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Multivariate analysis of the kinematics of an upper limb rehabilitation robot

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Purpose: The purpose of this work is to present a multivariate analysis of the kinematics of an upper limb rehabilitation robot. Comparing multiple concepts of kinematic chains makes it possible to identify advantages and disadvantages and, as a consequence, choosing the optimal solution to create a physical device. Such actions shall contribute towards automation of the rehabilitation process, bringing benefits to both therapists and patients in comparison with conventional rehabilitation. *Methods:* Multivariate analysis of kinematics was performed on the basis of three concepts of the kinematic chain of an exoskeleton, enabling the rehabilitation of both right and left upper limb within the area of the shoulder joint, elbow joint and wrist. The kinematic chain allows the performance of simple and complex movements. *Results:* The results of the conducted multivariate kinematic analysis define specific movements and angular ranges, which may be performed while applying one of the proposed concepts of the robot design. The results made it possible to determine the optimum solution to the kinematic diagram and construction design, which best satisfy the expectations for effective rehabilitation. *Conclusions:* The analysis of the kinematic diagram concept of the exoskeleton should be done in relation to its design (construction form). Considering the obtained parameters, it is necessary to find an optimum concept and wisely manoeuvre the values, in order to avoid a situation in which one significant parameter influences another, equally important one. It is noteworthy that the introduction of changes into particular segments of the kinematic chain often has a significant impact on other segments.

Key words: *rehabilitation robot, therapy, upper limb exoskeleton, kinematic chain of exoskeleton, kinematic analysis*

1. Introduction

More and more often, science has been combining several disciplines to find the best technical solutions leading to increased effectiveness and availability of therapy. Rehabilitation is yet another field of medicine which makes use of modern solutions and evolves with time. Contemporary rehabilitation applies various types of robots to rehabilitate and improve patients' condition, upgrade the quality of services, shorten the time of inpatients' stay in medical institutions or reduce the personnel's, in particular the therapists', involvement during their work with one patient. The above-mentioned activities aim, among other things, to reduce queues (which are getting longer and longer) by means of home care and rehabilitation, especially by increasing efficiency and thus precision of the performed exercises. Rehabilitation is applied especially to adult patients with neurological disorders, including patients after brain stroke with functional problems of the upper limb [2]. It should be noted that cerebral stroke is the third most frequent cause of death affecting annually 15 million people, including 60 thousand patients in Poland. This fact has a considerable influence on the cost and services of the health care system. Brain stroke is one of the main causes of disabilities in adults and is characterized by such symptoms as sensory, motor or cognitive deficits. That is why there is the necessity of finding a proper tool, procedure or rehabilitation in

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order to minimize the consequences of ischaemia or haemorrhage.

This work focuses on a multivariate analysis of the kinematics of an upper limb rehabilitation robot. It was conducted for various concepts of the kinematic chain, which is not very apparent in other works as they concentrate mostly on just one concept, which is then thoroughly studied and tested. The approach presented in this paper allows to compare different concepts and identify their advantages and disadvantages. This would help the engineers working with therapists choose the optimal solution for the kinematic chain, considering the type of rehabilitation being supported by the device. Nowadays, one of the challenges for scientists is whether creating a multipurpose upper limb exoskeleton which fits every kind of rehabilitation is possible. Currently, there are many works in progress trying to make medical devices more and more versatile, and this article should be of help to it.

1.1. Advantages of automated rehabilitation

Automated rehabilitation is an innovative method making it possible to conduct rehabilitation using an exoskeleton. In relation to conventional therapeutic activities, such rehabilitation brings numerous benefits to both the patient and therapist. Automated rehabilitation is used in the therapy of patients with injured spinal cord, patients after stroke and with disorders such as: multiple sclerosis (SM), infantile cerebral palsy, muscular dystrophy and many other diseases. The above-mentioned diseases often lead to the deterioration of life quality, physical disability and finally to death [9]. Taking the above into consideration, in order to improve life quality and minimize symptoms as well as regain at least partial ability, the patients should be subjected to not only standard therapeutic methods but also to automated rehabilitation. The advantages of such rehabilitation include partial automation of the diagnostic and therapeutic process, which reduces the involvement of the therapist in the rehabilitation of a single patient, thus enabling simultaneous rehabilitation of several patients.

Proper sensor systems in devices enable an objective assessment of rehabilitation progress both from a quantitative and qualitative perspective. It is possible to precisely set the parameters of exercises using the implemented patterns of movements. Thanks to the application of a robot which can work relentlessly without getting tired, it is possible to conduct rehabilitation incessantly while maintaining constant parameters. What is also important is the use of feedback, which often significantly influences the patient's motivation and, as a result, has impact on the rehabilitation effectiveness.

While analyzing the advantages, usability and application of automated rehabilitation in connection with the growth of the number of patients, a question arises of when the automated rehabilitation will be available in a bigger number of medical establishments to improve the patients' quality of living [12], speed up the effects of rehabilitation and reduce an incredible long period of waiting for free-of-charge rehabilitation. A properly conducted process of rehabilitation makes it possible to increase positive results. Other important factors are the time of starting rehabilitation, co-existing diseases and the patient's commitment.

The above-mentioned cerebral stroke is one of the main causes of long-term disability almost all over the world [6]. It is also the third major cause of death and the first cause of disability in the population above the middle age [11]. In spite of the fact that there are numerous advantages in the rehabilitation of patients after stroke, the use of robots is still very rare [4], [6], [15], [17], [18].

