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Original article

New solution to increase the safety of operating system with hydrostatic drive

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ABSTRACT

Hydraulic actuators that commonly used in machine work systems are not equipped with protection features preventing the autonomous insertion and extension of a piston rod because of the influence of external forces. Consequently, a spontaneous fall of working circuits in the event of the loss of tightness of supply lines of an actuator may occur. Currently applied safety features that are sometimes mounted directly on hydraulic cylinders as in the case of mining machinery intended for exploitation in black coal mines protect working systems from uncontrolled lowering. However, their design forces the drive to be started to make it safe to leave the work system. If, for any reason, the drive system of a machine cannot be started and the work system is raised, its lowering can take place only by unsealing the hydraulic system, which is unforeseeable for constructors and carries the danger of crushing a person or persons involved. The paper presents a new solution for hydraulic cylinders, which enables, among other things, the controlled and safe insertion of a piston rod under load without the need for having the drive system started.

KEYWORDS

hydraulic cylinder, work system, safety of servicing operations, emergency movements

1. Introduction

The development of the hydraulic propulsion technology and its undoubted advantages, the main of which is the ratio of the propulsion mass to the volume of power transmitted, has affected the universality of this type of drive in technology. Frequently, such a propulsion system is used to drive machine operating systems. The executive element (motor) in which the liquid energy is converted into the mechanical energy of motion in these applications is usually the hydraulic actuator. Its design provides significant resistance to external influences, ease of application and control executed through valves being an integral part of the hydraulic system. However, the relatively simple construction of the actuator providing a change in the energy of liquid to the mechanical energy also enables the reverse operation. In practice, this means that the hydraulic cylinder subjected to external load, connected to the liquid flow system from the actuator's chambers, will perform the working motion without the use of a hydraulic power supply source, i.e. a pump. This effect is commonly used in working systems to lower them. In this case, the amount of energy of the potential system that is used to induce liquid flow, i.e. ultimately to make the actuator or the actuator system operate, is reduced during motion. The presented process of lowering the working system does not require the use of the primary power source of the hydrostatic system, i.e. the hydraulic displacement pump. In the event of unsealing of the hydraulic lines that feed the actuator or the actuator system the describe method, the most energetically advantageous, results in an uncontrolled collapse of the operating system, thus creating a potentially hazardous situation. In order to prevent them, manufacturers of machinery and the OSH regulations prohibit staying under the raised working system. Another known solution concerns the use of return valves controlled in the so-called hydraulic locking system that prevents the working system from lowering without providing supply from the hydraulic pump. However, the abovementioned solutions and regulations do not eliminate completely the occurrence of dangerous situations, the analysis of which, together with the indicated way of preventing them, is presented in the study.

2. Construction of present hydraulic actuators

Hydraulic actuators as executing elements operate by extending or inserting moving parts as a result of liquid pumping. Single-acting actuators (for example forklift trucks, passenger cranes) and double-acting actuators (e.g. cantilever machine operating systems) are used in lifting systems. The single-acting actuator is equipped with only one hydraulic connection and one working chamber and allows the drive to be transmitted only during the insert, while its insertion is the effect of external force acting. The double-acting actuator is equipped with a piston that divides the inner space of the cylinder into two working chambers. The most common solution is a case in which the pressurized liquid is forced into the chamber under the piston, thus extending it out, which implies the lifting of the driven element of the operating system. The proposed way of applying actuators is not uncommon to be found in, for example, systems for lifting working elements of machines. A two-sided actuator has the ability to perform a working movement in the opposite direction when the liquid is pumped into the chamber on the piston side of the actuator. The possible location of lifting actuators is shown on the example of a loader in Figure 1.

The design of hydraulic actuators directly indicates the possibility of reversing their functions and performing work as an element transforming mechanical power into hydraulic power. For the analysis of this case, the dependencies commonly known from literature [Garbacik 1997; Stryczek 2003; Szydelski 1999] describing the work of actuators and their schemes (Fig. 2) can be used, taking into account the differences between single-acting (Fig. 2a) and double-acting actuators (Fig. 2b).

