Krzysztof BASZCZYŃSKI
CENTRAL INSTITUTE FOR LABOUR PROTECTION – NATIONAL RESEARCH INSTITUTE
DEPARTMENT OF PERSONAL PROTECTIVE EQUIPMENT
48 Wierzbowa St., 90-133 Łódź

The application of a Hybrid III anthropomorphic dummy in testing personal fall arrest equipment

Abstract

The paper deals with measurement of the mechanical parameters describing fall arrest by personal protective equipment in situations where the user collides with a vertical structure as a result of a swing movement. The process of swing fall arrest is characterized and the scope of tests needed to obtain a description of such events from the point of view of user safety is delineated. The paper also presents the developed test method and experimental stand incorporating a Hybrid III 50th Pedestrian ATD anthropomorphic dummy. Preliminary test results concerning acceleration, force, moment of force, and dummy deformation are discussed. The results indicate that the designed method and experimental stand are well suited for the purpose. It has also been found that swing falls pose a serious hazard to PPE users.

Keywords: anthropomorphic dummy, fall from height, pendulum motion, measurement of mechanical parameters.

1. Introduction

Analysis of annual reports from the Central Statistical Office (GUS) and the National Labor Inspectorate concerning accidents at work in Poland reveals that one of their main causes is fall from height. For instance, according to GUS data [1], in 2015 there were 5452 such accidents causing 29 fatalities and 55 grave injuries. The industrial sectors with the greatest incidence of accidents involving fall from height include manufacturing, construction, transport, and warehousing.

One of the most effective and widespread methods of preventing falls from height is the use of specialized personal protective equipment consisting of the following components [2,3]:

- anchor device,
- shock-absorbing connecting assembly,
- full body harness.

The anchor device is directly connected to the structural elements of the work site. Its aim is to transfer the fall arresting force to the aforementioned structural elements, which should meet appropriate strength characteristic. Examples of such devices include connectors [4], mobile anchor devices [5], webbing and rope connectors, etc.

The shock-absorbing connecting assembly connects the anchor device to the full body harness worn by the user. The purpose of this element is to safely arrest the fall of the user. Here, safety is defined as prevention of forces acting on the harness attachment point larger than 6 kN and minimization of the fall distance. Examples of shock-absorbing connecting assemblies are lanyards with integrated textile energy absorbers [6] and guided type fall arresters on flexible anchor lines [7].

The full body harness [8] is donned by the user. Its main purpose is to distribute the dynamic forces generated during fall arrest to those body parts that are characterized by suitable resilience and to ensure that both during and after fall arrest the user retains an appropriate position.

For many years now, the mechanics of fall arresting by personal protective devices has been investigated by research institutes and laboratories dealing with occupational safety. Research work has focused on the forces and accelerations exerted on the user upon fall arrest by different types of protective equipment, as well as on estimating fall distance [9–13]. However, while both theoretical simulations and laboratory experiments have been mostly employed to describe idealized situations in which the user falls vertically without any contact with the structural elements of the work site, analysis of actual workplace accidents under industrial conditions has shown that the user's collision with such elements may be equally harmful. Of particular note is impact resulting from the swing movement arising during fall arrest. This may occur if, at the beginning of the fall, the user is horizontally displaced with respect to the point at which the shock-absorbing connecting assembly is attached to the anchor element (see Figure 1).

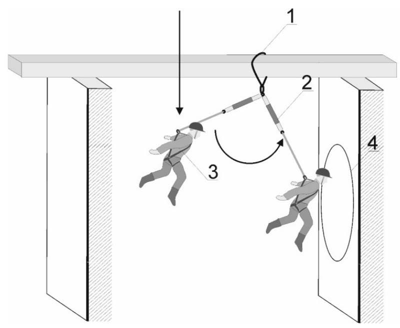

Fig. 1. Swing fall and collision with a vertical structural element of the work site during fall arrest; 1 – anchor device, 2 – lanyard with integrated energy absorber, 3 – full body harness, 4 – impact zone

Due to the user's high kinetic energy, a collision with a structural element, such as a wall, may pose a major hazard to his or her health or life. The high urgency of this problem with respect to persons working at height has provided a stimulus for research into these issues.

