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The Use of Generative Design Methods to Reduce the Parameters of an Actuator Used in the Positioning System of a Continuous Passive Motion (CPM) Device

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Abstract: This paper presents the results of a computer optimising a multibody system using Generative Design methods to select a lower-cost actuator that meets process requirements with its parameters. Optimisation was performed to reduce the mass of the motion apparatus components of the author's CPM device, used for the rehabilitation of patients after knee arthroscopy and total or partial knee replacement. An analysis of the kinematics and dynamics of the multibody mechanism, based on a virtual model, was carried out to identify the requirements for selecting an actuator. The main components of the motion apparatus mechanism were subjected to a series of numerical analyses using selected CAD/CAE tools, with the assumed criterion of varying material and component shapes to ensure that the required strength and accuracy of the mechanism links were maintained, assuming the same functionality. The results of the numerical analyses will be the basis for the selection of the optimum solution, for which a new, lower-cost actuator will be selected.

Keywords: positioning system; CPM device; arthroplasty; CAD/CAE; generative design; actuators selection

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1. Introduction

An active lifestyle, especially professional sport, which puts a heavy strain on the musculoskeletal system, as well as civilization-related diseases that are usually associated with a lack of physical activity, such as obesity, diabetes, etc., all contribute to damaging the knee. The knee is the largest joint in the human skeleton. Because of its complex structure and the stresses of everyday movement, it is highly susceptible to injury. Diseases and injuries of the knee joint generally exclude or severely restrict people from performing their daily activities due to the impaired motor function associated with a reduced or lost ability to move fully or partially. The main complaints in the knee joint are usually associated with meniscus injuries, sprains or dislocations, and damage to the cruciate ligaments. These conditions are usually temporary and can be reversed with appropriate rehabilitation. Many times, in order to make a proper diagnosis, a procedure is practiced to view the knee joint, called arthroscopy. Chronic joint inflammation is much more problematic from a rehabilitation point of view. This can be caused by advanced osteoarthritis of the knee or rheumatoid arthritis. The joint surfaces that cover the bones, which have been lost or mechanically damaged, need to be replaced in whole or in part by artificial implants that precisely restore motor function and eliminate pain. The treatment uses total endoprostheses, single-compartment endoprostheses, or bicompartmental endoprostheses. The medical procedures used to replace a total or partial knee are called total or partial knee replacement (also called knee arthroplasty) [1,2].

The above surgical procedures cause patients discomfort after surgery due to pain, swelling, and tenderness of the joint. Patients' limitation of motor function due to joint pain paradoxically leads to an increase in stiffness and thus a reduction in the initial mobility within the joint (Range of Motion—ROM). Most physio-therapists recommend continuous passive motion (CPM) devices immediately after knee surgery. Continuous passive motion (CPM) is a rehabilitation therapy that uses a machine to move a joint for a patient [3,4]. Such a device performs a controlled movement within a pre-set range to increase the initially limited ROM of the knee joint and restore muscle strength. The CPM device is powered by an actuator that provides continuous motion of the joint, performing regular flexion and extension of the limb at the knee joint without any effort from the patient. As a result, the knee joint tissue is better nourished by the rehabilitation device and therefore regenerates more quickly, reducing pain and minimizing the potential for new inflammation [5].

Various modifications of the CPM device are being used in many research centres around the world for mechanical kinesitherapy of various human upper and lower limb joints [6–8]. The Department of Automatic Control and Robotics at the Bialystok University of Technology, Poland has also developed a similar device for rehabilitation after arthroscopy and knee arthroplasty [9,10]. However, a problem with the drive of the ARTROBOT CPM device motion apparatus by an electric actuator coupled to a mechanical gearbox was identified during further research and the prototype solution was tested. From the analytical calculations carried out to select the right actuator for the solution, it became clear that the actuator selected would have to generate high torques, which would result in a high purchase cost for the motor with a gearbox, as well as its increased size and the mass of the solution. When it comes to mobile CPM solutions for use in independent rehabilitation, the mass of a geared actuator is an important parameter.

This paper was written in response to an engineering need to optimise the design of the motion apparatus of a CPM device using modern CAD/CAE tools and Generative Design methods, which are a form of artificial intelligence that use the power of the cloud and machine learning to speed up the whole process starting from design to execution [11,12]. The optimisation methodology proposed in this paper will lead to a reduction of the mass of the kinematic chain components of the motion apparatus which will translate into a bespoke selection of the correct electrical actuator. This results in lower operating costs. It also extends the life of the equipment and reduces the risk of equipment failure, thereby reducing service costs.

State of the Art of Scientific Research in the Field of CPM Devices Design

The use of the CPM device in kinesitherapy immediately after surgery and during the subsequent recovery period after knee arthroscopy or endoprosthetic is a common practice in many medical facilities. Continuous passive motion is designed to improve the ROM of the knee joint. This will consistently reduce pain. It is assumed that by bending the limb in a range of 90 to 106 degrees, it is possible to perform basic activities, including movements such as descending stairs, rising from a toilet or low chair, and tying shoes [13–16].

