An Original System for Controlling the Speed of Movement of Pneumatic Drives in Rehabilitation Devices

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ABSTRACT

The aim of the article is to present an original method of speed control and simultaneous stroke of the piston rods of two pneumatic cylinders using potentiometric position transducers, pneumatic solenoid valves, properly scaled throttle-check valves, solenoid valves and a microcontroller with power modules for solenoid valves. Initial experimental studies of the control system for simultaneous displacement of two piston rods of pneumatic actuators were carried out. The purpose of the research was to obtain the characteristics of the displacement of the extension of two pneumatic drives. The obtained results were analyzed. The results of the measurements confirmed the possibility of applying the presented control to rehabilitation devices for passive exercises of the lower extremities. The advantage of the proposed control system is its reaction speed, which is a response to changes in operating conditions of a given actuator, such as: external disturbances, own resistance of the controlled device, frictional resistance or movement caused by the patient exercising on the rehabilitation device moved by these actuators.

Keywords: pneumatic drive speed control, pneumatic drives, control of concurrent stroke control, binary control, double-acting pneumatic actuators.

INTRODUCTION

Pneumatic drives are used not only in industry [1, 2], but also in medicine, e.g. in rehabilitation devices [3, 5]. Pneumatic cylinders are used in rehabilitation devices for both the lower and upper extremities [6, 7]. Pneumatic actuators are also used for exoskeleton gloves [8].

Pneumatic muscles [9–11] are also used in rehabilitation devices. Pneumatic drives are used in rehabilitation robots [12] due to force control through proper pressure regulation in the actuator cylinder chambers, and also because of the safety of the drives [13].

During the movement of the piston rods of pneumatic actuators working simultaneously, variable dynamics of movement of the piston rods

of the drives is obtained [14]. The uneven movement of the actuator piston rods is affected by an uneven pressure drop in the emptying chamber of the actuator, and also by friction of the piston against the cylinder wall or the actuator piston rod in the cylinder. In addition, external loads or compressibility of the working medium also have an impact [15–17]. This problem can be solved by using, for example, throttle valves [18, 19], placing them after suitable regulation upon the pneumatic conduit leading to the actuator chamber. There are also proportional valves controlled by electronic systems with the use of the actuator piston rod position measurement system. There are also patents or utility patterns which represent valves for controlling pneumatic actuators [20] or utility models [21]. Scientific work has been a

done on the possibility of using the electro-pneumatic proportional valve [22] in industry. Other authors have controlled the operation of the actuator using (on/off valves) three-mode discrete-valued model predictive control [23].

The presented solutions ensure simultaneous extension of the piston rods of two pneumatic cylinders, but they have a complex structure [18, 19] and are expensive and complicated to implement, resulting in their limited use, especially in rehabilitation devices.

The Covid-19 pandemic has led to significant changes in the availability of health care, mainly in rehabilitation centers [24], including physiotherapeutic procedures, where the contact between the exercising person and the rehabilitator is close [25, 26].

Currently, passive exercises [27, 28] are used in patients suffering from Covid-19 in intensive care.

Passive exercise of the human lower extremities is important for proper functioning of the body. It prevents the appearance of, for example, pressure ulcers, critically ill myopathy, plantar flexor contractures or heterotopic ossification [29], or muscle atrophy [30]. The authors of the study proved [31] that during exercise, not only active but also passive, blood flow to the brain increases.

Currently, during Covid-19 disease, patients in a critically ill hospital bed use a bicycle ergometer [32] that implements passive movement of the lower extremities. The authors of [33] found that exercise on a bicycle ergometer significantly improved the strength of the quadriceps muscle.

Patients with Covid-19 spend a long time in intensive care [34] and need rehabilitation devices for passive exercises of the lower limbs. Additionally, such devices can support or replace physiotherapists, especially when the Covid-19 wards are staffed in limited numbers.

Furthermore, complete isolation during the Covid-19 pandemic prevented people in need of exercise from receiving adequate rehabilitation. Therefore, such rehabilitation devices on which patients could exercise themselves. The rehabilitator could supervise the progress of the exercising patient [35–37] during a telephone consultation or a tele-rehabilitation service.

In the device shown in Figure 3, it is possible to use a system of two pneumatic drives, with an innovative control (Fig. 1), which will lead the movement of the patients' lower limbs.