This work aims to present the multivariate analysis of the kinematics of the upper limb rehabilitation robot to verify the possibility and range of performance of rehabilitation exercises using a specifically designed exoskeleton. As a result, this will enable the selection of an optimum design solution for the rehabilitation robot that will meet the therapist's expectations. Rehabilitation may vary depending on a medical institution, hence, there is a possibility of creating personalized solutions dedicated to a given medical institution or a certain disease. The lack of guidelines in this field provides a certain degree of freedom in undertaken activities. At the same time, the optimization of the available solutions is also necessary. The chief objective of this work is to obtain, on the basis of a universal design, multiplanar movements in an ergonomical stationary device. The universal design of the rehabilitation robot aims to provide rehabilitation of the shoulder joint, elbow joint and wrist, which could be adjusted to a wide range of adult patients. Nowadays, rehabilitation and access to it are very important. The application of the rehabilitation robot may support this process and facilitate access to specialists, who, as a result, will have more time for a bigger number of patients. Properly trained personnel or even patients themselves may perform exercises under minimum supervision, which allows for execution of workout independently from third persons. The design and kinematic diagram of the exoskeleton is of a crucial importance. It should enable rehabilitation in the widest range of movements as possible, being at the same time safe for both the patient and therapist. Properly selected exoskeletons, for the whole upper limb or just limited to the wrist or the elbow joint, are able to measure and control the kinematics and kinetics, thus providing a repeatable, adaptive and intense therapy. The satisfaction of these requirements underlay the motivation for the performance of the analysis which constitutes the basis of this work.

In an extensive review conducted on the basis of the PubMed database and keywords, such as: “upper limb”, “rehabilitation robot”, “analysis of kinematics”, “kinematics”, “multivariate analysis”, the authors of this work did not find any related publications which would discuss the comparison of the movement ranges of several concepts of a rehabilitation robot – the comparison which would enable the selection of the optimum rehabilitation solution. The researchers found publications focusing only on the kinematic analysis of a specific kinematic solution of a robot [7], [8]. This fact only reinforces the importance of the presented subject matter and draws attention to valuable information constituting the basis of subsequent similar topics. An interesting solution was presented by Wang et al. [17], who described a new type of the upper limb rehabilitation robot equipped with 5 DOF. The final design was preceded by the performance of the kinematic analysis and simulation, which confirmed the correctness of the theoretical derivation. Narrowing down the field of interest, it should be mentioned that there are also publications describing several robots, however, they do not refer to the direct kinematic analysis, as presented in the works by Jiang et al. [8], Brewer et al. [3], Zeiaee et al. [19] and Sobiech et al. [14].

2. Materials and methods

During the development of the concept of kinematic chains, the researchers developed both the kinematic diagrams and testing digital models using software programme Autodesk Inventor 2013 (https://www.autodesk.eu/products/inventor/).

Taking the fact that the device was supposed to be a stationary device into consideration, the necessity arose to provide the device with a base on which the main part of the exoskeleton structure would stand. Several solutions of the base design were proposed. They make it possible to position the device in a comfortable position for the patient and allow for the rehabilitation of both the right and left upper limb.

Two main concepts of the base were developed. They enable the re-adjustment of the exoskeleton in the X axis (left-right) depending on the rehabilitated limb, whereas the seat is fixed. Concept P1 (Fig. 1) assumes the positioning of the trolley on rails located on the ground. The trolley may be positioned to work either with the left or right arm. The trolley features vertical rails which enable its up-and-down movement necessary to position the main part of the exoskeleton at a required height. On the other hand, concept P2 (Fig. 2) is based on a frame on which the rails and the trolley are located. The trolley features a lifting column

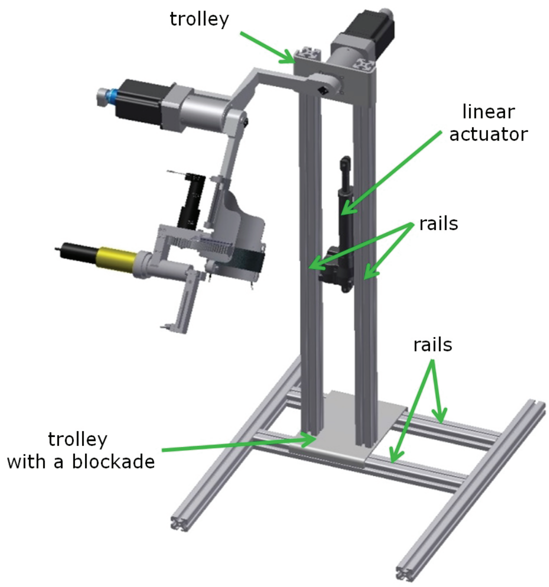

Fig. 1. Concept P1 featuring the trolley located on rails positioned directly on the ground. Own source

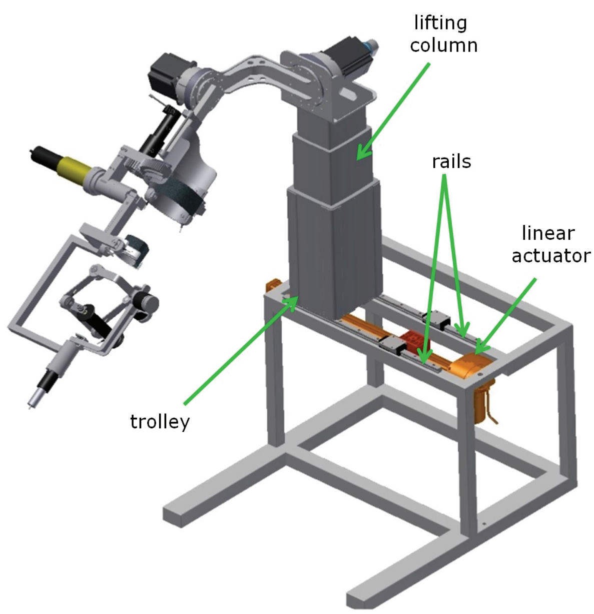

Fig. 2. Concept P2 featuring the frame where rails with the trolley are located. Own source

umn which adjusts the height of the main part of the exoskeleton to the patient. There is also a third concept of the base, in which the seat is adjustable to the exoskeleton and the lifting column makes it possible to regulate the height of the exoskeleton position.

