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TESTING A PROTOTYPE FRICTION DRIVE TRANSMISSION

BADANIA PROTOTYPOWEGO MECHANIZMU TARCIOWEGO PRZENIESIENIA NAPĘDU

Key words: linear motion drive, slide screw, friction drive, mechanism converting rotational motion to linear motion.

Abstract The article presents research on the mechanical properties of a drive system using an innovative mechanism converting rotary motion to progressive motion. The operating principle of the mechanism uses the friction-based transmission of drive from the motor to the drive shaft by means of two oppositely arranged unidirectional clutches. A side effect of such a solution utilized in the mechanism is the possibility of shifting the couplings while transmitting torque. The clutches were combined with a mechanism converting rotational motion to linear motion by utilizing friction between radial ball bearings and the shaft. This has resulted in an innovative mechanism for converting rotary motion to progressive motion, with the drive source being bound with a "friction screw" (a "slide" screw). A characteristic feature of this solution is the fact that there is no need for the nut to rotate in order to achieve progressive movement. Known solutions are based on a rotating nut and a fixed shaft system. The mechanism uses a fixed pitch nut, but it is possible to use a regulated pitch nut as a possible modification of the mechanism at a later stage of the system development. The main advantage of the mechanism tested is the possibility of uncoupling, which occurs when the maximum force transmitted by the nut is exceeded. This force is related to the friction force resulting from the pressure exerted by angularly shifted ball bearings on the drive shaft. The bearings are a substitute for the screw line in the classical ball screw mechanism. The research results presented in the article give an overview of the mechanical properties of the solution developed. The article also presents the influence of rotational speed and load on the mechanical parameters of the drive. The application of the described invention as the basis of the linear motion mechanism driving the tool of a surgical robot is a safe solution with unique and desirable characteristics.

Słowa kluczowe: mechanizm ruchu liniowego, śruba ślizgowa, napęd cierny, zamiana ruchu obrotowego na postępowy.

Streszczenie Analizowano cechy mechaniczne układu napędowego wykorzystującego innowacyjny mechanizm zamiany ruchu obrotowego na postępowy. Zasada działania mechanizmu wykorzystuje cierny sposób przekazania napędu z silnika na wał napędowy za pomocą dwóch przeciwstawnie ustawionych sprzęgieł jednokierunkowych. Efektem ubocznym takiego rozwiązania, wykorzystywanym w mechanizmie, jest możliwość przesuwu sprzęgieł przy jednoczesnym przekazywaniu momentu obrotowego. Sprzęgła połączono z mechanizmem zamieniającym ruch obrotowy na liniowy, wykorzystując tarcie pomiędzy rolkami w postaci łożysk tocznych a wałem. Uzyskano dzięki temu innowacyjny mechanizm zamiany ruchu obrotowego na postępowy, w którym źródło napędu jest związane z śrubą „cierną" (slide screw). Charakterystyczny dla mechanizmu jest brak konieczności obrotu nakrętki w celu realizacji ruchu liniowego. Dzięki zastosowanemu mechanizmowi uzyskuje się efekt zbliżony do znanych rozwiązań, które bazują na obrotowej nakrętce i nieruchomym wale. W przedstawionym w artykule mechanizmie zastosowano nakrętkę o stałym skoku, ale istnieje również możliwość zastosowania nakrętki o skoku regulowanym, co może stanowić dalszą modyfikację mechanizmu. Główną zaletą badanego mechanizmu jest możliwość rozsprzęglenia napędu, co następuje w przypadku przekroczenia maksymalnej siły przenoszonej przez nakrętkę. Siła ta związana jest z siłą tarcia będącą wynikiem docisku przesuniętych kątowo rolek w stosunku do wału napędowego. Rolki te stanowią w mechanizmie substytut linii śrubowej występującej w klasycznym mechanizmie śrubowo-tocznym. Zastosowanie opisanego wynalazku do mechanizmu ruchu liniowego narzędzia robota chirurgicznego stanowi bezpieczne rozwiązanie o unikatowych i pożądanych cechach użytkowych.