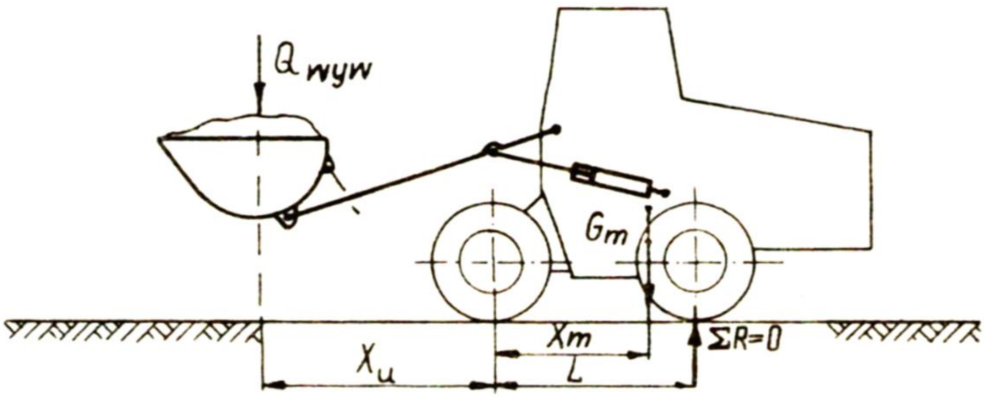

Fig. 1. Hydraulic actuator as the driving element of the lifting system on the example of a loader [Pieczonka 1975]

The basic dependence combining the parameters of the loading force of the single-acting actuator with the pressure values in the working chamber is as follows:

$$F_{z1} = p_{11} * A_{11} * \eta_{hmsłj} \tag{1}$$

where:

F_{z1} – external loading force,

p_{11} – pressure in the single-acting actuator operating chamber,

A_{11} – active surface of the single-acting actuator piston,

$\eta_{hmsłj}$ – mechanical-hydraulic performance of the single-acting actuator.

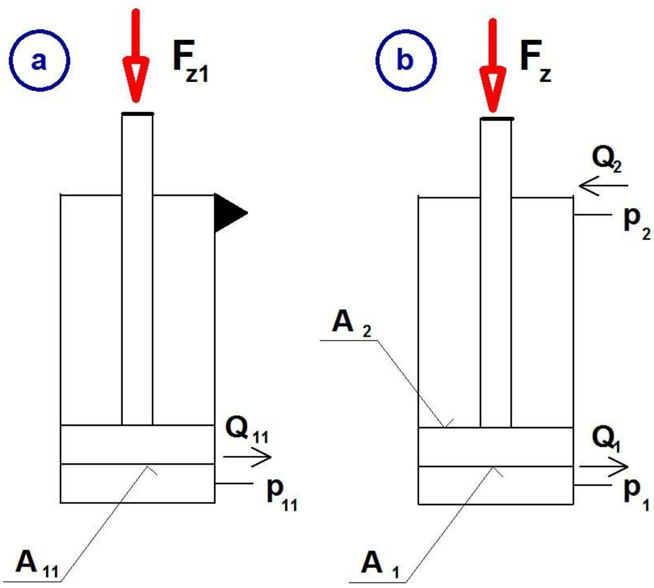

Fig. 2. Hydraulic and geometric parameters and loading forces of single-acting actuators (a) and double-acting actuators (b) – description in the text

Conversion of the above formula allows for the determination of the pressure value in the working chamber:

$$p_{11} = \frac{F_{z1}}{A_{11} * \eta_{hmsłj}} \tag{2}$$

Where the flow in the power supply line is possible and the supply pressure of the line is less than the pressure generated by the load (p_{11}) the liquid flow from the actuator (Q_{11}>0) will appear. In practice, this phenomenon occurs in two cases. The first one appears when the system is overdriven in such a way that the hydraulic power line is connected to the tank, which enables the liquid flow. The indicated configuration is used in the technology for lowering the loaded actuators without the hydraulic energy generated by the pump. The second case occurs when the hydraulic line feeding the actuator is damaged and the fluid can escape from the system. This case is an example of a sudden operation that is beyond control and, as a result, can cause the actuator, and consequently the elements that are driven by it, to fall freely.