During the development phase, three concepts of the exoskeleton kinematic chain were subjected to the kinematic analysis. They were called K1, K2 and K3, respectively. The first one, K1 (Fig. 3) has seven main class-five kinematic pairs, which enable rehabilitation of the whole upper limb in the shoulder joint, elbow joint and wrist. Moreover, in order to ensure the adjustability of the exoskeleton to the patient, additional kinematic pairs were provided, which are responsible for the lengthening or shortening of individual parts of the robot.

In the K1 concept, the first main kinematic pair is responsible for both the abduction and adduction movement of the shoulder joint as well as for the adjustment of the exoskeleton to work with the other limb. Flexion and extension in the shoulder joint are performed by the second main kinematic pair.

The next concept K2 (Fig. 4) also has 7 main degrees of freedom and also auxiliary ones. In this case, the axis of the first rotational kinematic pair is parallel to the vertical axis of the patient. What is essential to

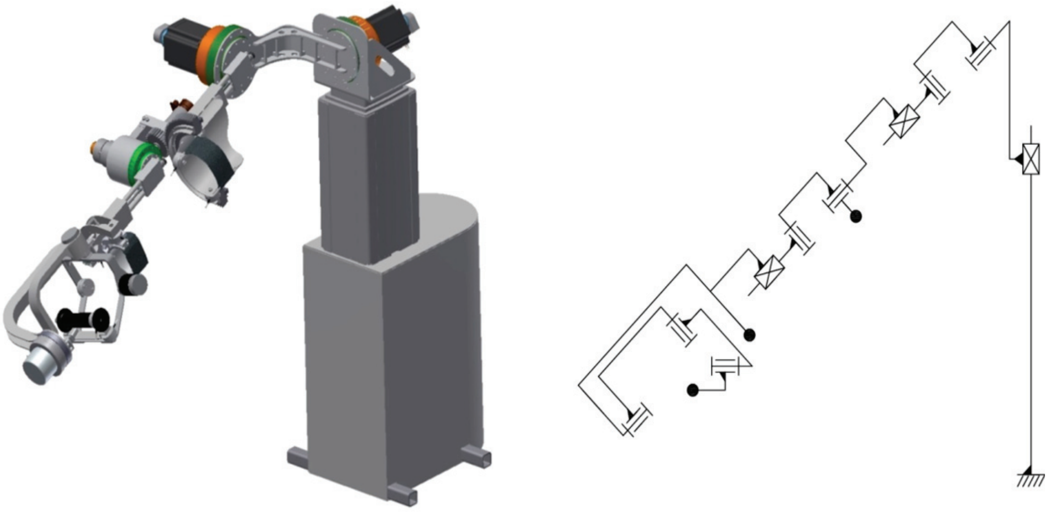

Fig. 3. Concept K1 featuring seven main kinematic pairs of class five. Own source

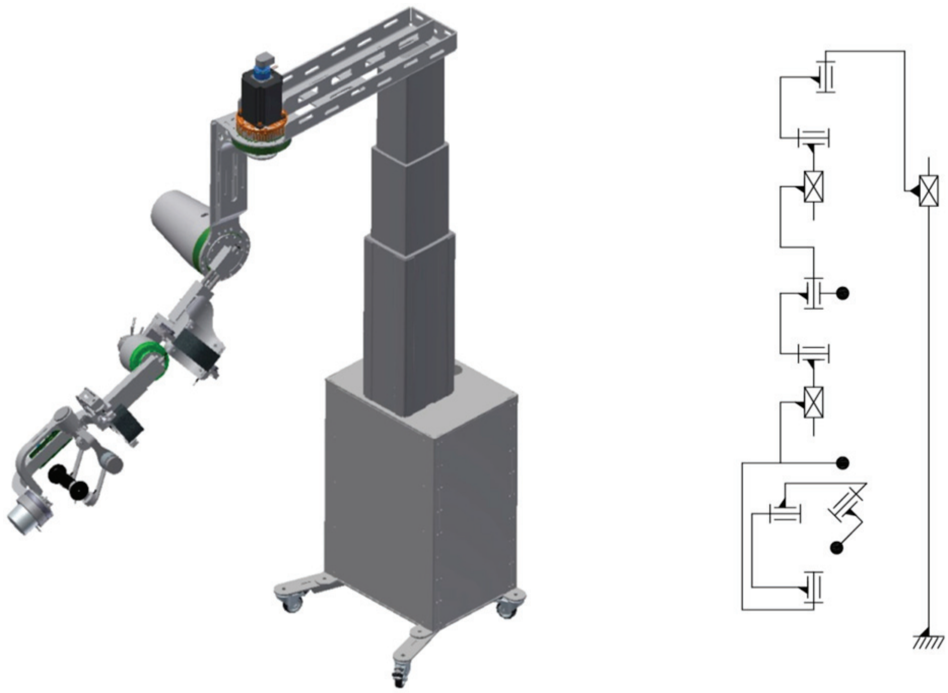

Fig. 4. Concept K2 featuring seven main kinematic pairs of class five. Own source