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INTRODUCTION

The dynamic development of the industry and the awareness of the need to provide ever more competitive solutions make it necessary to use ever cheaper and more easily mounted drive systems. Modular systems enabling fast construction of new solutions and the modernization of the existing ones have been available on the market for many years. Generally, they can be divided into systems that perform rotary motion and linear motion. They find application in various industries and are related to the performance of such operations as assembly, packaging, printing, transport, and material processing [**L. 1**]. This type of equipment is often required to be accurate in tracking and positioning itself. The equipment should be quiet, clean, maintenance free, and it should ensure long-term and efficient operation. In the case of linear movement, the following mechanisms are used: pneumatic, hydraulic, linear motors, and mechanisms that enable the conversion of rotary motion into progressive motion. These mechanisms may include belt transmissions, ball screws and lead screws, crank and yoke systems, and NB SlideScrew mechanisms (**Fig. 1**) [**L. 2–4**]. The latter consists of two aluminium blocks, each of which has three ball bearing rollers with a fixed angle between them. A smooth shaft is located between the two blocks, and its rotation causes a linear movement with a pitch defined by the angle of the rollers relative to the shaft. The force which this mechanism can transfer is adjustable, and after applying excessive load, the mechanism disengages itself by slipping, thus preventing damage. This mechanism has been modified and adapted by the FRK (Cardiac Surgery Development Foundation) team to build prototype drive systems and drive systems for the Robin Heart robot and the RobinHand actuator as an alternative to pneumatic actuators, belt drives and ball/lead screws [**L. 5–7**].

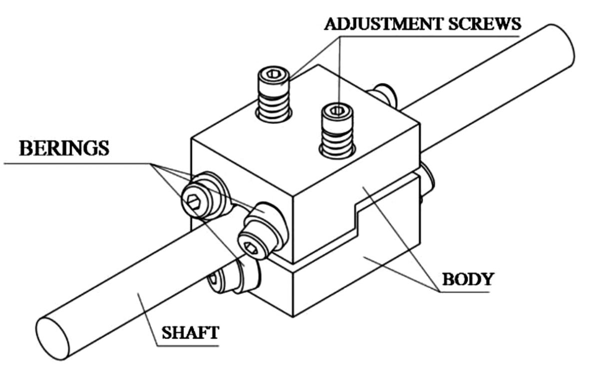

Fig. 1. Concept structure and operation of a friction screw mechanism [L. 4]

Rys. 1. Idea budowy i działania mechanizmu śruby ciernej [**L. 4**]

The force transferred by the drive using this mechanism depends on the force exerted by the bearings on the shaft F_N and is adjusted by means of screws exerting pressure on the springs (**Fig. 1**), which in turn cause compression of the body blocks. Subsequently, the force is transmitted through the blocks to the bearings which are in contact with the shaft. Force F_1 that the mechanism can bear without slipping depends, therefore, on the friction force F_T between the bearings and the shaft. This force in turn results from the coefficient of friction μ between these elements and the compression force F_N [**L. 8**].

$$F_1 < F_T \tag{1}$$

It can be determined by using the following formula:

$$F_T = \mu \cdot F_N \tag{2}$$

The coefficient of friction is related to the steel-steel friction. The producer of the mechanism [NB catalogue] suggests that a safe value of $\mu = 0.01$ should be used for the calculations. Another force that adds to the load on the mechanism and which should be taken into account is the inertial force F_2.

$$F_2 = m \cdot \frac{dv}{dt} \tag{3}$$

In extreme cases, the mechanism bears the following load:

$$F_{\max} = F_1 + F_2 \tag{4}$$

In an ideal case, the mechanism has a constant pitch resulting from the angle of the tilt of the bearings; and, in the case of a mechanism with an adjustable angle, the pitch is also adjustable and may be controlled.

In theory, the pitch also does not depend on the load put on the mechanism up to the point when the load exceeds force $F_{\max}$. Then the mechanism will stop despite the rotation of the shaft. This is due to the rollers (ball bearings) slipping on the shaft due to exceeding the maximum force that the mechanism can transfer for a given coefficient of friction μ [**L. 8**].

CONSTRUCTION OF THE MECHANISM

The construction and the operating principles of the developed drive system are shown in **Figure 2**. The mechanism consists of a body (1), in which the following elements are mounted: a rotary shaft (2) driven by a motor and a guide (3) with a sliding platform mounted on it (4). The rotary shaft has a smooth outer surface and it is driven by the shaft of the motor (5) fixed to the platform by means of a belt transmission (6). Inside the clutch wheel mounted on the shaft, there