AN INNOVATIVE SYSTEM FOR CONTROLLING THE EXTENSION SPEED OF TWO PNEUMATIC CYLINDERS

The solution presented in this article can be used when it is required to obtain simultaneous movement of the piston rods of two pneumatic cylinders in less demanding applications, such as, for example, rehabilitation devices. The measure of the control signal are the weight values of individual bits on its output port determined at a given moment by the microcontroller and sent directly (electrically) to the valves. The electro-pneumatic system controlling each of the actuators is characterized by a low degree of complexity – it uses two-stage solenoid valves and properly calibrated throttle-check valves (differing in throttling of the assumed setting increment for each successive valve). The advantage of the proposed control system is its reaction speed (the quick change of the valve opening combination), which is a response to changes in operating conditions of a given actuator – such as external disturbances – own resistance of the controlled device, frictional resistance or movement caused by the patient exercising on the rehabilitation device moved by these actuators.

Construction of the control system

Figure 1 below illustrates a patented control system [38] of two pneumatic cylinders with the specification of its elements.

The control system of speed and concurrent movement (Fig. 1) of the extension of the piston rods consists of two actuators (1, 2) and a set of two-state valves (electro-pneumatic valves) (4, 5) and appropriately scaled throttle check valves (6, 7). In the control system, four electro-pneumatic valves (4, 5) are used to control one of the two actuators. The throttle-check valves (6, 7) are scaled ascendingly in relation to the bit weights - the throttling varies with the step. The solenoid valve units (4, 5) are electrically (binarily) controlled (Fig. 2) by the microcontroller (14) through the power modules (15, 16). The pneumatic system also includes an additional throttle-check valve (8, 9) per actuator (1, 2).

The control system of two pneumatic cylinders (1, 2) includes a 5/3 pneumatic solenoid valve (3), which is connected to the left chamber of the pneumatic cylinder (1, 2) for the return movement (retraction). The solenoid valve (3) is, at its other
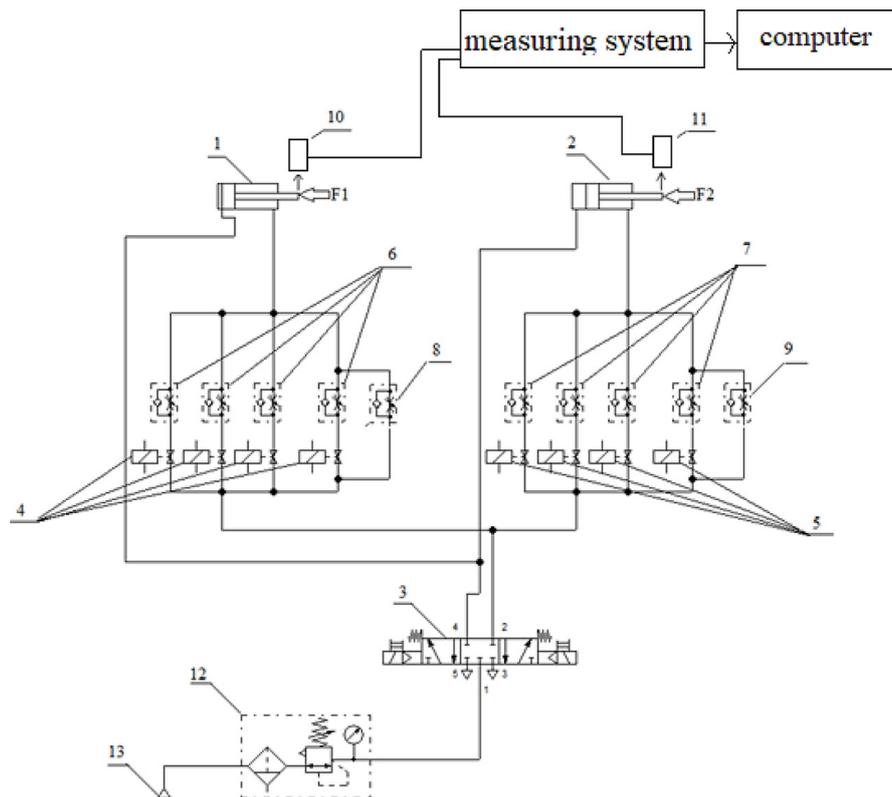
Fig. 1. Scheme of the control system; where: 1 – the first pneumatic drive; 2 – the second pneumatic drive; 3 – 5/2 pneumatic solenoid valve (five-way, two-position); 4, 5 – electro-pneumatic (two-stage) valves; 6, 7 – graduated throttle-check valve assemblies; 8, 9 – single throttle check valves; 10, 11 – potentiometric position transducers, 12 – air preparation unit, 13 – supply pressure

end, connected to the electropneumatic assemblies (4, 5), by means of the throttle check valves (6, 7). These units are electrically controlled by power modules (15, 16). Near the piston rods of the pneumatic cylinders, there are potentiometric position transducers (10, 11), which are mechanically coupled to the piston rods of the cylinders (1, 2).