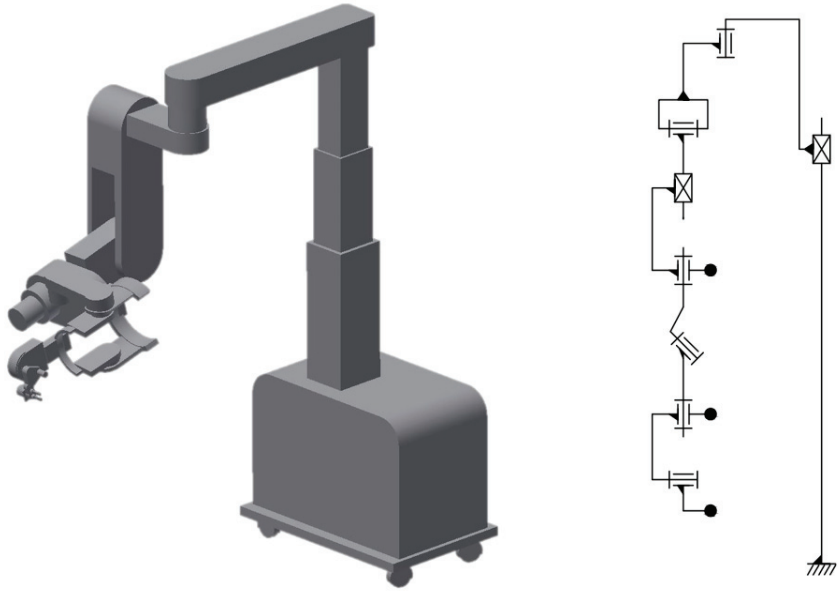

Fig. 5. Concept K3 featuring 6 degrees of freedom. Own source

this concept is the fact that both abduction and adduction movements as well as flexion and extension in the shoulder joint are executed by the second kinematic pair, positioned for a specific movement by the first kinematic pair.

The third concept of the design, namely K3 (Fig. 5) is a concept having 6 degrees of freedom. In this case, also the first kinematic pair has the vertical axis. In comparison with the previous concepts, the missing degree of freedom is related to the lack of one of kinematic pairs in the area of the wrist joint. It is possible to further develop this concept by supplementing it with the missing degree of freedom, which would enable the execution of an additional flexion movement (elbow and carpi radialis muscle flexion) in the wrist joint. However, this might restrict other movements. The above-mentioned concept is similar to the reference kinematic diagram available on the market of technological equipment – device Armeo Power (https://www.hocoma.com/).

The above-mentioned concepts were developed in the form of digital models, which made it possible to conduct investigations involving the analysis of the mobility ranges using the Autodesk Inventor software programme.

3. Results

The concepts (K1–K3) developed in the form of digital models allowed for the performance of the analysis of the mobility ranges. The investigation established ranges possible to achieve by verifying maximum boundary positions which could be achieved by the exoskeleton within a set task of a simple movement in a specific joint in a particular plane. The results obtained from the conducted analyses of the movements in the shoulder, elbow and wrist joints in all 3 concepts are presented in Table 1. The obtained movement ranges were compared to the movement ranges according to the ISOM standards = International Standard Orthopaedic Measurements.

The underlying idea of these concepts was to create an exoskeleton of a universal design addressed to a wide group of adult patients. That is why the proposed kinematic chain should enable the performance of natural spatial movements in the scope as wide as possible for simple and complex movements, in the case of both right and left limbs. The purpose of the device is to support rehabilitation of patients with a complete loss of functionality or with reduced functionality of their arm(s) caused by disorders or injuries of the central or peripheral nervous system. Due to the fact that the target exoskeleton is to be used as therapeutic equipment, it was assumed that it should be made in the form of a stationary device and not a wearable device as it would load the patient with additional weight.

In Figure 6, the analysis of the abduction and adduction movements in the shoulder joint are presented. The visualization is divided into the proposed three concepts and shows the respective movement ranges (in the shoulder, elbow and wrist joints). In the case of concept K1, the movement range falls within 0–95°. It turned out that that limitation resulted from the collision of one of the drives with the patient's head.

Table 1. Results of the analysis of movements in the shoulder, elbow and wrist joints in concepts K1–K3

	Shoulder				Elbow		Wrist	
	adduction/abduction coronal plane	extension/flexion transverse plane	extension/flexion sagittal plane	external/internal rotation sagittal plane	extension/flexion sagittal plane	supination/pronation	dorsal/palmar flexion sagittal plane	radial/ulnar deviation transverse plane
Concept K1	0°–0°–95°	40°–0°–130°	5°(35°)–0°–180°	75°–0°–75°	0°–0°–100°	90°–0°–80°	50°–0°–70°	20°–0°–20°
Concept K2	0°–0°–140°	40°–0°–130°	20°(35°)–0°–140°	(90°–10°)–x–(10°–90°)	0°–0°–100°	90°–0°–80°	50°–0°–70°	20°–0°–20°
Concept K3	x–40°–120°	50°–0°–170°	30°–0°–140°	90°–0°–90°	0°–0°–100°	60°–0°–60°	60°–0°–60°	impossible
ISOM*	0°–0°–170°	30°–0°–135°	50°–0°–170°	90°–0°–80°	0°–0°–150°	90°–0°–80°	50°–0°–70°	20°–0°–30°