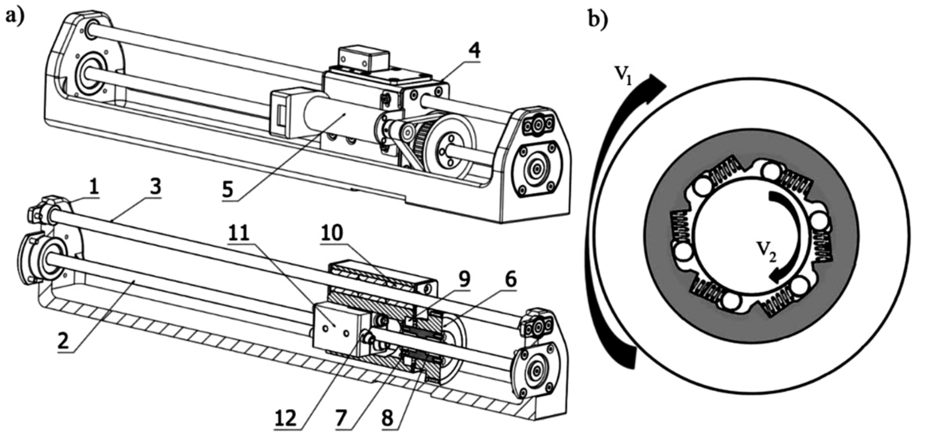

Fig. 2. Model of the mechanism: a) construction of the drive system, b) unidirectional clutch model [L. 9]
Rys. 2. Model opracowanego mechanizmu: a) budowa układu napędowego, b) model sprzęgła jednokierunkowego [**L. 9**]

are two unidirectional clutches (7 and 8) placed opposite one another. The belt transmission clutch wheel is connected rotatably to the sliding platform (4) by means of a bearing (9). Inside the sliding platform, in the part which is in contact with the guide (3), there are linear slide bearings (10) which enable free movement of the platform along the guide. The platform is integrated with the NB SlideScrew module (11), mounted on the smooth shaft. The NB SlideScrew mechanism contains ball bearing rollers (12) arranged in such a way that their points of contact with the smooth surface of the shaft define the course of a helix [**L. 9**].

The proposed solution for the mechanism converting rotary motion into progressive motion has a slip-based overload protection, which, in the case of an unintended arrest, prevents damage to the mechanism components. It is also possible that the mechanism will be shifted by an external force, if its value exceeds the maximum force that the mechanism can transfer. This can happen both during operation and in idle state. In the construction solution proposed, the drive of the mechanism consisted of the following: 120 W brushless motor by Maxon Motor, EC-4pole 22 series, with a shaft diameter of ϕ22 mm. The motor is powered by 24 V and has a rated torque of 54.5 mNm. Maxon Motor's BLDC EPOS 2 24/5 motor controller was used to control the motor. It operated in the amplitude control mode with encoder feedback. This type of control method ensures high torque stability at the level of the inverter drive [**L. 10**]. There is a 1:4.4 transmission between the motor and the clutch wheel.

INITIAL TESTS OF THE PROTOTYPE

In order to initially determine the operational properties of the mechanism, a test plan was proposed, within which the measurements of the angular position of the clutch wheel shaft α_2, the drive shaft α_w, and the linear displacement x were carried out. The measured parameters are shown in the mechanism diagram (**Fig. 3**).

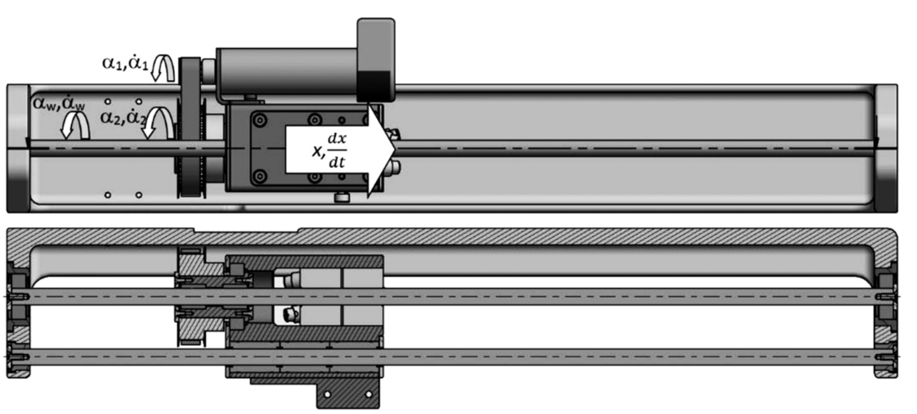

Fig. 3. Conceptual scheme of the mechanism
Rys. 3. Schemat ideowy opracowanego mechanizmu