When using a double-acting actuator, the relation between the force loading the piston and the pressure in the actuator chambers is as follows:

$$F_z = (p_1 * A_1 - p_2 * A_2) * \eta_{hmsł} \tag{3}$$

where:

F_z – external loading force,

p_1 – pressure in the chamber under the double-acting actuator,

p_2 – pressure in the piston chamber of the double-acting actuator,

A_1 –active surface of the double-acting actuator piston,

A_2 – active surface of the piston from the rod side in the double-acting actuator,

$\eta_{hmsł}$ – mechanical-hydraulic performance of the double-acting actuator.

By converting the formula as in the previous case, we obtain the following relation describing the pressure value in the chamber under the actuator piston:

$$p_1 = \frac{F_z}{A_1 * \eta_{hmsł}} + p_2 * \frac{A_2}{A_1} \tag{4}$$

In this case, the condition of the free flow of liquid from the under-piston chamber (Q_1>0) and the possibility of liquid supply to the piston chamber (Q_2>0) must be fulfilled to allow the free fall of the actuator as a result of the external force (F_z). In case of these actuators, the free fall under load is rarely used as working motion. It should be noted, however, that any damage to the hydraulic line feeding the actuator chamber under the piston allows the liquid to flow freely out of the chamber and the only, in practice insufficient, protection is the inability of the liquid supply into the piston chamber, in which case much less pressure than the atmosphere one is produced.

3. Analysis of hydrostatic structures of drive systems of tool-in-use systems

Currently used architecture of hydraulic systems introduces a division into the components of power, control and drive (motors) parts. A designer, based on his/her knowledge and experience, selects components in each of the aforementioned parts of the hydrostatic system in such a way that the assumed functions and operating parameters of the system are achieved. The individual parts of the systems are connected by hydraulic lines and possibly control lines. In the rest of this article, the analysis of the operation of exemplary hydraulic drive systems of actuators, broken down into systems with backstops and without. The analysis will be conducted for the following possible emergency situations, which may occur singly or in combination:

1) damage to the hydraulic supply line of the actuator;
2) damage to the hydraulic drive of the displacement pump, the pump itself or the discharge line;
3) damage to the hydraulic control system.

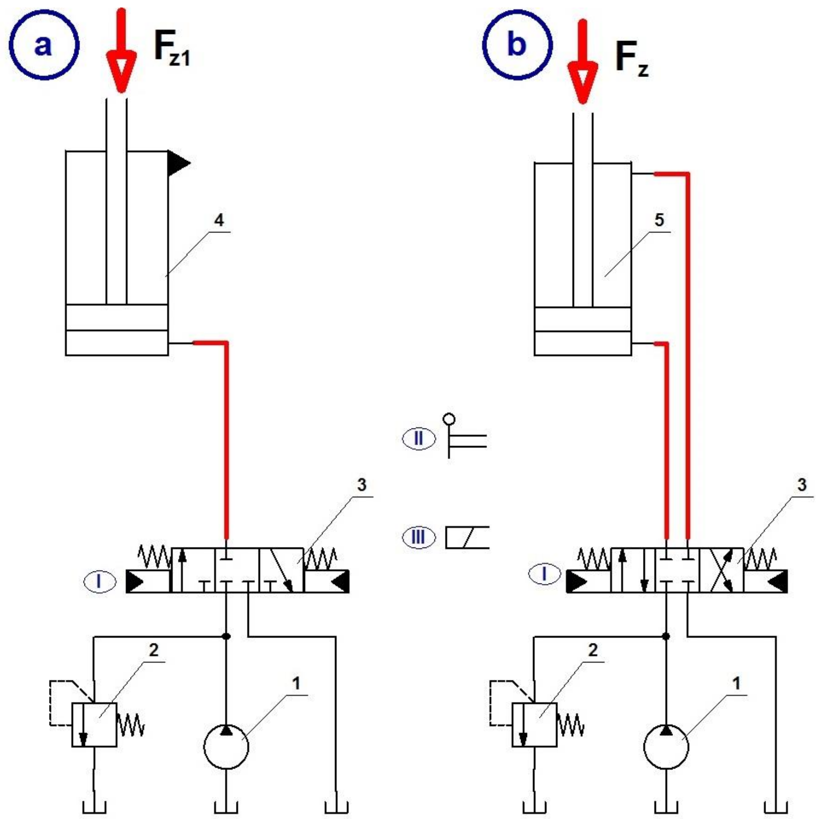

Fig. 3. Supply systems without safety check valves
for single-acting (a) and double-acting (b) actuators used – description in the text