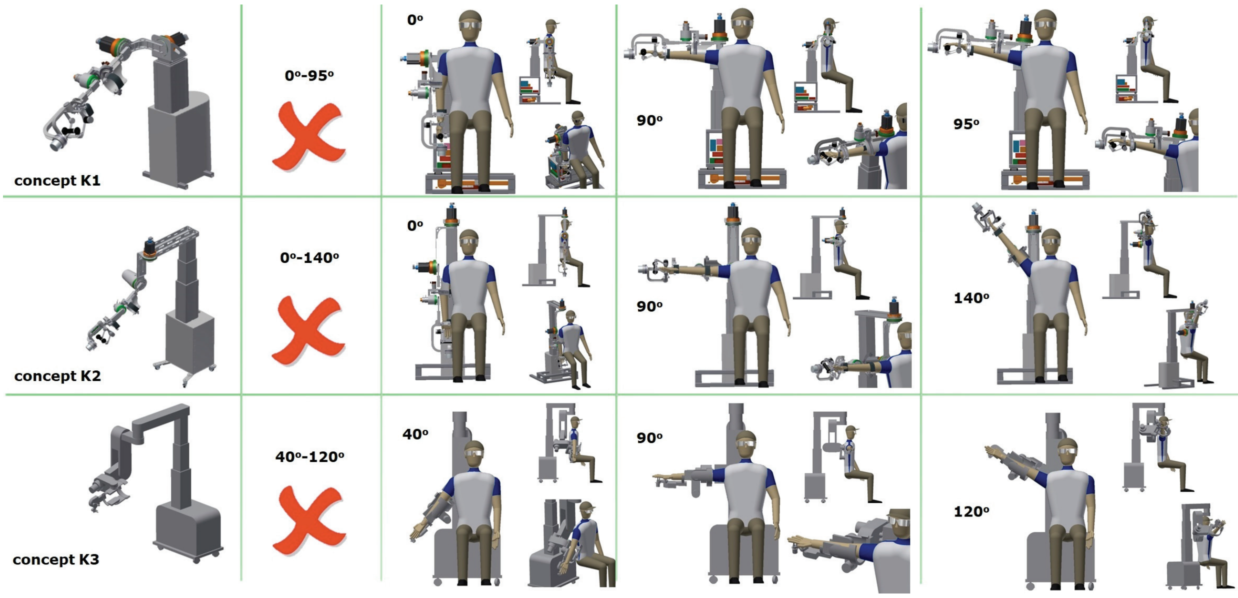

Fig. 6. Visualization of concepts K1–K3 showing the shoulder joint during the adduction and abduction movements. Own source

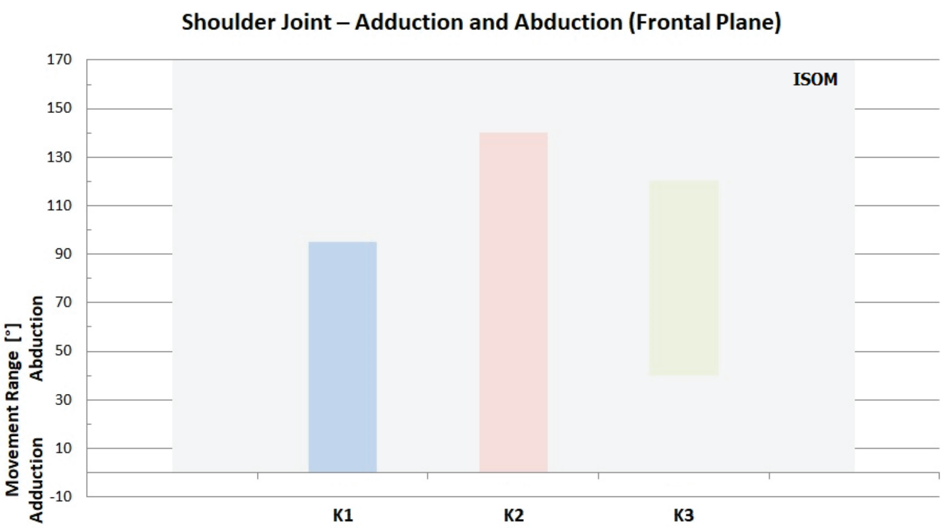

Fig. 7. Movement range of adduction and abduction in the shoulder joint in relation to the ISOM standards. Concepts were marked with respective colours: blue – concept K1, red – concept K2, green – concept K3, gray – ISOM

A greater range is displayed by concept K2, which enables the abduction of the arm up to an angle of 140°. However, above that angle, a collision between the exoskeleton parts occurs. As for concept K3, the movement range is from 40 to 120°. It results from the fact that below 40° some construction elements of the robot collide with the patient's body. Above 120°, a collision between the modules of the device occurs.

The diagram presented in Fig. 7 depicts the movement range of adduction and abduction of the shoulder joint in the frontal plane in relation to the movement ranges according to the ISOM standards.

The next step involved the analysis of movement in the shoulder joint for the above-mentioned three concepts during the performance of movement in the transverse plane. The analysis showed that the movement range is similar in concepts K1 and K2 and amounts to approximately 130° in the abduction movement and 40° in the adduction movement. The broadest range was displayed by concept K3, where the range overlaps with and is even broader than the one needed for rehabilitation. In the case of abduction movement in the transverse plane, the collision of the main part of the exoskeleton with its base (in concept K3 featuring

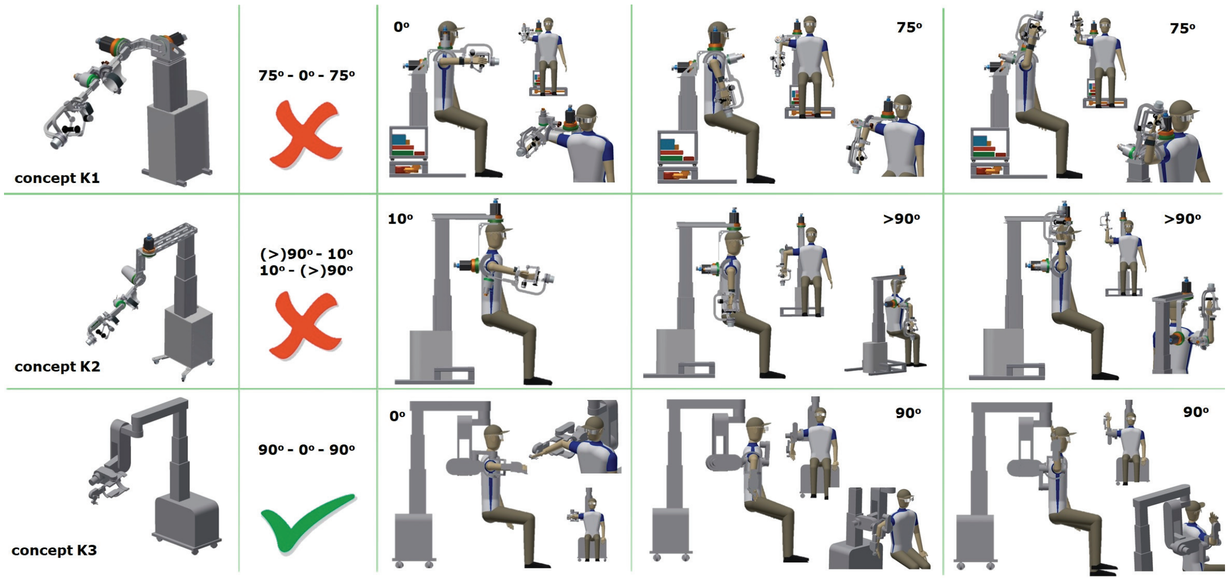

Fig. 8. Visualization of concepts K1–K3 showing the shoulder joint during the movement of internal and external rotation. Own source