To carry out the tests, a measurement station was designed consisting of two incremental rotary encoders for measuring angular position. One of them was connected to the clutch wheel. It was an optical incremental rotary encoder with digital output – Broadcom HEDL 5540 with a resolution of 500 PPR [**L. 11**], increased four times during the measurements. The second encoder was connected to the drive shaft. It was a Wobit MOK40 series optical encoder with a digital output with a resolution of 3600 PPR [**L. 12**]. The measurement procedure was carried with increasing the encoder's resolution four times, which gave a measurement resolution of 14400 PPR. The position of the sliding module was measured with an absolute linear encoder. Renishaw's LTA4D01-02 series encoder with a resolution of 1 µm, accuracy of ±10 µm and the SSI digital communication interface, which was integrated with the mechanism [**L. 13**]. During the tests, the motor controller operated in the profiled speed mode, using a speed and current controller. The view of the measurement station is shown in **Figure 4**.

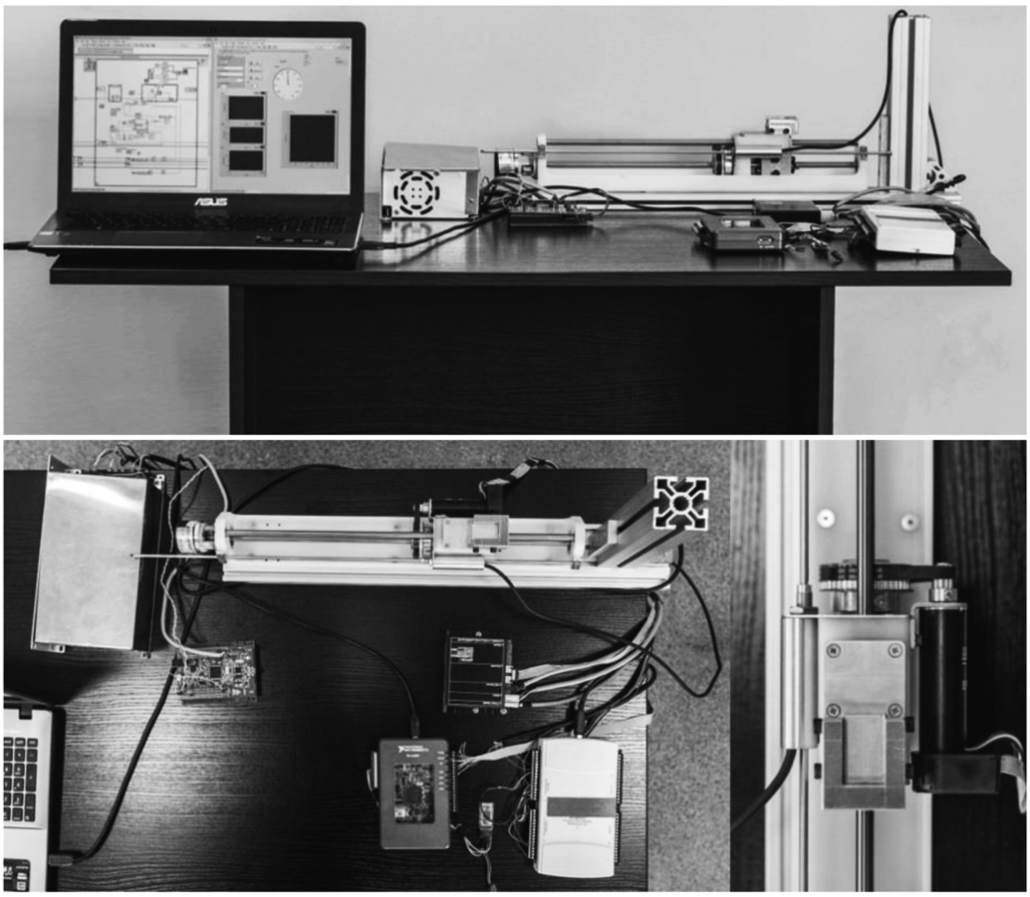

Fig. 4. The measurement station used for preliminary testing of the drive system prototype
Rys. 4. Stanowisko pomiarowe służące do badań wstępnych prototypowego układu napędowego

The testing plan included the performance of position measurements for four different linear motion speeds: 23, 45, 113, and 227 mm/min. Each time, the motor made 40 turns and the clutch wheel made about 9 turns in both directions. This reflected a linear displacement of about 80 mm. Based on the test results, it can be concluded that the latter two values depend on the speed of movement and the load placed on the mechanism. Based on the readings of the measuring systems (α_2, α_w, x), the corresponding instantaneous speed values α_2, α_w, x were determined. They were used to determine the instantaneous value of the transmission ratio between the following:

- Encoder and drive shaft: $i_1 = \frac{\dot{x}}{\dot{\alpha}_w}$ [mm/rev];
- Drive shaft and clutch wheel $i_1 = \frac{\dot{\alpha}_w}{\dot{\alpha}_2}$; and,
- Encoder and clutch wheel $i_1 = \frac{\dot{x}}{\dot{\alpha}_2}$ [mm/rev], which covers the total transmission ratio of the mechanism.