The existing body of knowledge on CPM research is mainly concerned with the validity of the use of CPM devices and determining the possible benefits for the patient's health. The vast majority are scientific papers, mainly of a strictly medical nature [17–21]. They look at the health effects of rehabilitation using a CPM device. As far as scientific work in engineering and technical sciences is concerned, in the case of CPM rehabilitation devices offered on the market, the research is not published, most likely due to the protection of the intellectual property of the solution. Therefore, the synthesis of knowledge on CPM design can only be based on selected articles and selected patents filed in international patent databases. Analysing selected solutions from patent databases, it is clear that the majority of CPM device designs are based mainly on the use of nut–screw-type linear guides driven by an electric actuator to move the positioner. Examples of these are presented in the following papers [22–25]. Another group are CPM systems where the actuator is directly coupled to the knee flexion mechanism (in the flexion axis) [26,27]. In these studies, the authors describe solutions that are usually offered by rental companies that specialize in rehabilitation equipment and operate in Poland. Among them are the products of the ARTROMOT family [28], Chattanooga OptiFlex3 CPM machine [29], and Jace K200 The Zero Machine CPM machine provided by Jace System [30]. In the above-mentioned CPM systems, the movement of the motion apparatus is carried out following the patents in question, either using a screw and nut system or using a direct drive in the flexion axis of the knee joint. There are also proposals for technical solutions based on the mechanism of a modified articulated quadrilateral [31], CPMs driven by a set of drive cables coupled by pulleys [32], or a driving rotating member in the form of a disc [33].

The technical solution of the motion apparatus presented in this study is unique. This is due to how the positioner motor of the CPM device is driven. A slider–crank mechanism coupled to an electric actuator was used [10]. The following Section 2 presents the technical details and the research carried out to optimise the CPM's positioner movement apparatus.

The content of this paper is structured as follows: (1) The Section 1 introduces the topic of rehabilitation using mechatronic CPM devices and defines the research problem, and presents reviews of scientific work in the design, use, and testing of CPMs; (2) the Section 2 describes the author's CPM solution as well as the numerical testing methodology employed in the selected CAD/CAE tools; (3) the Section 3 presents an analysis of the research results obtained in optimising the mechanical design of the positioner motion apparatus using Generative Design techniques; it proposes the technology for the manufacture of the resulting structures, in addition to the choice of the optimum solution; (4) the Section 4 critically summarises the numerical tests performed, points out their strengths and weaknesses, and makes recommendations for further development work on the CPM design in question.

2. Materials and Methods

2.1. The Main Components of the CPM Device—Research Object Characteristics

The design optimisation study will be carried out using Generative Design methods. It will focus on the main positioner of the CPM rehabilitation device. The research object will be a virtual model of the CPM device developed in the SolidWorks 2023 software environment. The main dimensions of the device components were taken from an analysis of design guidelines for this type of biomedical solution, based on an atlas of human measurements and data for ergonomic design and evaluation [34,35]. The kinematic configuration adopted for the study corresponds to the dimensions of male specimens according to the 95C centile model. A general view of the developed virtual CPM rehabilitation device model is shown in Figure 1.

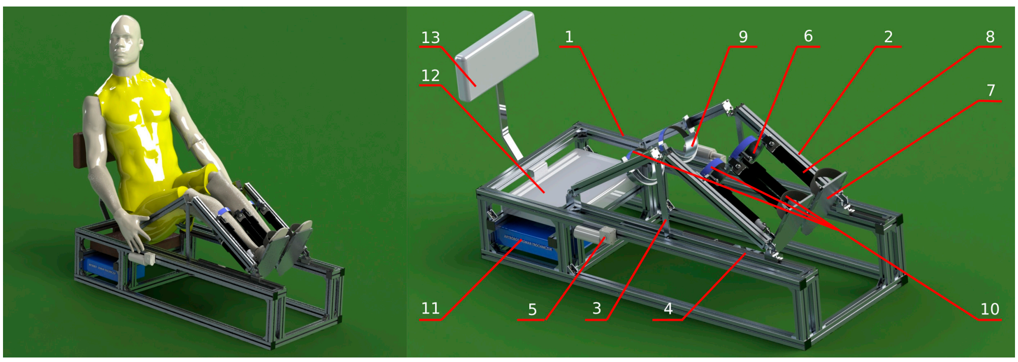

Figure 1. View of a virtual model of CPM rehabilitation device: (1) CPM unit; (2) main positioner; (3) crank–slider mechanisms; (4) movable sliding guide; (5) actuator; (6) calf support yoke; (7) support the patient's feet; (8) electric linear actuators; (9) limb support; (10) elastic straps; (11) control box; (12) seat; (13) height-adjustable backrest.