As experimental studies on the mechanical phenomena occurring during a swing fall cannot involve humans, an anthropomorphic dummy was applied to imitate the mechanical properties of the human body. Currently, one of the most advanced test dummies is the Hybrid III, which is widely used in vehicle safety testing. This paper presents an application of the Hybrid III dummy for investigations of performance of personal fall arrest equipment in situations of collision with vertical structural elements of the work site upon a swing fall.

2. The use of dummies in safety testing

The basic tool currently used in full body harness testing under dynamic conditions is a rigid dummy conforming to the standard EN 364:1992 [14]. It is a 100 kg torso model with the center of gravity determined on the basis of anthropometric measurements, and it is primarily used for testing strength properties. In this case, the only parameter linked to harness behavior upon fall arrest is the angle formed between the back of the dummy and the vertical plane. In terms of mechanical parameters, that dummy is not a very good representation of the human body, and so it is not suitable for advanced studies on mechanical behavior during fall arrest.

With the development of road transport and aviation, increasing attention has been given to the problems of safety. As a result, researchers have long worked on developing models of the human body that could simulate its behavior upon accidents, such as motor vehicle collisions. The first anthropomorphic dummies designed according to those premises were created at the end of the 1940s. A good, modern example of the development of anthropomorphic dummies is the Hybrid series [15]. Of particular note is the model Hybrid III, which has been used for human safety testing in various fields, such as the automotive and bicycle industries, sports (e.g., skiing), and falls on flat surfaces [16–22]. Importantly, the study [23] investigated the usefulness of the Hybrid III head/neck assembly in testing sports headgear. A Hybrid II dummy was also used for testing individual fall arrest equipment in the absence of collision with structural elements of the work site [24].

3. Method and experimental stand

For the purposes of determining the mechanical phenomena occurring during swing fall arrest accompanied by a collision with vertical structural elements of the work site, a test method and a dedicated experimental stand were developed. The method was based on the following main premises:

- ability to study the mechanical factors having a significant effect on human safety;
- simulation of the fundamental conditions of swing fall arrest,
- ability to test different types of personal fall arrest equipment,
- use of a dummy that would reflect, to the greatest extent possible, the mechanical properties of the human body.

The developed test method, meeting the above requirements, involves an anthropomorphic dummy which is dropped from a height and whose initial free fall is arrested by some personal fall arrest equipment. The horizontal displacement of the point of attachment of the shock-absorbing connecting assembly with respect to the initial position of the dummy causes pendulum-like swing motion. The final stage of a swing fall ends with an impact of the dummy against a vertical flat element (a weight-bearing wall reinforced with an aluminum plate). The time courses of the mechanical parameters characterizing the behavior of the dummy are recorded throughout the fall arrest and upon impact by means of sensors installed in the dummy, a force sensor connected with the shock-absorbing connecting assembly, and a high-speed digital video camera. The data are analyzed after the cessation of dummy movement. Tests are conducted according to this method using a purpose built experimental stand constructed at the Department of Personal Protective Equipment, Central Institute for Labour Protection – National Research Institute. For a schematic see Figure 2.