The tests were carried out for the drive system operating in the horizontal position loaded only with inertia and for the system operating in the vertical position loaded with the weight of the entire sliding module and its inertia. For data acquisition, the National Instrument's MyRIO 1900 controller was used. The controller operates a Xilinx Z-7010 processor with a programmable FPGA and the LabVIEW RT system. It was programmed to calculate the position on the basis of two quadrature rotary-pulse sensors and to record the readings of the linear encoder with the SSI interface. Position data was logged wirelessly to the memory of a computer linked up to the sliding module by means of the TCP/IP protocol. Position measurements were taken at the log rate of 100 Hz. As a result of the measurements, the transmission characteristics were obtained for the following pairs: the linear encoder and the clutch wheel (**Fig. 5**), the linear encoder and the shaft (**Fig. 6**), and the drive shaft and the clutch wheel (**Fig. 7**).

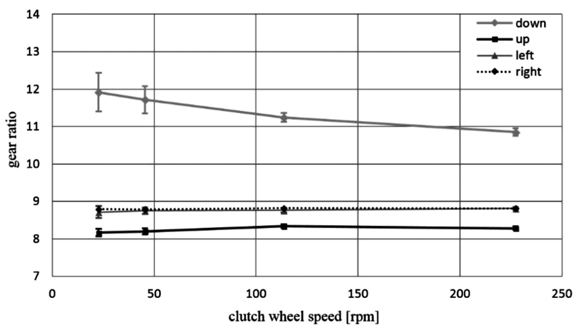

Fig. 5. The dependence of the transmission ratio between the linear encoder and the clutch wheel as a function of the clutch wheel speed

Rys. 5. Zależność przełożenia pomiędzy liniałem a kołem sprzęgłowym w funkcji prędkości koła sprzęgłowego

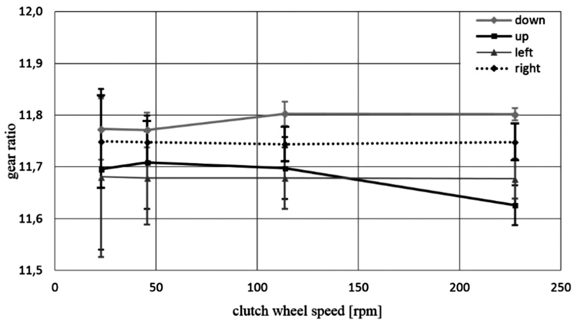

Fig. 6. The dependence of the transmission ratio between the linear encoder and the drive shaft as a function of the clutch wheel speed

Rys. 6. Zależność przełożenia pomiędzy liniałem a wałkiem napędowym w funkcji prędkości koła sprzęgłowego

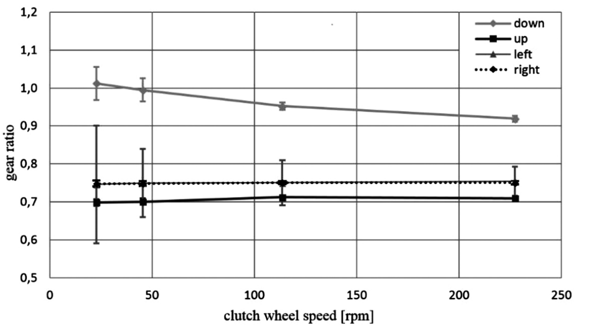

Fig. 7. The dependence of the transmission ratio between the shaft and the clutch wheel as a function of the clutch wheel speed

Rys. 7. Zależność przełożenia pomiędzy wałkiem a kołem sprzęgłowym w funkcji prędkości koła sprzęgłowego