The supporting structure of the CPM unit (1) and the main positioner (2) was based on commercially available 40 × 40 mm aluminium structural profiles with a single 10 mm groove. The entire support frame was mainly assembled using mounting brackets and 10 M6 slot nuts. This allows the unit to be assembled according to the instructions supplied, and also makes the unit smaller when folded for transport. The main two-leg positioner system is driven by two separate crank–slider mechanisms (3) driven by an electric actuator coupled to a mechanical gearbox (5). The CPM device is mainly used for rehabilitation of the lower limbs: left and right, synchronous and asynchronous. The control mode of the main lower limb positioner system is selected by the rehabilitation therapist for each patient individually, depending on the rehabilitation needs, both immediately after the procedure and in further stages of kinesitherapy supported by the mechatronic device.

The CPM has two independently controlled platforms, mainly used to support the patient's feet (7) during the movement of the main positioners. Structurally, the kinematic chain is formed by a calf support yoke (6), which forms a fixed platform, the aforementioned movable lower foot support platform and three electric linear actuators (8), which are coupled to the platform via rotary joints, thus forming a parallel tripod robot structure. The working position of the mobile platform can be either permanently fixed during the entire movement of the main positioner or dynamically changed during the movement. The movement of the platforms supporting the patient's feet is independent of the movement of the main positioners. This allows the device to be used as a CPM for the ankle, increasing its potential applications. The movable platforms adapt to the current position of the foot, increasing the range of applications, particularly for patients with clubfoot, valgus or spastic feet, characteristic of post-stroke patients, and patients with multiple sclerosis or other neurodegenerative diseases. It is therefore possible to perform passive movement exercises, taking into account the prescribed complex supination and pronation movements, as well as exercises with variable loads—exercises that actively stimulate the muscles. These exercises are usually performed at a later stage in the patient's rehabilitation.

The movable links of the main positioner are fixed to the support structure on the patient side and are movable on the other side using a movable sliding guide (4). The main positioner links are responsible for programmable displacement at the knee joint, increasing the value of the ROM and, in the second control mode, with simultaneous passive movement of the foot support plane. These links are also attached to the patient's limb support legs (6) and (9), which use elastic straps (10) to attach the limb to the mechanism at the foot, calf, and thigh surfaces. The CPM device motion control system is based on a real-time FPGA controller and is housed in a control box (11) located under the patient's seat (12). To ensure a comfortable position during rehabilitation, the patient's body can be supported by a height-adjustable backrest (13). A more detailed description of the operation of the device and the assumptions for the design development can be found in the papers [9,10].

2.2. Methodology Used in the Present Research

In order to be able to approach the problem of optimising the positioner design according to the criterion of reducing the mass of the links forming the structure of the kinematic chain using Generative Design methods, a preliminary numerical study was carried out for this purpose in the ANSYS Workbench 2022R2—Rigid Dynamics toolbox [36]. This allowed the kinematic and dynamic parameters of the main positioner to be determined. Based on the results of the kinematic and dynamic analysis, the parameters that have a significant influence on the control of the CPM positioner actuator were evaluated.

For the CPM numerical analyses, a simplified test model was prepared based on the geometry previously modelled in SolidWorks 2022, which was the basis for further analyses in ANSYS Workbench 2022. Simplifications were made to the computer model by removing process chamfers and roundings, eliminating holes for connecting elements that attach the motion apparatus to the structure's support frame, and replacing bolted connections with fixed mates. These modifications were duly justified so as not to compromise the quality of the final test result while at the same time speeding up the numerical calculations. Figure 2 shows the kinematic structure of the single-limb positioner.

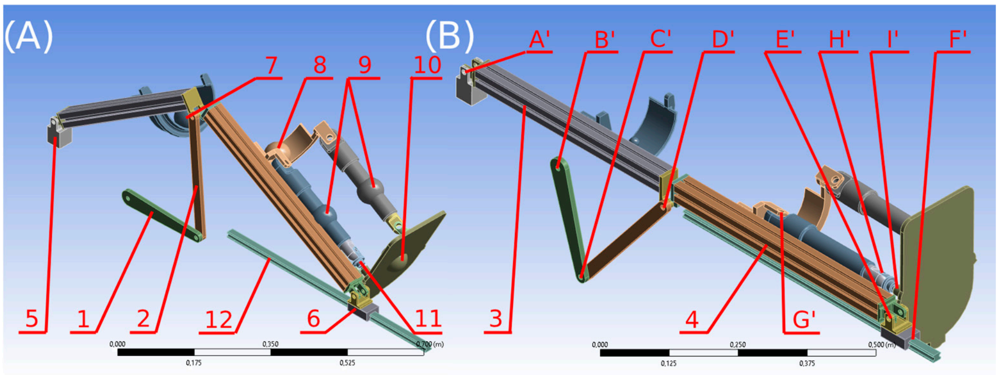

Figure 2. View of the three-dimensional virtual model of the CPM positioner using CAD/CAE analysis: (**A**) position of the mechanism in the bending knee phase; (**B**) starting position of the mechanism ready for analysis.