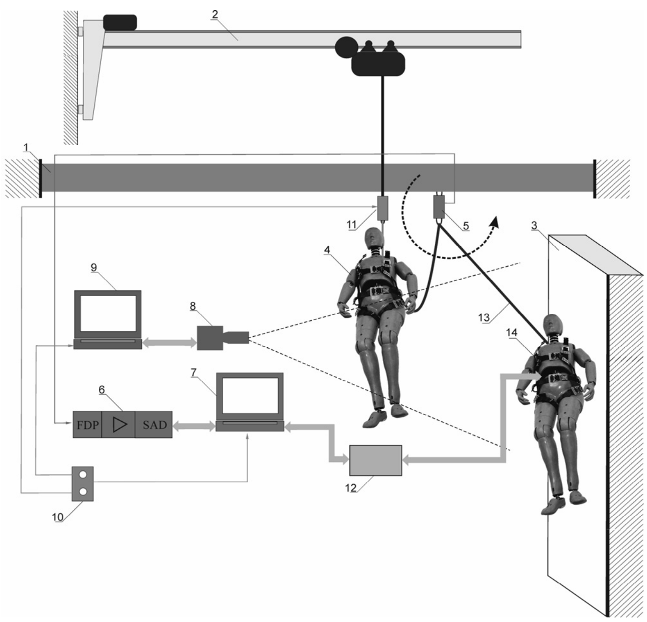

Fig. 2. Experimental stand for studying mechanical phenomena accompanying a swing fall arrest terminated with an impact against a vertical flat structural element. 1 – rigid beam, 2 – wall-mounted crane, 3 – weight-bearing wall with an aluminum plate, 4 – anthropomorphic dummy, 5 – force transducer, 6 – data acquisition system with an analog filter and amplifier, 7 – computer, 8 – high-speed digital camera, 9 – computer connected to the camera, 10 – latch controller, 11 – electromagnetic latch, 12 – interface, 13 – shock-absorbing connecting assembly, 14 – full body harness

The main structural element of the stand is a 3-meter long square-section rigid beam (1) installed in the weight-bearing walls of the laboratory. The beam is made of welded steel elements. Its rigidity at the point of loading conform to the standard EN 364:1992 [14], which specifies requirements on measurement apparatus used in testing personal fall arrest equipment. The beam is equipped with a mobile holder for a force measurement transducer (5). One end of the beam (1) is installed above the weight-bearing wall (3) with a 5 mm thick aluminum plate with a size of 1.5 x 3.0 m. That aluminum-reinforced wall fragment forms a rigid surface for testing dummy behavior (4) upon impact while in a swing fall. The experimental stand is equipped with a wall-mounted crane (2) which can move the dummy both vertically and horizontally to a desirable position with respect to the point of attachment of the shock-absorbing connecting assembly (13) to the beam (1). The hook of the crane (2) is attached to an electromagnetic latch (11), which holds the dummy prior to fall initiation. The latch can be released by means of an electrical signal from the controller (10). Furthermore, the experimental stand has a system measuring the force acting at the point of attachment of the shock-absorbing connecting assembly during fall arrest. The system consists of a 9B-20kN force measurement transducer from Hottinger (5) connected to MGA II amplifiers from Hottinger, a MS210R/ET6 programmable analog filter from IMD and a KUSB 3116 data acquisition system from Keithley Metrabyte (6). The system records the time course of the force arresting the fall of the dummy in the computer memory (7). The amplitude and frequency parameters of that force measurement system comply with the standard EN 364:1992 [14] and the Recommendation for Use [25]. The data acquisition system (6) is activated by a signal from the device (10) controlling the electromagnetic latch. Thus, the recorded force time course encompasses both the free fall and fall arrest stages.

A Cube 7 MotionBLITZ®EoSens fast-speed digital camera (8) from Mikrotron GmbH records the movement of the dummy upon collision with a vertical surface (3). The camera is connected to a computer (9), which is used to program the recording mode and to download data (images recorded at a preset speed). The camera is triggered in sync by the controller (10). The experimental stand is used in conjunction with a Hybrid III 50th Pedestrian ATD anthropomorphic dummy from Humanetics (4). The internal measurement system of the dummy is programmed prior to testing by means of a computer (7) through an interface (12). Following the tests, data from the internal memory of the dummy are transferred to the computer (7) for further processing.

4. Anthropomorphic dummy

The selection of an anthropomorphic dummy to be used in conjunction with the constructed experimental stand was informed by the following requirements:

- the closest possible correspondence with the mechanical properties of the human body under the studied circumstances,
- the most accurate simulation of falls arrested by personal protective equipment,
- ability to be used with individual fall arrest equipment, and especially safety harnesses conforming to the standard EN 361:2002 [8],
- ability to measure mechanical parameters linked to the safety of the users of personal fall arrest equipment.

Based on publications [19, 23, 24], it was found that the above conditions were met by the Hybrid III 50th Pedestrian ATD anthropomorphic dummy from Humanetics [15]. This dummy was primarily designed to simulate pedestrians in traffic safety testing. Its pelvis enables both an upright and seated position, due to which it can be used in conjunction with fall-arrest harnesses. This 78.15 kg dummy was constructed based on the 50th percentile of selected anthropometric traits from the US population. The dummy was equipped with measurement transducers, as described in Table 1 and shown in Figure 3.