Voltage signals (Fig. 2) from potentiometric position transducers (10, 11) are transmitted to the inputs of the A/C converter of the microcontroller (14), which acts as the controller of the entire system. The signal paths of potentiometric sensors are equipped with properly selected filters eliminating interference. The 5/3 pneumatic solenoid valve (3) is controlled from the microcontroller (14) through the power modules (15, 16). This valve determines the direction of movement of the actuator piston rods.

Two separate throttle-check valves (Fig. 1) (8, 9) allow the cylinder piston rods (1, 2) to return to their starting position after the extension is completed. The two-stage electropneumatic valve units (4, 5) are controlled binarily in such a way that when adjusting the stroke of cylinder pistons

(1, 2), the microcontroller treats successive solenoid valves (4, 5) as weights of individual bits in a binary system, and switches them on in the appropriate combination on or off.

A program in C language has been written for the microcontroller, which has functions that carry out specific readings: from potentiometric sensors, from pressure sensors and from the location of the zone in which a given actuator is located. The algorithm checks in which previously assumed zone (the difference in extension of cylinder piston rods) the actuators (1, 2) are located. Depending on this difference, it appropriately controls the sets of electrovalves (4, 5) by providing them directly with a binary combination, it turns them on or off in the right order.

For proper operation of the system, the appropriate pressure of the air that supplies the actuators (1, 2) is also required, which should be within the limits selected previously for the specific mechanism controlled by the actuators. To monitor the supply air pressure value (Fig. 2), a pressure sensor (18) was used in the system with a voltage (analog) output. The analog signal from the sensor
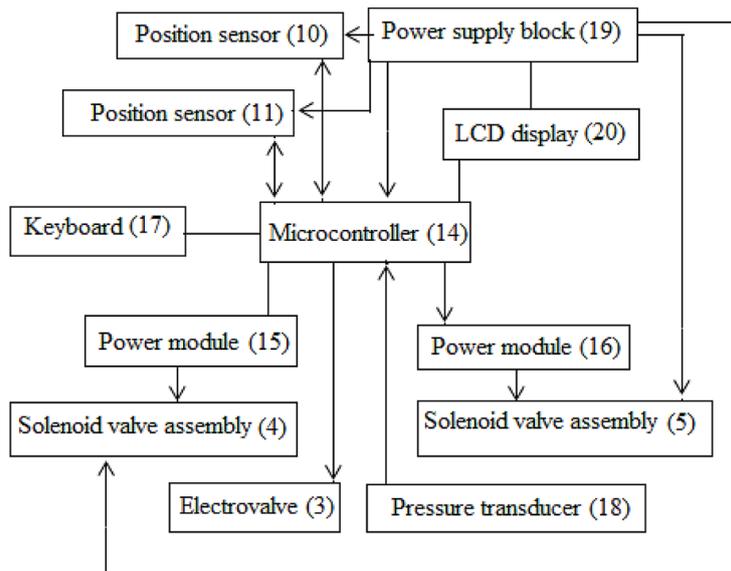
Fig. 2. System diagram – test stand (part II)

is fed into the input of the A/C converter of the microcontroller (14). The system also houses an LCD display (20) and a power block (19).

The current speed of extension of the piston rods of actuators (1, 2) is calculated during the adjustment by the microcontroller (14 in Fig. 2) on the basis of successive measurements of the displacement in successive units of time.

The system shown in the diagrams allows to adjust the speed of the actuators (1, 2) in one direction (stroke) only. If it is necessary to control the actuators in both directions, a second such system of connections of solenoids and throttle-check valves is needed, as well as adapting the algorithm to the new connection system.

A PROTOTYPE OF A REHABILITATION DEVICE FOR PASSIVE EXERCISES OF THE LOWER LIMBS

The rehabilitation device for which the patent was granted [39] with the use of an innovative control is shown in Figure 3. The device allows you to perform passive exercises of the lower extremities. While exercising on the presented device, the patient does not have to engage their muscles and thus does not require the patient's limb force input. After consulting experts in the field of physiotherapy, the device with the proposed control is suitable for rehabilitation, e.g. after flaccid and spastic paralysis, paralysis of a significant degree, or it allows to regain optimal physical performance faster after arthroscopic

surgery. The rehabilitation device uses the movement of actuators to simulate the natural movement of the limbs. Additionally, it reactivates physical performance of the patient's lower limbs.