Figure 2 also shows the components of the positioner. We can distinguish between them: (a) links (1), (2), and (3) form the articulated quadrilateral mechanism; (b) links (3), (4), and (6), form the crank–slider mechanism; (c) (5) indicates the fixed attachment to the device frame forming a rotating kinematic pair with link (3); (d) (6) is the translational car of the linear guide, and forms a rotating kinematic pair with link (4); (e) (11) is the Delta robot articulated joint connecting the electric actuators to the patient's foot support platform (10), via spherical joints; (f) (12) is the linear guide track. Major changes to the geometry from the original 3D virtual model in SolidWorks include (a) removal of any chamfers and small holes for connectors; (b) removal of the screws connecting the kinematic chain components; (c) removal of bearings and shafts from rotating pairs; (d) replacing the mass of individual electric linear actuators by masses concentrated at a point, to obtain a representation of the real mass of a commercial solution (9); (e) adding a mass points loading of the thigh, calf, and foot supports to model the impact of the patient's lower limb at points of direct contact with the CPM device positioning system (7), (8), and (10).

A summary of the masses of each joint and element is highlighted in Figure 1 and an indication of the material of manufacture of the joints is given in Table 1.

Table 1. Summary of materials, masses, and loads of components of CPM device.

Detail	Mass [kg]	Material
1—link 1	0.61516	316 Stainless Steel
2—link 2	0.63436	316 Stainless Steel
3—link 3	0.81712	Aluminium, 6061
4—link 4	0.89385	Aluminium, 6061
5—link 5	0.61152	Stainless steel, AISI 201
6—translation system 6	0.36466	Stainless steel, 201 + Aluminium, 6061
7—thigh support + point mass	0.1455 + 24.00	Plastic, ABS
8—calf support + point mass	0.19186 + 10.70	Plastic, ABS
9—electrical linear drive	2.24429	Aluminium Alloy
10—foot support + point mass	1.2617 + 3.50	Aluminium, 6061
11—delta robot link	0.08714	Stainless steel, 201

The study of the design of the motion apparatus to optimise the solution for reducing the mass of the main components that make up the positioner of the CPM device, and finally the selection of a new actuator for the positioner drive system, was divided into several stages. In the first stage, a kinematic analysis of the motion apparatus mechanism of the CPM positioner will be performed, using the Rigid Dynamics toolbox of ANSYS Workbench 2022R2. This allows the determination of displacement, velocity, and acceleration values in specific kinematic pairs. These parameters will be defined for the geometry of the virtual model output previously designed in SolidWorks. As a result of the analysis, we obtain the parameters of the characteristic points of the mechanism. In the second stage of the study, the dynamic parameters of the mechanism will be determined—kinetic, potential, external (this is all the energy the loads and joints bring to a system [36]), and total energy (this is the sum of the potential, kinetic, and external energies in a Rigid Dynamics analysis [36]). These analyses will also be performed in the ANSYS Workbench. The assumed motion of the drive link (actuator rotation) allows the values of the forces and torques in the individual links of the kinematic pairs to be determined. The values obtained in this way will form the basis for further research into optimising the design to reduce the mass of the motion apparatus mechanism, which in the original solution is made of aluminium and stainless steel. The optimisation of the mass of the links will be realised using the Generative Design tool of the Creo Parametric 9.0.3.0 software [37]. For optimisation, the Generative Design toolbox is used to create test models using different materials and varying degrees of structural optimisation. Based on the computer simulation results obtained, structures are selected that meet the minimum mass conditions relative to the initial solution. Displacement values are not allowed to exceed the maximum values tested for the original solution, and von Mises stresses are also maximum at the level of the original solution. Structures that are not in compliance with the above conditions will be rejected and will not be the subject of further analysis. Once the optimum solution for each link has been selected, the basic design of the CPM device will be rebuilt and tests repeated to determine the kinetic, potential, external, and total energy values. For the new design, the torque values in the drive pair are also determined. These values will be compared with those of the original solution. The results of these analyses will be used to accurately determine the need to select a new actuator for the solution in question, with lower parameters than the original solution.