Firstly, the analysis will cover the operation of the actuator supply system for lifting without the use of safety check valves. Exemplary and simplified schemes of hydraulic systems of this type are shown in Figure 3. In the examples shown, the displacement pump is the hydraulic energy source (1). The maximum valve acting in the role of the bypass valve allows for the limitation of pressure acting on the pump (2). The liquid flow direction is controlled by the distribution valve (3), which can be performed by a hydraulic signal (I), manually (II) or by an electrical signal (III). A single-acting (4) or a double-acting (5) actuator loaded by external force constitutes an executive element. It should be noted that in the absence of damage to the hydraulic system or the control system, the examples shown in the text fulfill all the required functions.

It can be concluded from the analysis of the operating way of actuators and the architecture of the systems in question, that damage to the hydraulic power lines marked red in the scheme can lead to the uncontrolled movement of the actuator. In the presented configuration of the system and with the external load acting on the single-acting actuator, any damage to the sole supply line will inevitably lead to the uncontrolled actuator's fall. In the case of a double-acting actuator this phenomenon will most likely occur during simultaneous damage to both supply lines probably due to damage to the hydraulic line feeding the chamber under the piston and will not occur if the supply line is damaged from the piston side.

However, the behavior of the system is still to be analyzed if it has not been damaged, but the displacement pump supply system or the diverter valve control system is faulty. In the case of a single-acting actuator, the failure of the hydraulic pump supply will not affect the possibility of the safe insertion of the actuator by the overdriving of the diverter valve. In the case of a double-acting actuator, such movement may be impeded, since filling the chamber on the piston side will require sucking liquid through the pump, the bypass valve, or internal leaks in the system. In both cases, any damage to the electric or hydraulic valve control system virtually impairs the assembly of the actuator without partial dismantling of the system, which is a potentially hazardous situation resulting from the need of the crew's ingeration in the system structure when the actuator is extended. The unauthorized ingeration may take the form of a partial dismantling of the actuator's hydraulic supply lines to enable the liquid flow and may occur in the close proximity to the operating system. The moment of unsealing the system by the crew thus allowing the liquid to flow may be sudden and result in a worker's injury. However, in the analyzed example, the safety level can be increased by the use of mechanically controlled diverter valves or the possibility of emergency manual overdriving. Nonetheless, it should be noted that the diverter valves should be located outside the movement area of the operating body driven by the actuator.

Figure 3 shows that the simplified hydraulic diagrams of the lifting systems for the cantilever and supporting systems of the structure under which people's work is carried out are equipped with hydraulic check valves controlled to improve safety. The diagrams of systems expanded with these elements are presented in Figure 4.

The control valves (6) used in these systems have two functions. The first one is to overcome the adverse effect of internal leaks in the spool valves, causing the motion of the actuator that is loaded and theoretically inhibited on the splitter (free falling under load). The second function is to limit the length of the hydraulic line, since its damage may be the reason for the uncontrolled movement of the actuator. In some constructions, the controlled check valves are coupled with actuators to minimize the length of the line between the inlet channel to the cylinder chambers and the check valves. In case of supplying the hydraulic pump, these systems are characterized by a higher degree of safety. However, the analysis of the system's behavior in the absence of supply from the main pump indicates that then the check valve system is adversely affected from the point of view of safety. Systems of this type are based on the premise that the pressure increase in the supply line is the signal that controls the flow opening in the check valve direction. However, in the event of hydraulic pump failure, this signal cannot be generated independently of the system control signals. In other words, the damage to the pump drive, the pump itself or the line supplying the hydraulic system with the liquid conveyed by the pump prevents the actuator's movement. In this case, the only possibility of lowering the actuator is to interfere with the hydraulic line between the actuator and the controlled check valves. If these valves are clamped to the actuator, an employee working in the immediate vicinity of the actuator, and thus the operating system lifted, must unseal the system. The unsealing is usually performed by disassembling hydraulic connections, and during the process it is impossible to ensure control over the amount of liquid that flows out of the system.