Figure 3 shows the prototype of the device with load blocks. The load F1, F2 with the assumed weight was set on the block.
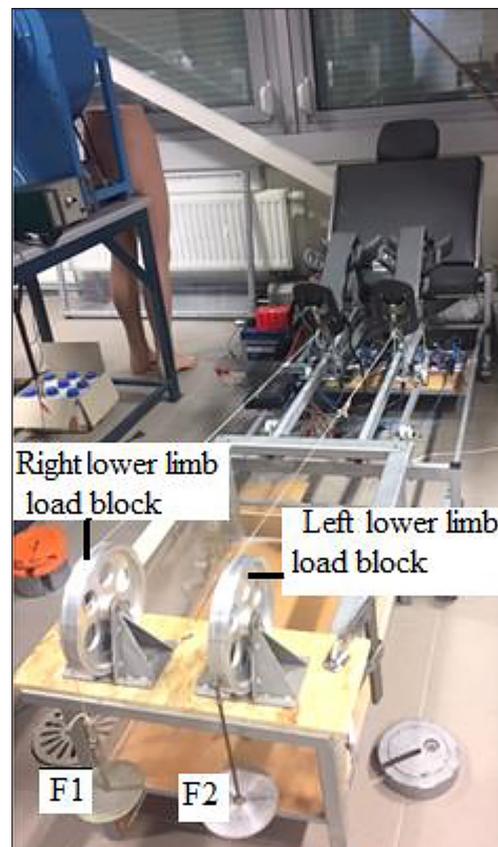
Fig. 3. A prototype of the device with a load block

MATERIALS AND METHODS

Experimental tests were performed on the presented measuring stand (Fig. 1). The test stand made it possible to test the uniformity of the piston rod displacements of two pneumatic drives. At the same time, the displacements of the drives were measured using an innovative electronic system at different values of the load on the piston rods of the actuators. This article presents three experimental studies.

In each test, the measurements were made with the system supply pressure $5 \cdot 10^5$ Pa. The tested objects were pneumatic drives with a piston diameter of 0.04 m. During the test, the drive piston rods traveled a distance equal to the maximum extension of 0.4 m. Measurements were carried out for assumed loads.

The loads values during the extension of the piston rods of the tested object were for the first experimental test, the first piston rod F1 = 20 N for the second piston rod F2 = 60 N. For the second experimental test, the load on the first piston rod was F1 = 20 N, for the second piston rod it was F2 = 80 N. For the third experimental test, the load on the drive first piston rod of the tested was F1 = 20 N, and for the second piston rod F2 = 100 N.

Measurement of displacement of the piston rods of the actuators (Fig. 1) was performed using a potentiometric position transducer (10, 11). The measurements of the experimental study were collected and archived via USB 231. The measurement system was designed in the DasyLab environment and is shown in Figure 4.

RESULTS AND DISCUSSION

I experimental study

In the first experimental test, the displacement of the drive piston rods was measured when:
- The first actuator tested was loaded with a force of F1 = 20 N.
- The second tested actuator was loaded with a force of F2 = 60 N.

The value of the difference in the loaded forces in the piston rods of the tested objects has a value ΔF = 40 N. Figure 5a shows the displacements of the stroke of the actuator piston rods as a function of time X(t). Figure 5b shows the course of the stroke velocity of the piston rods of the drives as a function of time V(t).

Analyzing graph 5a, it was observed that the stroke time of the actuator piston rods for both the first and the second piston rods was 22 s.

$$D = \left(\frac{|D1_{śr} - D2_{śr}|}{D1_{śr}} \right) \cdot 100 \, [\%] \qquad (1)$$

where: D – relative displacement;
   $D1_{śr}$ – mean displacement of the piston rod of the first drive [m];
   $D2_{śr}$ – mean displacement of the piston rod of the second drive [m].

The relative movement of the drive positions of the piston rods (according to equation (3.1)) has the value of 3.284%. On the basis of the results of the piston rod displacement, the average speed of the tested drives was calculated. For the first test drive, the value of the average speed of

Fig. 4. Block diagram in the DasyLab program
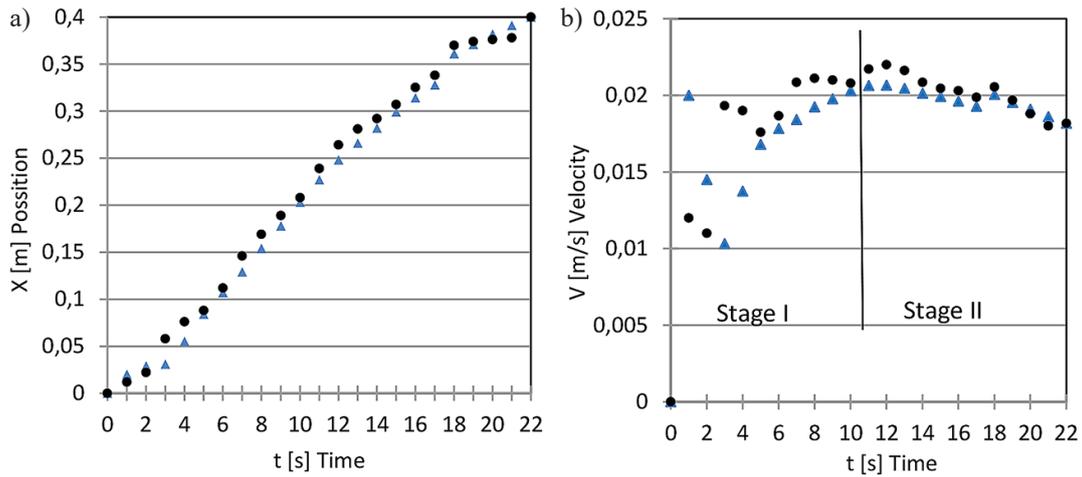
Fig. 5. a) Position of the tested drive piston rods; b) Speed of the tested drives, where: black points – displacement of the first piston rod of the actuator drive, blue triangles – displacement of the second piston rod of the actuator