Tab. 1. Measurement transducers installed in the anthropomorphic dummy

No.	Measured parameter	Number of transducers	Measurement range
1	Head acceleration in three orthogonal directions	3	± 1500 g
2	Chest acceleration in three orthogonal directions	3	± 1500 g
3	Pelvis acceleration in three orthogonal directions	3	± 1500 g
4	Chest deformation	1	± 75 mm
5	Force in the cervical segment of the spine acting at right angles to its axis	2	± 10000 N
6	Force in the cervical segment of the spine acting in parallel to its axis	1	± 14000 N
7	Moments of force in the cervical segment of the spine	3	± 300 Nm
8	Force in the lumbar segment of the spine acting at right angles to its axis	2	± 15000 N
9	Force in the lumbar segment of the spine acting in parallel to its axis	2	± 20000 N
10	Moments of force in the lumbar segment of the spine	3	± 600 Nm
11	Forces in the right and left thighs	2	± 14000 N
12	Forces in the right and left arm	4	± 12000 N
13	Forces in the right and left forearm	4	± 11000 N
14	Moments of force in the left and right arm	4	± 340 Nm
15	Moments of force in the left and right forearm	4	± 340 Nm

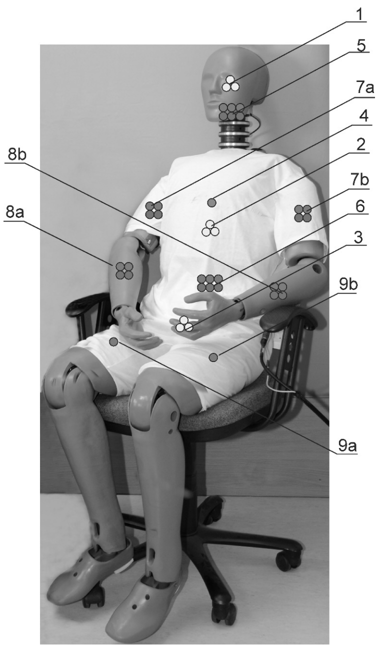

Fig. 3. Location of transducers in the Hybrid III 50th Pedestrian ATD dummy. 1, 2, 3 – three-axial accelerometers, 4 – chest deformation transducer, 5 – three-axial force and moment of force transducer in the cervical segment of the spine, 6 – three-axial force and moment of force transducer in the lumbar segment of the spine, 7a and 7b – two-axial force and moment of force transducers in the arms, 8a and 8b – two-axial force and moment of force transducers in the forearms, 9a and 9b – force transducers in the thighs

The dummy is equipped with an internal data activation system connected to the transducers, which is used to:
- power the mechanical quantities transducers,
- amplify and filter analog signals from the transducers,
- provide analog and digital processing of signals from the transducers,
- trigger measurement when a preset criterion is met,
- record measurement data,
- exchange control and measurement data with an external computer,
- signal of the current status, e.g., waiting for measurement trigger, completion of data recording, data transfer, etc.

Data acquisition modes are programmed using an external computer connected by a cable interface (12) (see Figure 2). After programming, the cable connection is removed, and the dummy is ready for measurement initiation (trigger). In tests of fall arrest equipment, measurement is most often initiated by a head acceleration threshold. The use of a measurement system that does not require a cable connection between the dummy and an external computer during measurement is particularly important in testing fall arrest equipment. On the one hand, the abrupt movements of the dummy during fall arrest could break the connection, while on the other hand the cables could interfere with the mechanical parameters of fall arrest.

5. Sample test results

A series of preliminary tests were conducted to evaluate the study methodology and the experimental stand. The anthropomorphic dummy was equipped with a full body harness with thoracic and dorsal attachment points [8] and a lanyard made of aramid fibers with low extensibility and terminated in a snap hook. In the tests, the input variables were:
- dummy free fall distance,
- dummy position prior to fall, e.g., upright with its front, back, or side facing the wall; horizontal with its head or legs facing the wall; leaning with the legs supported, etc.;
- horizontal distance between the electromagnetic latch (11) and the force measurement transducer (5) (see Figure 2),
- horizontal distance between the force measurement transducer (5) and the vertical wall (3) (see Figure 2).

The output variables included all the parameters given in Table 1 as well as the fall arrest force measured by a transducer at the point of attachment of the lanyard (5).

Sample photographs showing the position of the dummy upon collision with the vertical wall are presented in Figures 4 and 5.