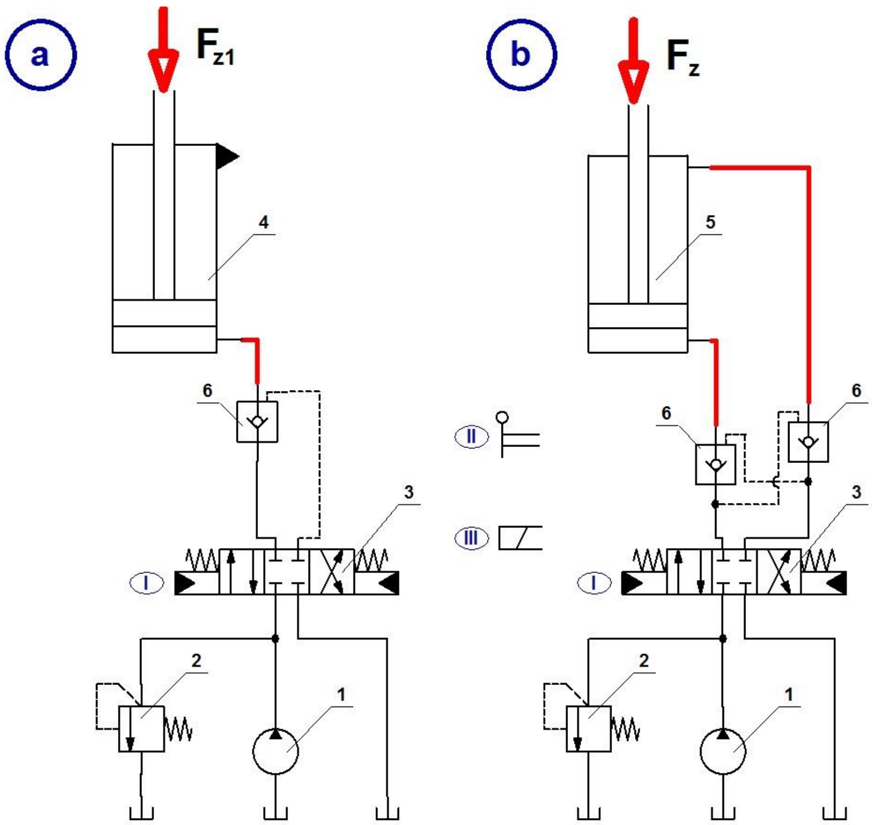

Fig. 4. Supply systems for actuators with controlled check valves
for single-acting (a) and double-acting actuators (b) – description in the text

The same effect as described above is also achieved by a failure of the check valve control system, which can be mechanical (II), hydraulic (I) or electric (III) [Bartnicki 2016]. When it is impossible to overdrive the diverter valve, the liquid stream supplied by the pump cannot be directed to the actuator supply line and consequently it is not possible to unlock the liquid flow in the check valves in the barrier direction. Thus, in the case when the pump works efficiently and only the check valve control system is damaged it is also necessary to partially disassemble the actuator supply line to lower the actuator under load, which implies the risks described above.

4. New technical solution of the actuator and the hydraulic system

The analysis of currently used hydraulic systems indicated that the use of controlled check valves increases safety only when the hydraulic liquid supply from the pump is provided. However, in the opinion of the authors, the direction of development work intended to increase the safety of the hydrostatic drives by the use of control valves is the most appropriate. In conclusion of the analysis results, a new type of hydraulic cylinder has been developed, characterized by interlocking of the check valve or valves with the actuator and the introduction of a parallel hydraulic line to each of the check valves fitted with a normally closed valve. The schemes of systems using the described solution are shown in Figure 5.