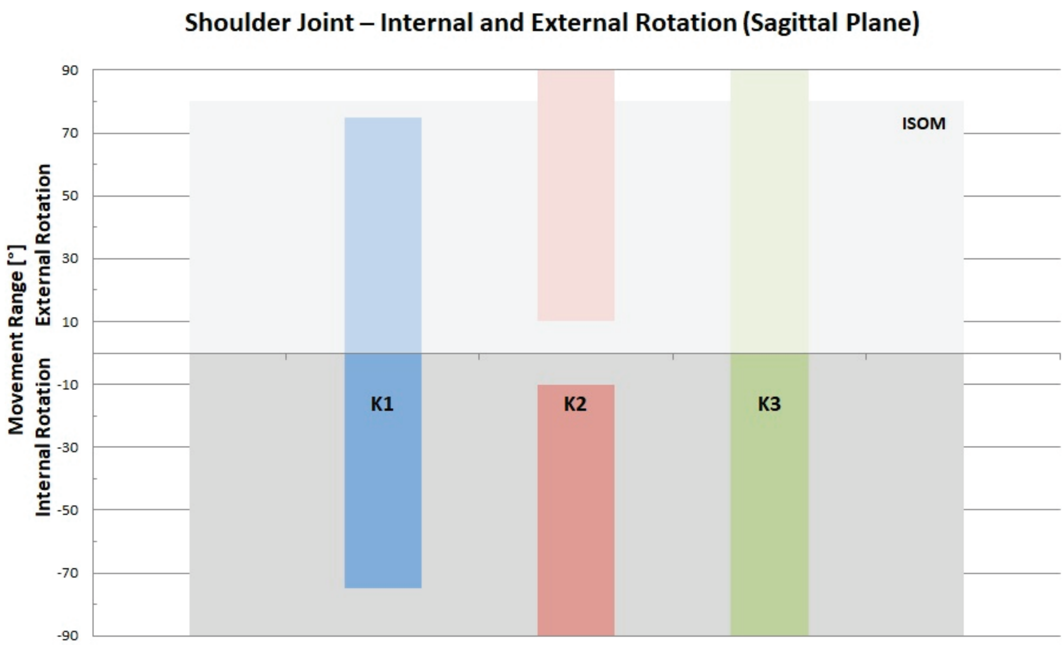

Fig. 9. Movement range of internal and external rotation in the shoulder joint in relation to the ISOM standards. Concepts were marked with respective colours: blue – concept K1, red – concept K2, green – concept K3, gray – ISOM

a lifting column) constitutes the restriction of movement. In the case of adduction movement in the transverse plane, there occurs a collision between the exoskeleton and the patient's body. Having compared ranges according to the ISOM standards, it can be stated that the movement ranges in all three above-mentioned concepts are sufficient.

The next stage involved the analysis of movement ranges in the shoulder joint in the sagittal plane, in which the flexion and extension movement is performed. The highest value of extension was displayed by concept K3, whereas the lowest was shown by concept K1. However, it must be said that in all concepts there was a problem with the collision of the main part of the exoskeleton with its base. In the case of concept K1, the extension angle may be increased up to 35° with a simultaneous abduction of the shoulder joint by 20°, which is, in fact, quite a natural movement. An increase in the hyperextension in concept K2 is also possible by applying delicate rotation in the vertical axis. As for flexion, only in concept K1 the obtained value of the angle complied with the expected value. In fact, there is still potential to increase this value. In the cases of concepts K2 and K3, there was a collision between exoskeleton modules, which resulted in the limitation of mobility.

The analysis of the kinematics of internal and external rotation has been presented in Fig. 8, whereas Fig. 9 includes the diagram showing the movement range of the shoulder joint rotation (external and internal rotation) in the sagittal plane with reference to the movement ranges according to the ISOM standards. It is clearly visible that concept K2 shows the lack of movement continuity in a certain range, whereas concept K3 displays a broader range of movements than it is defined by the ISOM.

In the case of concepts K1 and K2, the rotational movement of the shoulder joint is performed by changing the position of the modules integrated with the trolley, which moves on a curved linear guide of an angle of 180°. Taking into consideration the fact that in concept K1 the initial position of this movement (i.e., 0°) puts the trolley in a symmetrical location on the guide, the movement itself is also symmetrically restricted for both internal and external rotation. Such restriction depends on the width of the trolley and the necessity of applying a blocking system preventing the derailing of the trolley. In concept K2, extreme positions place the trolley in the middle of the guide, which results in the discontinuity of the rotation movement, because in order to move the trolley to the opposite extreme position only a half of the guide length can be used.

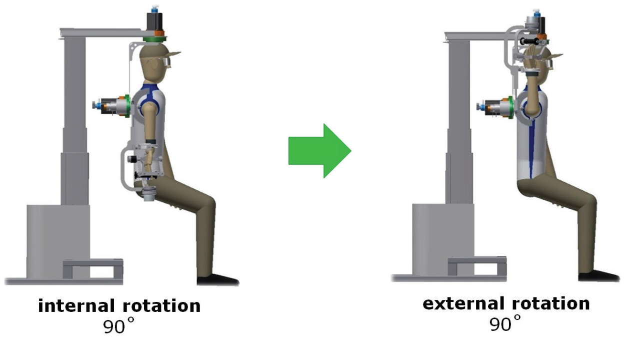

Fig. 10. Extreme positions of internal and external rotation in the shoulder joint in concept K2. Own source