2.3. Kinematic Analysis of the Positioning of the Mechanical Actuator System

To analyse the kinematics of the CPM device, a scenario corresponding to the real use of the device was assumed. After defining the kinematic pairs in each link joint (link 5 is permanently fixed to the ground and is a fixed link; a rotational kinematic pair A' is defined between links 5 and 3; links 3 and 4 form a rotating pair D'; a rotating pair E' is defined between links 4 and 6; the linear guide car 6 together with the guide form a translational pair F'; between the linear electric actuator 9 and the calf support 8, a fixed stationary connection G' is defined; similarly, connections are defined between links 9 and 11, i.e., the actuator and the link of the Delta robot—H' and between 10 and 11, i.e., the link of the robot and the platform supporting the patient's foot—kinematic pair I'—as these kinematic pairs are excluded from further analysis; link 1 forms a rotating pair B' with the ground and is connected on the other side to link 2, forming a rotating pair C' with it; link 2 is connected to links 3 and 4 by a rotating pair D'; the thigh and calf supports are permanently attached to links 3 and 4 and this connection is defined as fixed); all components of the combined mechanism are positioned in the configuration shown in Figure 2B. The starting position defined in this way allows the lower limb to be positioned and fixed to the movement apparatus of the CPM device. The mechanism analyses did not include the mass and impact of the elastic bands used to attach and secure the limb to the thigh, calf, and foot supports (Figure 1, Detail 10). The actuator is attached to link 1 and forms with it a rotating pair B'. The operating mode of the device includes the speed of the actuator, which can be set to 4, 2, or 1 rpm. For the analysis, a variant of actuator movement was assumed with a maximum speed of 4 rpm (i.e., 24°/s), in the angle range $0° \rightarrow 157° \rightarrow 0° \rightarrow -3° \rightarrow 0°$. For the most part, this covers a regular range of motion of the knee (from $-10°$ to 155°) [38], with the imposition of the restriction that the motion after the phase of complete knee extension $-0°$ is still only deepened by a value of 30, rather than the maximum value of 10° assumed for the healthy knee. The motion in the maximum range was increased by 2°, to a value of 157°, to compensate for the effect of structural clearances on the accuracy of the displacements. The CPM allows fully programmable actuator control within specified incomplete ranges of motion with specified speed and acceleration parameters. This is due to the need for targeted rehabilitation, individually defined by the therapist for each patient, with specific requirements depending on the type of disease entity.

Displacements of the Delta robot's end effector (the platform that supports the patient's foot) were not included in the analysis. During the robot's motion phase, the support platform is assumed to be in a fixed position throughout the motion and is therefore not considered further. The finite element mesh required for numerical analysis is automatically generated by the CAE tool. For this type of study, this is of little importance as the final result does not depend on the accuracy and type of mesh chosen.

2.4. Dynamic Analysis of the Positioning of the Mechanical Actuator System

For the dynamic analysis of the limb positioning mechanism of the CPM device, CAE studies were also carried out using the Rigid Dynamics toolbox of ANSYS Workbench. A scenario similar to the kinematic analysis has been assumed for the definition of the drive operation, i.e., resulting from the rotation of the drive link in the range of angles: $0° \rightarrow 157° \rightarrow 0° \rightarrow -3° \rightarrow 0°$ with velocity 4 rpm (i.e., 24°/s). The effect of gravity force (9806.6 mm/s^2) on the links of the mechanism has also been taken into account. The simulation results obtained make it possible to determine the components in the XYZ axes of the torques (bending and torsion) acting on the mechanism links under the influence of the defined forces. Additional mass points (240 N; 107 N; 35 N) were defined to simulate the effect of the patient's limb mass (parts of the thigh, calf, and foot) on the mechanism links. These correspond to the masses of the lower limbs of a male patient at 95C, determined using data from the Atlas of Human Measurements [34] and assuming a 20% safety margin. The resulting torque values will be used in further numerical simulations using the Generative Design tools of the Creo Parametric programme [37]. The finite element mesh required for the numerical analysis is generated automatically, as in the previous study.

2.5. Optimisation Mechanical Part of the Actuator System Using the Generative Design Method

The optimisation of the links (Figure 2—(3) and (4)) of the CPM device will be carried out using the Creo Parametric v. 9.0.3.0. The input parameters for the analysis will be the obtained values of the moments in the XYZ axes, acting on a single link of the positioner mechanism, obtained from analyses in the Rigid Dynamics toolbox of ANSYS Workbench. Numerical strength tests using the finite element method are used to qualitatively verify the results obtained. The resulting geometric structures are evaluated in terms of the displacement resulting from the interacting bending and torsional moments and the magnitude of the von Mises stresses. The resulting structures from the Generative Design tool that do not meet the test conditions, due to the higher mass of the generated structure and the maximum strain values, are discarded and not considered for further analysis. The tests are carried out using construction materials. The detailed parameters are given in Table 2.

Table 2. Material properties used in Generative Design simulation for links 3 and 4.

Parameter	ALUMINIUM 6061	MG AL ALLOY	MG AL ZN ALLOY
Density, [kg/m^3]	2710.2	1800	1800
Young's Modulus, [Pa]	6.89476×10^{10}	4.61×10^{10}	4.5×10^{10}
Poisson's Ratio	0.3	0.357	0.305
Yield Stress, [Pa]	2.41×10^8	1.44×10^8	1.91×10^8
Shear Stiffness, [Pa]	2.65183×10^{10}	1.6986×10^{10}	1.72414×10^{10}
Thermal Expansion, [1/K]	2.34×10^{-5}	2.58×10^{-5}	2.74×10^{-5}
Conductivity, [W/(mK)]	180.073	73.9	78

The same procedure as described above for links 3 and 4 is used to optimise the mass of the drive mechanism links (Figure 2—(1) and (2)). It was assumed that the research would be carried out using only one construction material, the mechanical parameters of which are summarised in Table 3.