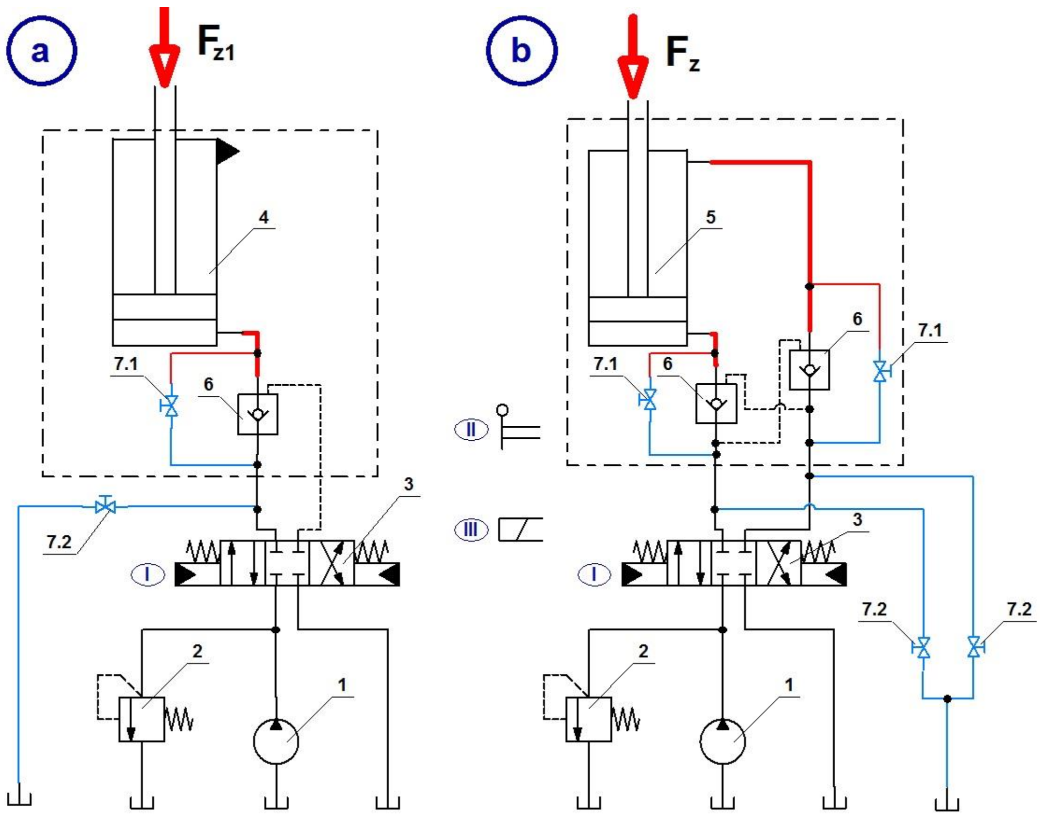

Fig. 5. Proposal for single-acting (a)
and double-acting (b) actuator supply systems – description in the text

In the case of a single-acting actuator (Fig. 5a), the modification introduces a new hydraulic line marked in blue, the flow through which is blocked by two additional valves. The first one is located in the valve block which is a component of the hydraulic actuator (7.1), hence it is possible to maximally shorten the unprotected power supply line and make it as a channel in the block, practically preventing it from being damaged and thus creating a potentially hazardous situation. The second one is located on the additional catchment line (7.2) connected between the diverter valve and the actuator. In the case of any of the emergency situations considered, the configuration shown enables safe folding of the actuator under load. To this end, firstly the valve at the actuator must be opened (7.1) and then, after withdrawing from the hazardous area, the valve on the additional catchment line (7.2), which is mounted in a safe place and accessible to the service personnel, is to be opened.

The same procedure should be used in case of an emergency movement of a double-acting actuator under load. In the first step, the valves at the actuator (7.1) are opened. Then, after moving to a safe place, the personnel open the valves on the additional catchment lines (7.2). It is advantageous to open, in the first place, the valve allowing the liquid flow into the chamber, the volume of which will increase during the movement.

It should be emphasized that the application of the described solution requires the use of valves characterized by high degree of tightness and a special version, which allows them to be opened only with specialist tools at the disposal of supervision people. This implementation will largely exclude unauthorized interference in the system, which should only be used in emergency situations under supervision. The configuration of actuators and valves as one component is the basis for No. P417208 patent application [Siwulski and Warzynska 2016].

Conclusion

The innovative proposal aimed at improving the safety of hydrostatic drive systems in emergency situations is, in the opinion of the authors, an essential complement to the current solutions. The presented analysis of possible emergency situations indicates that not all of them were included in the design of hydrostatic systems currently in use. The described new design of the valve system, which is placed directly on the hydraulic actuator, needs to be introduced into the production, however, it is a process that does not require substantial expenditure and is feasible with the forces of the domestic industry. Furthermore, the analysis presented may be the basis for the work of legislative bodies, which may result in changes to the provisions relating to the safety requirements of hydraulic systems, which is likely to contribute to future work safety.

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Conflict of interests

The author declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Tomasz Siwulski – The author declared that he has no ORCID ID's

Urszula Warzynska – The author declared that he has no ORCID ID's

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