Due to the encountered problem connected with the transition from internal rotation to external rotation (Fig. 10), several solutions to this problem were proposed. The first solution consisted in a shift of the fixation of the curved guide in relation to the load

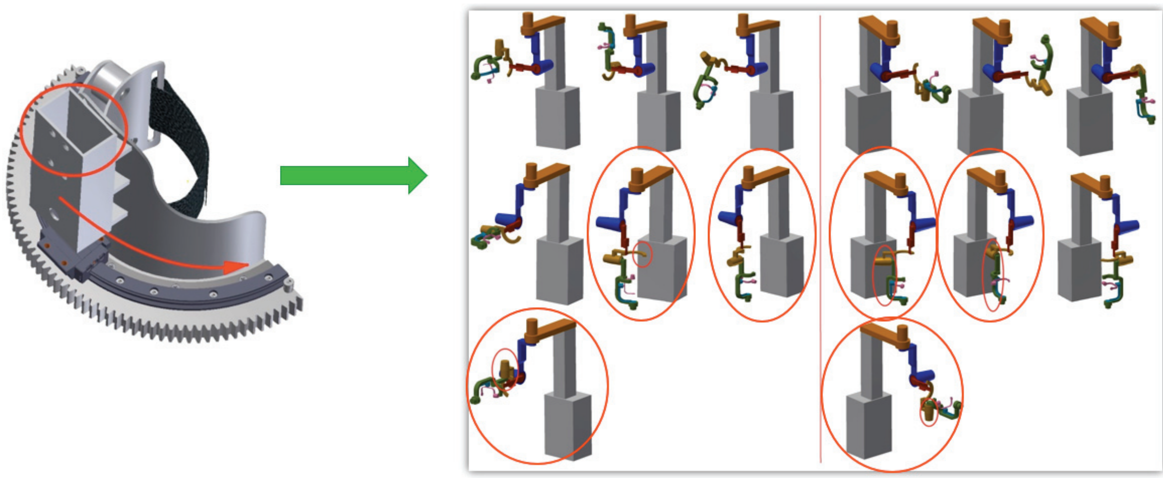

Fig. 11. Concept K2: a proposition how to solve problematic movements – a shift of the fixation of the guide. Own source

bearing module in an unsymmetrical way, which is shown in Fig. 11. After the introduction of the above-mentioned change into the testing model and the performance of simulation in the software programme, it turned out that such a solution improved and enabled the transition between the rotations of the shoulder joint. However, some limitations still remained.

Asymmetry of the guide in relation to the load bearing module led to the collision of the guide with the patient's body in different configurations of the exoskeleton's positions, especially after re-configuration of the robot to work with the opposite limb.

Another attempt at solving the problematic movement was to increase the length of the curved guide aiming at its "closure". The guide is a product available on the market and thus has to meet high strength requirements. It is important as the connection between the trolley and the guide must bear considerable loads (static moments of the trolley). The guide itself is made in the form of modules and thus consists of segments, which are mutually adjustable by machining and grinding. The lengthening of the guide involves adding a subsequent segment, which increases its range from 180 to 240°. However, the extension of the guide leads to the collision of the guide with the patient's body in different configurations of the robot setting. Disregarding the fact of the guide collision with the patient, the "guide closure" solution (Fig. 12) leads to the decrease in security and patient's discomfort caused by the fact that it is impossible to quickly free the patient's limb from the exoskeleton clamp.

In addition, another concept was also considered: putting into motion the module along with the guide and rack co-operating with drive 3 with simultaneous immobilization of the trolley in relation to module 3. To do that, simplified 3D models were generated and the rotation movement was simulated, however, this solution did not bring the desired effect.

In consequence, it should be remembered that the decision to select the exoskeleton based on the kinematic diagram of concept K2 entails the lack of the motion continuity during the transition from internal rotation to external rotation.

Apart from simulations related to the shoulder joint, researchers also conducted simulations of movements in the elbow joint and wrist for the three proposed concepts of the kinematic chain. In the case of the flexion movement in the elbow joint, a similar value of the flexion angle was achieved practically in all variants equalling approximately 100°. If this value is exceeded, a collision occurs between modules beginning to overlap.

As for the rotation movement of the forearm, practically all concepts meet the requirements. However, in the case of concept K3 the movement is restricted to some degree, which results from the limitations of the designed robot construction. If this concept was to be further developed, it is possible to extend the range of this movement.

Presented results of the analysis allow to emphasise advantages and disadvantages of given concepts. Every kinematic chain concept brings certain movement limitations, but also superiority to other solutions at the same time. For teams designing a similar exoskeleton, these results may serve as a reference for choosing an optimal solution for their device's construction form, regarding the planned rehabilitation range that will be supported.

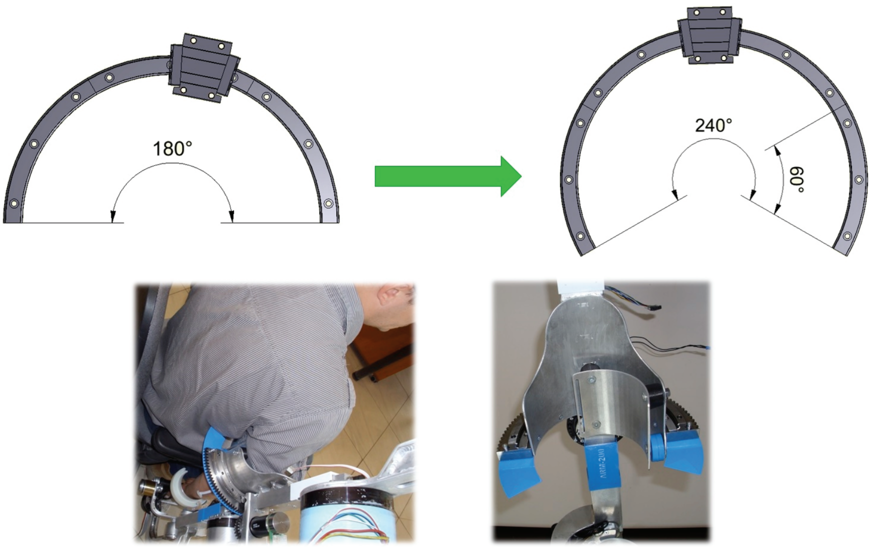

Fig. 12. Concept K2: a proposition of how to solve problematic movements – closure of the curved guide. Own source