Selected results from tests in which the initial position of the dummy was upright and the free fall distance was 0.5 m are given in Figures 6 and 7. The horizontal displacement between the electromagnetic latch (11) and the measurement force transducer (5) was 0.5 m.

Fig. 4. Collision of the dummy with the vertical structural element for a full body harness with a dorsal attachment point

Fig. 5. Collision of the dummy with the vertical structural element for a full body harness with a thoracic attachment point

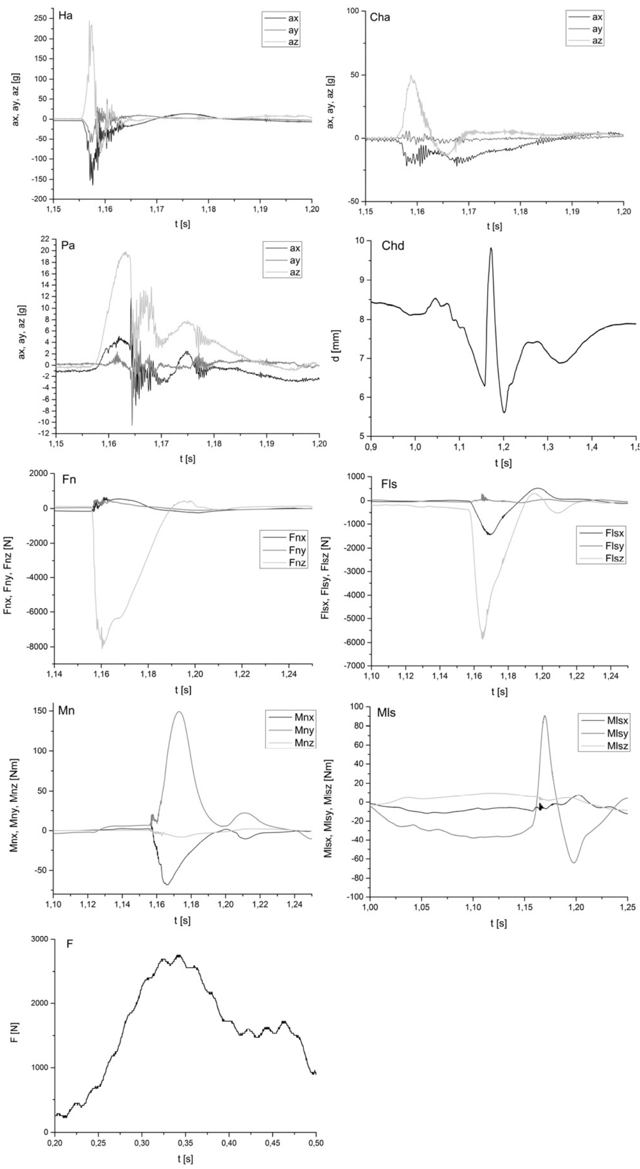

Fig. 6. Test results for a full body harness with a dorsal attachment point. Ha – head acceleration, Cha – chest acceleration, Pa – pelvic acceleration, Fn – forces in the cervical segment of the spine, Fls – forces in the lumbar segment of the spine, Mn – moments of force in the cervical segment of the spine, Mls – moments of force in the lumbar segment of the spine, F – force at the anchor point of the lanyard, Chd – chest deformation