the piston rod with a load of 20 N was 0.018 m/s. Subsequently, the average speed of the second piston rod with a load of 60 N was 0.019 m/s. The difference in the average speed of the drives piston rods of the tested is 0.001 m/s and is related to the difference of the piston rod F = 40 N.

The recorderd characteristics of Figure 5b V(t) show that the velocity of each piston rod is realized in two sequences (stages). In the first stage, the drive piston rod speed increases to 12 seconds and then it is reduced to 10 seconds.

II experimental study

In the second experimental study, displacement of piston rods of the pneumatic drives was tested (Fig. 1) in situations where:

- The first pneumatic drive was loaded with a force of 20 N.
- The second tested pneumatic drive was loaded with a force of 80 N.

The value of the difference in the loaded forces of two piston rods of the tested drives is ΔF = 60 N.

Figure 6a) shows the displacement of the drive piston rods as a function of time X(t). Figure 6b) shows the course of the stroke velocity of the drive piston rods as a function of time V(t).

The displacement time (Fig. 6a) of the two piston rods of the tested objects has a value of 29 s. According to the equation presented in (3.1) above, the relative movement has the value of 2.8%. The average speed for the first piston rod of the pneumatic drive loaded with a force of 20 N is 0.011 m/s. For the second piston rod loaded with a force of 80 N, the speed reaches 0.012 m/s.
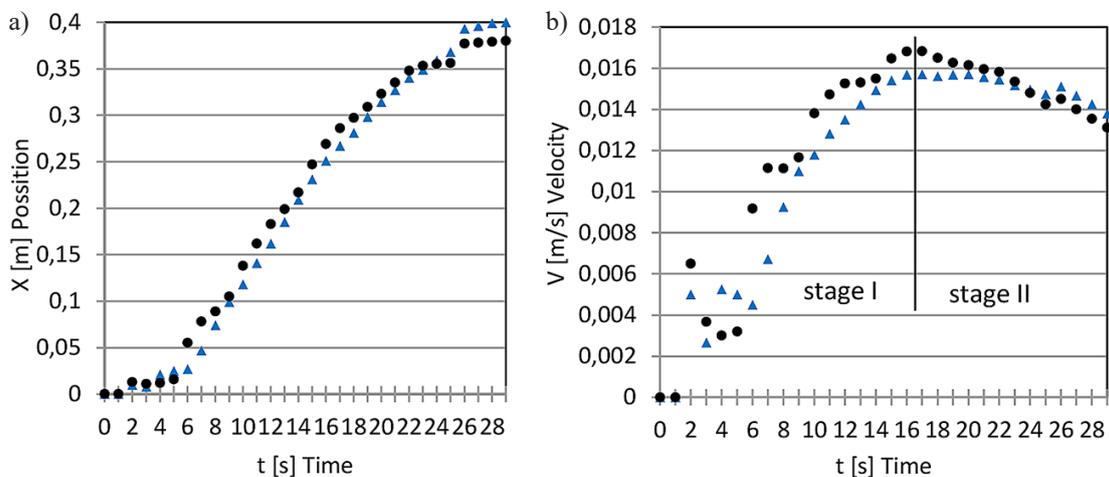
Fig. 6. a) Position of the tested drive piston rods; b) Speed of the tested drives, where: black points – displacement of the first piston rod of the actuator drive, blue triangles – displacement of the second piston rod of the actuator

It can be inferred from Figure 6b the movement of the piston rod can be divided in two stages depending on the speed. In the first stage, the speed increases to 16 s, whereas in the second stage the speed decreases for 13 s.

Comparing the measurements read from Figures 5b and 6b, it was noticed that the time of the first stage increased by 4 s, while the second stage increased its time by 3 s. Comparing the relative movement of the piston rods of the drives of the first and second experiment, a reduction of 0.484% was observed. A comparison of diagrams 5a and 6a indicates an increase in the piston rod extension time from 22 to 29 s.