CONCLUSIONS

During the tests, unidirectional clutches were never disengaged absolutely so that they would transfer no torque from the clutch wheel to the shaft at all. This mechanism, however, is characterized by slippage. It can be seen in **Fig. 7** showing the transmission ratio between the shaft and the clutch wheel. It is not constant but varies in the range from 0.7 to over 1 depending on the speed of the mechanism and the load. The value of the transmission ratio between the linear displacement and the shaft rotation, which nominally should be 12 mm/revolution for the mechanism applied, also fluctuates (**Fig. 6**). Its average value in the experiments conducted was 11.72 mm per shaft rotation, with a slight deviation of up to 1.6%, mainly dependent on the load and, to a lesser extent, on the speed. **Figure 5** shows the total transmission ratios of the mechanism. When unloaded, their values depend on the speed and direction of movement only to a small extent. However, the impact of load is significant and correlates with the speed of the mechanism. During the tests, the slide screw mechanism itself was not decoupled as a result of the rollers-shaft pair exceeding the friction force.

APPLICATION

The test results obtained confirmed the applicability of the mechanism for the execution of linear motion in the Robin Heart PVA robot. Placing the mechanism at the end of the robot's arm permitted insertion of the laparoscopic camera or a surgical instrument into and removal out of a patient's abdominal cavity. If the robot stops operating, the slip designed into the mechanism allows safe removal of the robot's tools from the patient's body. The prototype was first used in Robin Heart PVA 0 robot. Its later versions with modified construction were used in Robin Heart Pelikan robots and Robin Heart PVA 1 and 2 robots. The prototypes and robots are presented in **Figure 8**.

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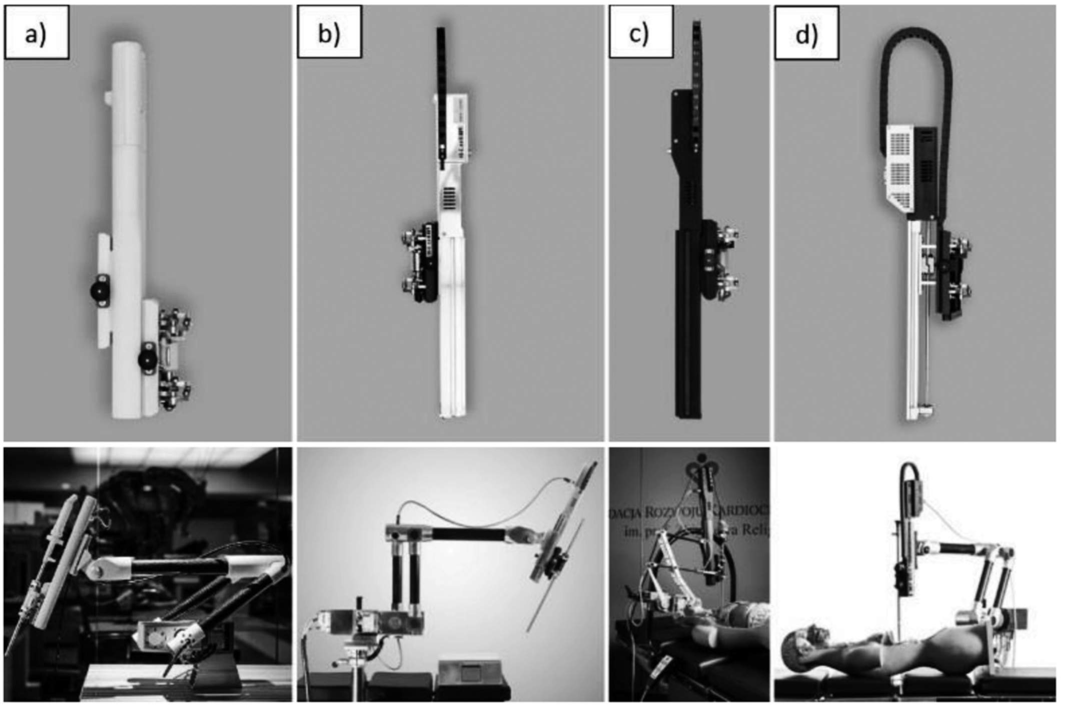

Fig. 8. Application of the slide screw drive: a) Robin Heart PVA 0, b) Robin Heart 1, c) Robin Heart Pelikan, d) Robin Heart 2 [L. 5, 6, 14, 15]

Rys. 8. Aplikacyjne zastosowanie mechanizmu toczno-ciernego: a) Robin Heart PVA 0, b) Robin Heart 1, c) Robin Heart Pelikan, d) Robin Heart 2 [**L. 5, 6, 14, 15**]

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