Table 3. Material properties used in Generative Design simulation for links 1 and 2.

Parameter	316 STAINLESS STEEL
Density, [kg/m^3]	8000
Young's Modulus, [Pa]	2.05×10^8
Poisson's Ratio	0.28
Yield Stress, [Pa]	2.9×10^8
Shear Stiffness, [Pa]	7.37×10^{10}
Thermal Expansion, [1/K]	2.34×10^{-5}
Conductivity, [W/(mK)]	21.5

The finite element size used to perform the Generative Design analyses was 3 mm and the finite element mesh was 23,012 finite elements for link 3. For link 4, the finite element size was 3.3353 mm with the same number of finite elements, i.e., 23,012. For link 4, the finite element size was 3.3353 mm, with the same number of finite elements, i.e., 23,012. The choice of these values was dictated by the optimum settings suggested by the Creo Parametric software, which ensured the shortest possible generation time for the new structure while maintaining a high-quality result.

3. Results and Discussion

This section describes the results of the numerical analyses carried out in ANSYS Workbench and Creo Parametric, which will form the basis for selecting a smaller (cheaper) and more suitable actuator to drive the CPM device positioner.

3.1. Results of Kinematic Analysis in Selected Kinematic Pairs of the CPM Mechanism

Mathematical equations describing how to solve the forward kinematics of the CPM mechanism are derived and detailed in Trochimczuk et al. [9]. For this reason, the analysis of the kinematics in this thesis will only add to the knowledge of the displacements, velocities, and accelerations in the specific kinematic pairs that have the greatest impact on the rehabilitative movement that initiates the continuous passive movement of the positioner of the CPM device. Figure 3 presents the results of the analysis of displacements, velocities, and accelerations in the kinematic pair C'.

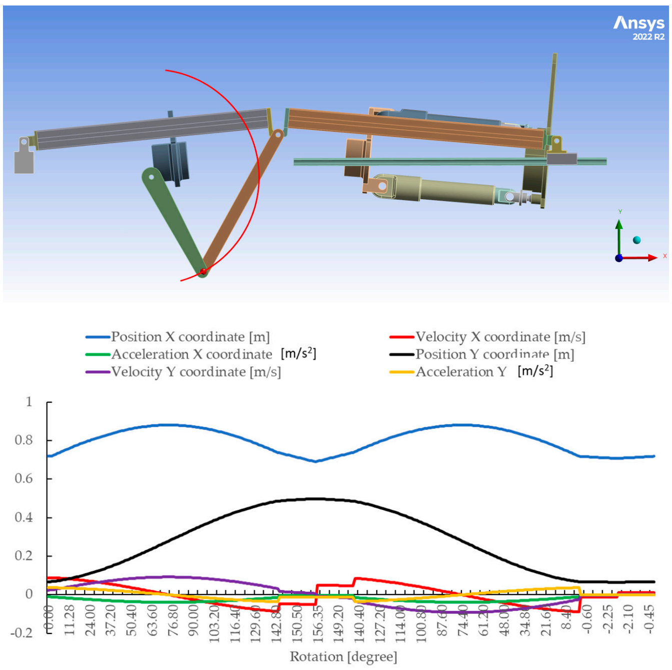

Figure 3. Results of the kinematics analysis of the C' kinematic pair (position, velocity, and acceleration in a range of motion) and the graphical representation of the path of movement.

The graph shows the changes in the kinematic parameters excluding the *Z*-axis which, due to the flat nature of the mechanism, has a constant value and is irrelevant for the purposes of the analysis, so it was deliberately omitted. The analysis was carried out assuming maximum actuator speed. In rehabilitation practice, such speeds can only be applied in the final stages of rehabilitation, when the ROM in the knee has already been deepened. The actual actuator velocity values at the beginning of the rehabilitation process are four times lower, so the obtained parameter values are also four times lower than those shown. The above comment applies to all kinematic analysis results presented below.

When analyzing the result in Figure 3, special attention should be paid to the maximum value of the *X*-axis velocity, which is 8.8897×10^{-2} m/s, and the maximum value of the *Y*-axis velocity, which is 9.2152×10^{-2} m/s. The maximum acceleration in this case on the *X*-axis is 1.2826×10^{-4} m/s^2, and on the *Y*-axis is 3.7237×10^{-2} m/s^2. As the movement of the mechanism corresponds to the flexion and extension phase of the knee, the minimum values of the given parameters are the same, but with opposite signs. Figure 3 also shows a graphical representation of the path of the C' point of the positioner mechanism of the CPM device.

Figure 4 shows the results of the kinematic analysis for the kinematic pair D' of the positioner mechanism of the CPM rehabilitation device. Consideration of this kinematic pair is very important because it is through this kinematic pair that the main flexion movement of the knee that we rehabilitate after knee arthroscopy or knee arthroplasty is built.