When analyzing the average speed of the piston rods (Figs. 5b and 6b), it was observed that for the piston rod load of 20 N the speed was 0.018 m/s, and for the second piston rod with a load of 60 N it was 0.019 m/s. When the same load to the first piston rod, the average speed is reduced to 0.011 m/s. However, by increasing the load for the second piston rod to 80 N, the speed decreased to 0.012 m/s. For the first and for the second piston rod, the difference in mean velocity between the two experiments decreased by 0.007 m/s.

The reduction in speed was caused by the change in piston rod loads from 40 N to 60 N. Increasing the load by 20 N resulted in both a longer extension time and the reduction of the extension speed of the two piston rods.

III experimental study

In the third experimental test, the displacement of the drive piston rods was measured (Fig. 1) in the following situations, when:

- The first test drive was loaded with a force of 20 N.
- The second tested drive was loaded with a force of 100 N.

The value of the difference in the loaded forces in the two piston rods of the tested drives is $\Delta F = 80$ N. The displacement of the stroke of the drive piston rods as a function of time $X(t)$ is shown in Figure 5a, whereas the course of the stroke velocity of the piston rods of drives as a function of time $V(t)$ is illustrated in Figure 5b.

According to Figure 7a, the displacement time of two drive piston rods is 37 s. The relative movement of the drive piston rod positions (according to Equation (3.1)) is 0.12%. Based on the obtained results, the average speed of the drives was calculated. The mean velocity was 0.012 m/s both for the first piston rod loaded with a force of 20 N and for the second tested object loaded with a force of 100 N. According to Figure 7b, the speed of the piston rods can be divided into two stages. In the first stage, the speed increased to 16 s and then, in the second stage, it decreased to 20 s.

Comparing the results read from Figures 6b and 7b, it was noticed that in both cases the time of the first stage had the same value up to 16 s. However, the second stage increased by 7 s.

When analyzing the measurements in Figures 6a and 7a, attention was paid to the extension of the piston rod extension time by 8 s.

Comparing the relative motion of the piston rods of the actuators of the second and third experiments, it was noticed that it decreased by 1.68%.
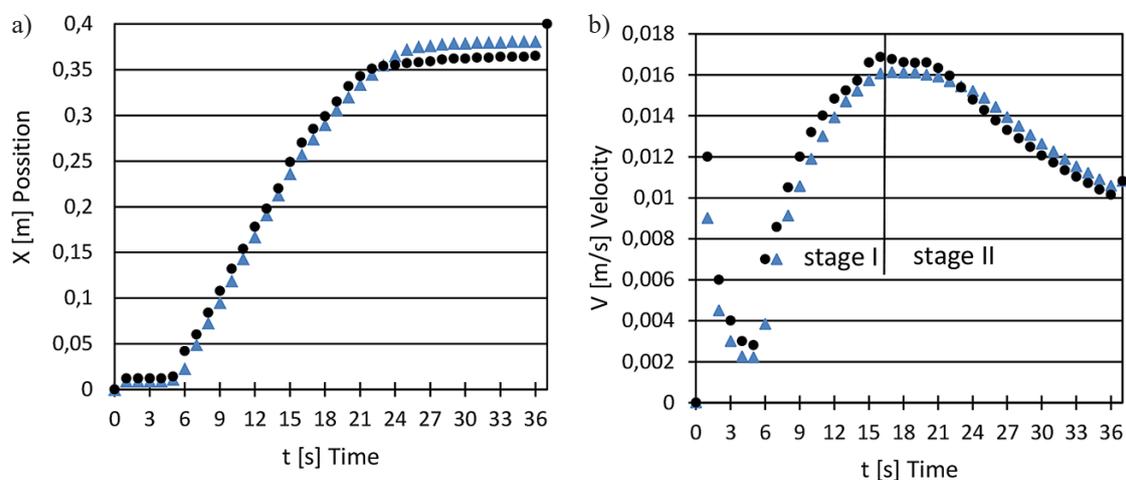
Fig. 7. a) Position of the tested drive piston rods; b) Speed of the tested drives, where: black points – displacement of the first piston rod of the actuator drive, blue triangles – displacement of the second piston rod of the actuator

When the average speed of the second experiment and the third experiment was analyzed, a decrease in the speed of the piston rods of the drives was noticed. For the second experiment, the average speed of the first piston rod (Fig. 4b) loaded with a force of 20 N was 0.011 m/s. For the second actuator loaded with the value of 80 N, the average speed was 0.012 m/s. For the third experiment, the value for both the first and the second piston rod was also 0.012 m/s with a load force of 100 N.