4. Discussion

Can the robotic devices replace the physical contact with a therapist during the rehabilitation process? – an obvious answer to this question is that they cannot. The conducted multivariate analysis of the kinematics confirms that every exoskeleton introduces some limitations in the limb mobility, which is related to the multiplanar rehabilitation of the whole limb making use of both simple and complex movements. This results from the fact that the exoskeleton is a device which "girds" or "encases" the limb and the exoskeleton dimensions or "body" will always lead to a collision with the patient's body – always sooner than in the case of the limb itself. A crucial fact is that the analysis of the concept of the kinematic diagram of the exoskeleton mobility should be performed in relation to its construction form, as it considerably affects the robot's design and introduces limitations. It is difficult to select such parameters that satisfy all assumptions of the concept. The improvement of one parameter often leads to the deterioration of another one. During the search for an optimum concept, the simulation of movement and improvement of one specific movement range often had a significant impact on a different movement, restricting it in a considerable way, thus, leading to the necessity of returning to the previous solution. The above-mentioned conclusions were also confirmed by the deliberations on concept 2 related to the transition from internal to external rotation.

The analysis has highlighted problems connected with specific solutions, which the researchers might try to eliminate by introducing some modifications. In the case of the initial version of concept K1, the main issue is the range of abduction in the shoulder joint due to the fact that at the abduction above 95°, a collision between the drive and the patient's head occurs. To increase the abduction range it is necessary to move drive 2 behind the patient's head simultaneously preserving the rotation axis in the patient's frontal plane. However, it requires the application of an additional mechanism to transfer the rotation movement from the drive to the place of actual rotation of the exoskeleton. Such a change enables an increase in the angular range of abduction reducing at the same time the patient's discomfort caused by the previous location of the drive in the vicinity of the patient's head. However, it should be born in mind that any modifications to particular segments of the kinematic chain significantly influence other segments. For instance, every change of the exoskeleton in the wrist joint which alters the mass of this segment results in different loads exerted on the drives and segments of the elbow and shoulder joints. Their alteration, in turn, may lead to the change of exoskeleton dimensions, which may finally affect the mobility in the shoulder joint.

While designing the exoskeleton, an ideal assumption would be to position the axes of the exoskeleton rotation with the natural axes of rotation in individual joints. However, it is difficult to implement due to the fact that often during movements, especially complex ones, the joint itself is moving and because of that the exoskeleton rotation axis no longer overlaps with the natural axis of rotation in the joint. Another aspect that should be taken into consideration is profitability of the expansion of movement ranges, as it may entail a complex construction design leading to an increase in the cost of the whole project. What should be remembered is the fact that even the most cutting-edge equipment meeting the highest standards will not serve its purpose without trained specialists and proper guidelines. Rehabilitation of the upper limb is the main and fundamental element of the rehabilitation of patients after stroke. This subject has been extensively investigated and the literature includes evidence that rehabilitation in an early phase after stroke is indispensable and effective [1]. Unfortunately, there are very few Polish studies aiming at the determination of an optimum model of rehabilitation and restoring motor functions of the upper limb. Many questions still remain without answer, for example about the effectiveness of an early physiotherapy of the upper limb, the boundaries of biological improvement, or the amount of workout on the upper limb in an early phase of physiotherapy after cerebral stroke. These and other questions need answering in order to find solutions improving the quality of the performed rehabilitation or to optimize both the existing and future solutions. The above-described objective constitutes the main subject of interest of the field of automated rehabilitation and will finally make it possible to achieve the desired goal. In spite of a growing number of proofs over the past 10 years that it is necessary to increase the amount of therapeutic workout of the upper limbs, the number of such exercises is still very small and the time for therapy (in minutes) allowed in daily therapeutic practice is still very short. Recent investigations into the kinematic standard of the restoration of the arm's functioning revealed that the quality of the movement may have a considerable influence on the improvement of the upper limb functions [4], [10], [13], [16]. Kinematic tests of the formation of the movement standard right after stroke show that the normalization of movement during the recovery process is expressed in an increase in the number of controlled degrees of freedom (in the same way as it is observed in healthy individuals in the same age group).

The main advantage of using an exoskeleton for rehabilitation is improvement of service quality and efficiency along with the possibility of handling multiple patients simultaneously and reducing therapists' involvement. Unfortunately, a serious disadvantage of the automated physiotherapy is a very high cost of the rehabilitation equipment, a complicated certification process and very limited availability for patients. The subject literature concerned with the upper limb rehabilitation indicates that effectiveness of rehabilitation is high in patients who survived cerebral stroke, however, the length of a period in which one can sustain the re-learnt motor abilities is still little known and insufficiently researched [5]. Despite a growing interest in exoskeletons, it is still a topic which requires further development. Subsequent investigations into kinematics will enable precise development of the method, diagrams and, finally, the robot itself in its physical form, which will translate into elevation of standards in many medical fields, particularly in neurology, physiotherapy and rehabilitation.

5. Conclusions

The conducted research showed that the analysis of the kinematic chain concepts of the exoskeleton has to be done in relation to the construction form of the robot taking into consideration all parameters. It should be emphasized that during the design phase of the exoskeleton the ideal solution would be to position the exoskeleton rotation axes to overlap with the natural rotation axes in individual joints. The introduction of changes in particular segments of the kinematic chain considerably affects other segments. During the search for an optimum concept, researchers should carefully "manoeuvre" the parameter values in order to avoid significant changes of other equally-important parameters caused by the alteration of a single parameter.

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