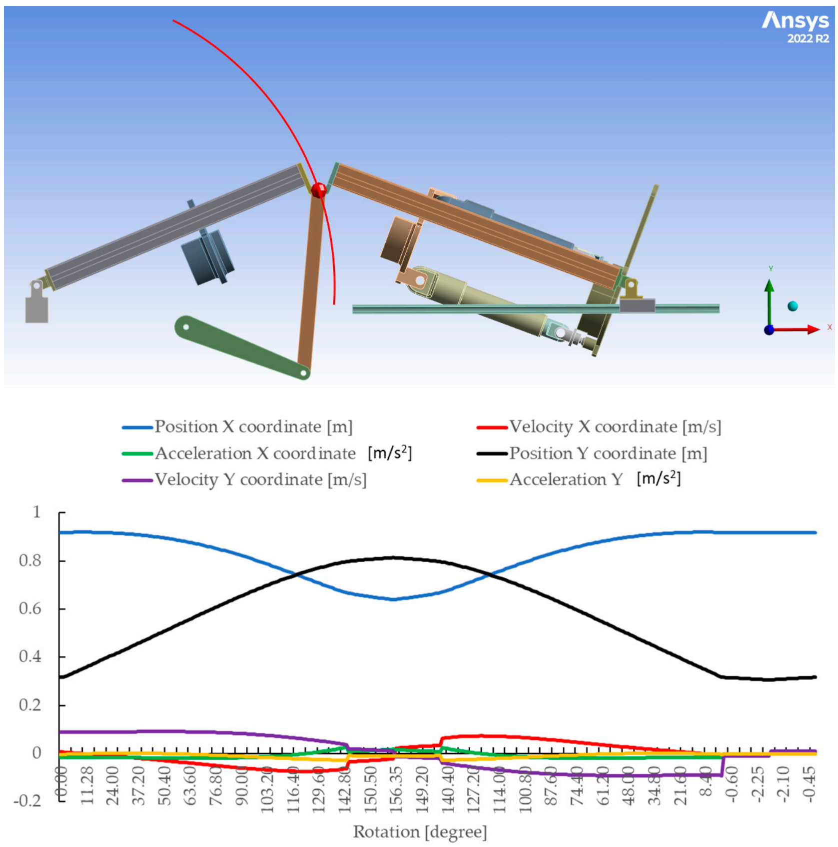

Figure 4. Results of the kinematics analysis of the D' kinematic pair (position, velocity, and acceleration in a range of motion) and the graphical representation of the path of movement.

The results show maximum velocity values in the *X*-axis of 7.3364×10^{-2} m/s^2 and the *Y*-axis of 9.1371×10^{-2} m/s^2, respectively. The maximum acceleration, in this case, in the *X*-axis is 2.7614×10^{-2} m/s^2, and in the *Y*-axis is 1.4632×10^{-3} m/s^2. The minimum values of the given parameters are the same, but with the opposite sign, in the same way as above.

Figure 5 shows the result of the analysis of the positions, velocities, and accelerations of the translational kinematic pair E' of the slider connected to the linear guide. The change in position was only recorded for the X-axis, as only this coordinate is variable due to the nature of the movement of the mechanism. The analysis confirmed the design distance of the linear slider movement, i.e., approximately 0.52 m. The maximum velocity value in this case was 0.13382 m/s and the maximum acceleration was 5.3397×10^{-2} m/s^2, respectively.

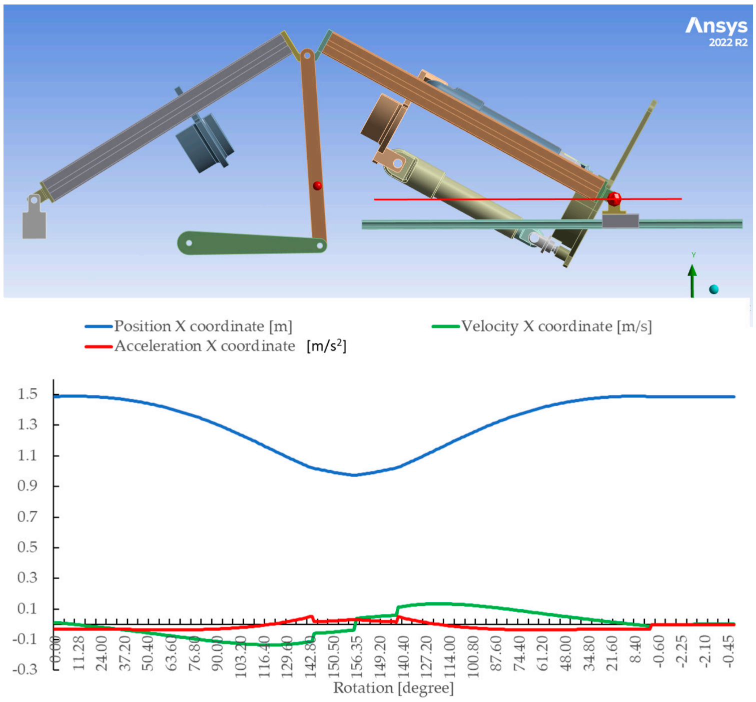

Figure 5. Results of the kinematics analysis of the E' kinematic pair (position, velocity, and acceleration in a range of motion) and the graphical representation of the path of movement.