CONCLUSIONS

The characteristics of the cylinder piston rods' stroke-out (Figs. 5a–7a) suggest that the extension time of the piston rods increases with increasing load. An important issue is the smooth movements of the piston rods under various loads. This is the result of properly adopted regulations divided into zones. Depending on the difference between the displacements of the actuators' piston rods, individual zones are activated, causing a rapid change in the combination of valve opening.

Small discrepancies in the movement of the two pneumatic drives, ranging from 0.12% to 3.284%, are due to set loads or overcoming the resistance of friction forces on the seals.

Analyzing the average speeds of the conducted experiments, it can be seen that the speed for two piston rods stabilized in the third test and was 0.012 m/s for two piston rods. In other cases, the average speeds differed slightly from each other. In the first and second tests, the difference in average speed was 0.001 m/s. This is the correct result in terms of the recommended passive limb movement, as these movements are to be slow and performed simultaneously.

When analyzing the graphs in Figures 5b–7b, attention should be paid to two stages of the speed of the drive piston rods. In the first test, the speed increased within 12 seconds; in the second and third tests, this value increased within 16 seconds. From the point of view of physiotherapy, this is beneficial for the patient's limbs, as rapid increases in speed are not recommended. Consequently, passive exercises of the patient's lower extremities are performed properly.

The results of the measurements confirmed the possibility of using the control presented in the article for the rehabilitation device for passive exercises of the lower limbs.

REFERENCES

1. Sughashini K.R et al. A pneumatic robot arm for sorting of objects with chromatic sensor module. Materials Today: Proceedings 2021; 45: 6364–6368.

2. Praveena B.A. et al. Design and Fabrication of a Scaled Down Self Load Pneumatic Modern Trailer. In: IOP Conference Series: Materials Science and Engineering 2021; 1013(1): 1–8.

3. Yokota M., Takaiwa M. Gait Rehabilitation System Using a Non-Wearing Type Pneumatic Power Assist Device. Journal of Robotics and Mechatronics 2021; 33(4): 927–934.

4. Xu Y., Qin Y., Han J. Hysteresis Compensation of an Elbow Joint Rehabilitation Robot Featuring Flexible Pneumatic Artificial Muscle Actuation. In: IEEE International Conference on Real-time Computing and Robotics (RCAR), 2021, 227–232.

5. Azlan N. Z.et al. Soft Pneumatic Exoskeleton for Wrist and Thumb Rehabilitation. International Journal of Robotics and Control Systems 2021; 1(4): 440–452.

6. Dao D. M. et al. Study on the transient response of lower limb rehabilitation actuator using the pneumatic cylinder. Journal of Mechatronics, Electrical Power, and Vehicular Technology 2018; 9(2): 65–72.

7. Żyłka M.I., Szczerba Z., Szczerba K. Experimental Research on the Velocity of Two Pneumatic Drives with an Element for Concurrent Motion. Advances in Science and Technology Research Journal 2022; 16(2): 81–88.

8. Stilli A. et al. AirExGlove—A novel pneumatic exoskeleton glove for adaptive hand rehabilitation in post-stroke patients. In: 2018 IEEE International Conference on soft robotics (RoboSoft), IEEE 2018; 579–584.

9. Magnetti G.S. et al. Feasibility study of a passive pneumatic exoskeleton for upper limbs based on a mckibben artificial muscle. In: International Conference on Robotics in Alpe-Adria Danube Region. Springer, Cham 2021; 208–217.

10. Żyłka M., Żyłka W. Overview of solutions used in rehabilitation devices using muscles and pneumatic actuators. Science, Technology and Innovation 2020; 10(3): 15–22.

11. Mendoza M.J., Gollob S.D., Lavado D., Koo B.H.B., Cruz S., Roche E.T., Vela E.A. A Vacuum-Powered Artificial Muscle Designed for Infant Rehabilitation. Micromachines 2021; 12(8): 971.

12. Gudapati N. et al. Design and Control of a Low-Cost EMG-Based Soft Robotic Ankle-Foot Orthosis for Foot Drop Rehabilitation. In: Machines, Mechanism and Robotics. Springer, Singapore 2022; 1367–1382.

13. Goergen R. et al. Development of a Pneumatic Exoskeleton Robot for Lower Limb Rehabilitation. In: IEEE 16th International Conference on Rehabilitation Robotics (ICORR). IEEE 2019; 187–192.

14. Jamian S., Salim S.N.S., Kamarudin M. N., Zainon M., Mohamad M.S., Abdullah L., Hanafiah M.A.M. Review on controller design in pneumatic actuator drive system. Telkomnika 2020;18(1): 332–342.

15. Inoue Y. et al. Application to Pneumatic Servo System in Bilateral Control Based on Wave Variable. IEEE/SICE International Symposium on System Integration (SII). IEEE; 2020: 460–464.

