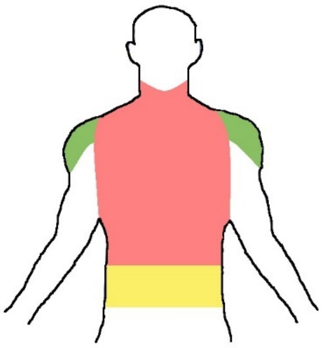
Fig. 3: Design of protection zones according to the degree of protection.

Based on the knowledge gained, the highest level of protection of protective vests against stabbing weapons in the torso and neck area is recommended, i.e., protection level II-IV depending on the type of standard [13–17]. This area contains vital organs and arteries and is also the most affected area in the event of a stabbing attack. At least a medium level of protection is recommended in the abdomen, i.e., protection level II-III depending on the type of standard [13–17]. This area does not contain vital organs and is not a site of fatal injury. In the event of the overarm action, the shoulder area may also be affected. In the event of a hit, it does not act as a lethal zone, so the lowest level of protection, protection level I, is sufficient [13–17].

Discussion

This study shows that the average value of a straight action stab is about 66 J, an underarm action stab is

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about 67 J, and an overarm action stab is about 92 J. The overarm action stab shows much higher values compared to previous attacks. This can be explained by the fact that the execution of the overarm action stab takes place in an arc, so the attack path is longer. In that case, the body segment will reach a higher speed, so the kinetic energy of the segment is higher and consequently the kinetic energy of the attack. The energy of these three most common types of attacks is, on average, around 75 J, which corresponds to IV. degree of protection of the VPAM KIDW 2004 standard (65–80 J) [17]. NIJ Standard-0115.00 specifies safety vests for security corps at NIJ level II (33 J and 50 J) [13], a medium level of protection and lower than the study results (75 J). Although the values of energies obtained during the measurement seem to be somewhat high, it should be noted that the subjects were from security corps and armed forces with special training. Large and strong subjects also figured in the measurement. These values, therefore, represent the maximum threat that can be faced. If the average person did not have special training, the values are likely to be much lower, and therefore a lower level of protection would suffice.

When designing safety vests, we recommended three zones, which suggest degrees of protection according to valid international standards for testing the resistance of protective vests against stabbing weapons. In order to achieve the appropriate degree of protection, materials are often combined, or in the case of a soft type of protective vest, layers of material are combined. This, in turn, affects the weight and overall flexibility of the vest. Therefore, it is impractical to design a vest with the highest degree of protection in all zones of a protective vest.

The primary purpose of this study was to provide information on methods for measuring knife biomechanics. We chose the first approach in the study—evaluating stab attacks using the Mocap system (Vicon Nexus). The advantage of this approach is that it is possible to analyze the entire course of individual attacks, unlike other approaches. Furthermore, several parameters can be evaluated. The disadvantage is the time-consuming processing of data and results. The biggest challenge of this method is that the marker must be captured at least by two cameras and must not be obscured by anything for the image to be displayed correctly. When measuring stab attacks, the subject had an inactive upper limb in the so-called combat position, which meant that the markers were covered. The program could not automatically assign it to the relevant body segments. Therefore, a manual so-called "cleaning" of data was required when the undefined marker had to be manually marked and redefined. This process is time-consuming but necessary for further evaluation. The solution to this problem may be that the subject will have an inactive upper limb close to the body during the next measurement, covering several markers in the lower band which, however, are not necessary for the evaluation. For this type of study, it is important to see the upper limb segments that perform the attack and the torso segment. The other two approaches to measuring the biomechanics of stabbing have the advantage of not having a complex procedure to obtain results. However, the disadvantage is that these methods make it possible to monitor only the parameters of the force and the stab speed, so to calculate the kinetic energy of the stab, it is necessary to rest over the appropriate physics formula.

Conclusion

This study presented different perspectives on the measurement of stabbing biomechanics, mainly focusing on motion capture and evaluation using the Vicon Nexus software program. A group of volunteers performed simulated stabbing attacks and control parameters were measured. The results showed that the kinetic energy of the straight action stab and underarm action stab averaged 66–67 J. The kinetic energy of the overarm action stab averaged 92 J. This study developed methods for the comprehensive evaluation of knife stabbing mechanics. This study can be used for further research to quantify the energy levels of the most common stabbing attacks and can also be conducted on the general population.

Conflict of Interest

None to report.

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