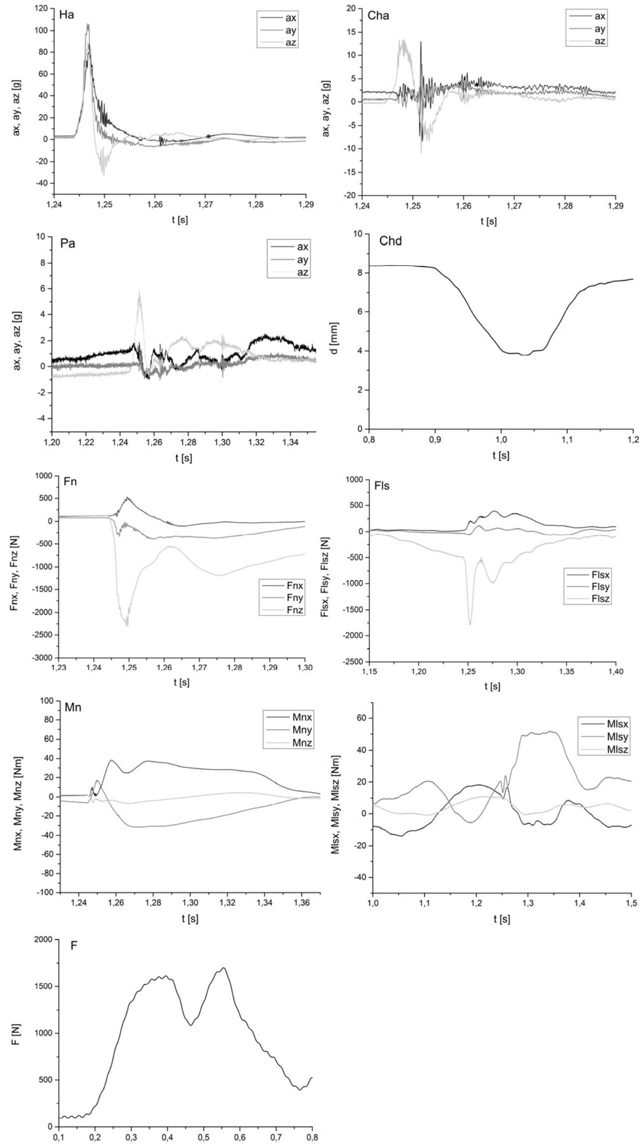

Fig. 7. Test results for a safety harness with a thoracic attachment point. Abbreviations as in Figure 6

Summing up the test results, it may be concluded that:

- the experimental stand made it possible to generate swing falls with the required parameters (amplitude, radius, final velocity of the dummy upon impact),
- the position of the dummy upon impact was significantly affected by the type of harness attachment point: when the dorsal attachment point was used, the dummy leant forwards and when the thoracic attachment point was used, it leant backwards;
- the maximum force recorded at the lanyard anchor point did not exceed 3 kN, and so it was less than 50% of the permissible value of 6 kN [6],
- the maximum head acceleration levels were 400 g, which is approx. 100 times as much as in a fall arrest without a pendular movement,
- the relationship between head, chest, and pelvis acceleration levels was determined by the position of the dummy upon impact against a flat wall,
- forces in the thighs reached approx. 2000 N when the knees impacted the vertical wall,
- forces in the arms and forearms reached up to 500 N when the arms hit the wall,
- forces in the cervical segment of the spine upon impact were up to 9000 N and were more than 60 times higher than those generated during fall arrest without a swinging movement,

- the recorded chest deformations did not exceed 10 mm, which is acceptable from the standpoint of human safety,
- the effects of the harness on the dummy did not lead to any dangerous situations, such as the displacement of the adjustment buckles, which could potentially injure the face.

6. Summary and conclusions

Analysis of the results of preliminary tests shows that the presented method and experimental stand enable excellent simulation of swing fall arrests terminated by a collision with a flat vertical surface. If a horizontal initial position of the dummy is desirable, then special “stretchers” released by the electromagnetic latch must be used. A Hybrid III 50th Pedestrian ATD dummy equipped as described above enables measurement of the most important parameters characterizing hazards to users of personal fall arrest equipment. Yet another advantage of the presented method and experimental stand is synchronous image recording by means of a fast-speed camera coupled with a data acquisition system, which facilitates the interpretation of the mechanical phenomena accompanying a collision with a vertical flat surface. The obtained results show the gravity of the swing movement problem during falls arrested by personal protection equipment. To date, the problem has not been adequately addressed either in the research literature or in practical guidelines for OSH services. The presented experimental stand is unique in Poland and further tests conducted on it may provide valuable information both for the safe usage of personal fall arrest equipment and for the development of new generation equipment.

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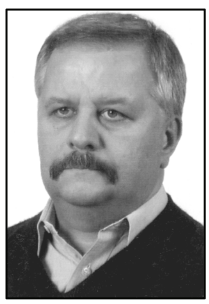
Krzysztof BASZCZYŃSKI, PhD, eng.



Krzysztof Baszczyński received MSc degree in electronics in 1985 and PhD in 1994 from the Technical University of Łódź, Poland. From 1985 he works in Department of Personal Protective Equipment of Central Institute for Labour Protection – National Research Institute. His research interests include especially test methods and studies of dynamic mechanical quantities associated with the operation of personal protective equipment.

e-mail: krbas@ciop.lodz.pl