16. Jiménez M., Kurmyshev E., Castañeda C.E., Experimental study of doubleacting pneumatic cylinder. Experimental Techniques 2020; 44(3): 355–367.

17. Mohan B., Muthuramalingam T.A. Review on recent research trends in servo pneumatic positioning systems. Precision Engineering 2017; 49: 481–492.

18. Takosoglu J., Dindorf R., Łaski P., Woś P. Positioning of the electropneumatic servo drive with direct measurement of the displacement and speed of the actuator piston, Acta Mechanica et Automatica 2010; 4(1): 86–91.

19. Węsierski Ł.N. Pneumatics. Elements and layouts. Wyd. UR, 2015.

20. Takosoglu J., Łaski P., Błasiak S. et al A valve for controlling fluid drives, especially pneumatic actuator drives and a valve control system for fluid drives, PL 221414, 2015.

21. Żyłka M., Szczerba Z. An element that synchronizes the work of two actuators. Utility model number W.126971, 2020.

22. Zhao T., Huang D., October. Research and Implementation of Constant Pressure Control with Electro-pneumatic Proportional Valve. In Journal of Physics: Conference Series 2020; 1626(1).

23. Qi H., Bone G.M., Zhang Y. Position Control of Pneumatic Actuators Using Three-Mode Discrete-Valued Model Predictive Control. Actuators 2019; 8(3): 56

24. D'souza J. et al. Barriers leading to increased disability in neurologically challenged populations during COVID-19 pandemic: a scoping review. Disability and Rehabilitation 2021; 1–14.

25. Who. Rapid assessment of service delivery for NCDs during COVID-19. 2020. Accessed September 29, 2020. http://www.emro.who.int/noncommunicable diseases/publications/rapid-assessment-of-service-delivery-for-ncds-during-covid19.html?ver=2 (accessed 13 March 2022)

26. Rao, P.T. A paradigm shift in the delivery of physical therapy services for children with disabilities in the time of the COVID-19 pandemic. Physical therapy 2021; 101(1).

27. Cieloszczyk A., Lewko A., Sliwka A., Wloch T., Pyszora A. Coronavirus: SARS-Cov-2: Recommendations for physiotherapy of adult patients with COVID-19, 2020.

28. Jang M., Shin M., Shin Y., Pulmonary and Physical Rehabilitation in Critically Ill Patients. Acute Crit Care 2019; 34(1): 1–13.

29. Sagarra-Romero L., Viñas-Barros A. COVID-19: Short and long-term effects of hospitalization on muscular weakness in the elderly. International journal of environmental research and public health 2020; 17(23): 8715.

30. Bloomfield S. Changes in musculoskeletal structure and function with prolonged bed rest. Med. Sci. Sports Exerc. 1997; 29(2): 197–206.

31. Doering T.J., Resch K.L., Steuernagel B., Brix J., Schneider B., Fischer G.C. Passive and active exercises increase cerebral blood flow velocity in young, healthy individuals. Am J Phys Med Rehabil. 1998; 77(6): 490–493.

32. Pincherle A., Jöhr J., Pancini L., Leocani L., Vecchia L.D., Ryvlin P., Schiff N.D., Diserens K. Intensive Care Admission and Early Neuro-Rehabilitation. Lessons for COVID-19. Front. Neurol. 2020; 11: 880.

33. Dinçer C. Safe Rehabilitation Practices For COVID-19 Patients on Mechanical Ventilators in the Intensive Care Units. Batı Karadeniz Tıp Dergisi 2020; 4(3): 114–121.

34. Kiekens C., Boldrini P., Andreoli A., Avesani R., Gamna F., Grandi M., Lombardi F., Lusuardi M., Molteni F., Perboni A., Negrini S. Rehabilitation and respiratory management in the acute and early post-acute phase. Instant paper from the field on rehabilitation answers to the COVID-19 emergency. Eur J Phys Rehabil Med. 2020; 56(3): 323–326.

35. Dantas L.O., Barreto R.P.G., Ferreira C.H.J. Digital physical therapy in the COVID-19 pandemic. Brazilian J Phys Ther. 2020; 24(5): 381.

36. Lee A.C. COVID-19 and the advancement of digital physical therapist practice and telehealth. Phys Ther. 2020; 100(7): 1054–1057.

37. Rao P.T., Paradigm Shift in the Delivery of Physical Therapy Services for Children With Disabilities in the Time of the COVID-19 Pandemic. Phys Ther. 2021; 101(1).

38. Żyłka M., Biskup M. System for controlling the speed and concurrent extension of the piston rods of two pneumatic cylinders and the method of controlling the speed and simultaneous extension of the piston rods of two pneumatic cylinders, PL 240501, 2022.

39. Żyłka M., Kucaba-Piętal A. Device for rehabilitation of lower limbs, PL 233326, 2019.