Knowing the results of such analyses, an actuator controller can be designed to select the appropriate CPM regime for the patient's rehabilitation needs.

3.2. Results of the Analysis of Moments in the Kinematic Pairs of the CPM Positioner

In order to research to optimise the links of a CPM multibody mechanism using the Generative Design method, it is necessary to divide the mechanism into individual links, which are then optimised as separate components. The input parameters for such studies, in addition to knowledge of the geometry, are of course the values of the forces or moments and other constraints to be taken into account in the optimisation. To determine the parameters to be used for the simulation in Creo Parametric, a preliminary study of the dynamics was carried out using the Rigid Dynamics toolbox of ANSYS Workbench. Analyses included kinematic pairs A', B', C', D', and E'. They involved determining the values of the moments in each pair, in the X, Y, and Z axes, during the working movement of the mechanism in ROM.

Figure 6 shows the results of determining the values of the torques in the X, Y, and Z axes of the kinematic pair A' in ROM. Only the maximum values of these torques will be important from a Generative Design optimisation point of view. These investigations determined the following maximum values: in the X-axis, the maximum torque is 2.7042×10^{-14} Nm; in the Y-axis, it is 8.0357×10^{-14} Nm; and in the Z-axis, it is -1.0565×10^{-14} Nm. The maximum value of the total moment, in this case, is 2.8503×10^{-8} Nm. The results obtained indicate that the kinematic pair in question does not practically transfer the torques induced by the motion of the drive link connected to the actuator.

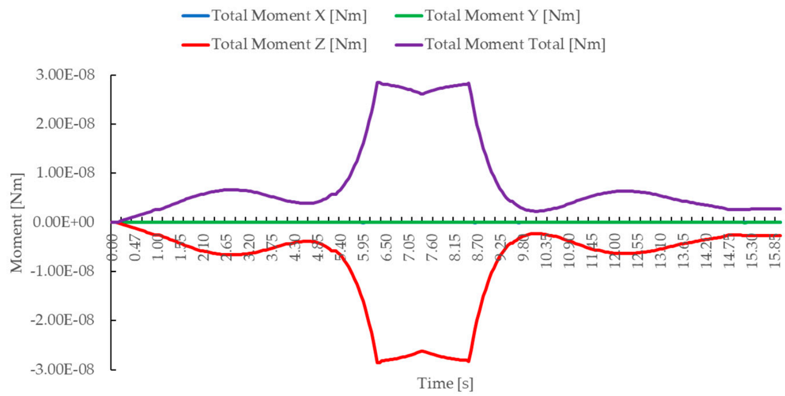

Figure 6. Graphs of torques in the X-, Y-, and Z-axes in A' kinematics pair in a range of motion.

Figure 7 shows the results of determining the values of the torques in the X, Y, and Z axes of the kinematic pair B'. These tests determined the following maximum values: in the X-axis, the maximum torque is 68.788 Nm; in the Y-axis, it is 1.0039 Nm; and in the Z-axis, it is 59.215 Nm. The maximum value of the total moment in this case is 90.691 Nm.

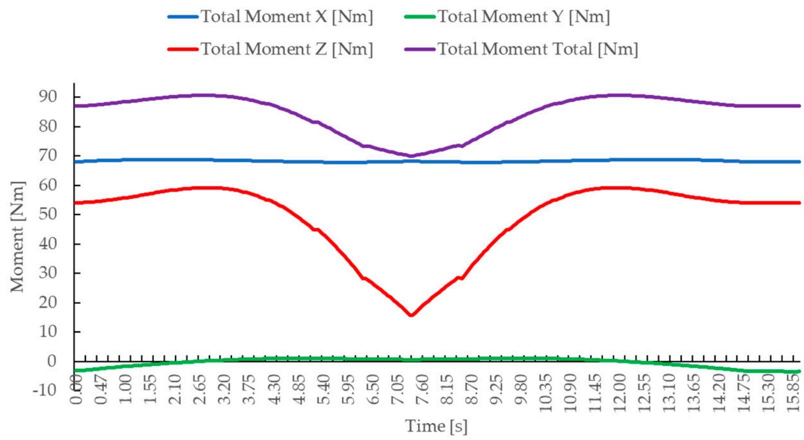

Figure 7. Graphs of torques in the X-, Y-, and Z-axes in B' kinematics pair in a range of motion.

Figure 8 shows the results of determining the torque values in the X, Y, and Z axes of the C' kinematic pair. These tests determined the following maximum values: in the X-axis, the maximum torque is 68.117 Nm; in the Y-axis, it is 5.4788×10^{-2} Nm; and in the Z-axis, it is 8.6341×10^{-14} Nm. The maximum value of the total moment, in this case, is 68.791 Nm.

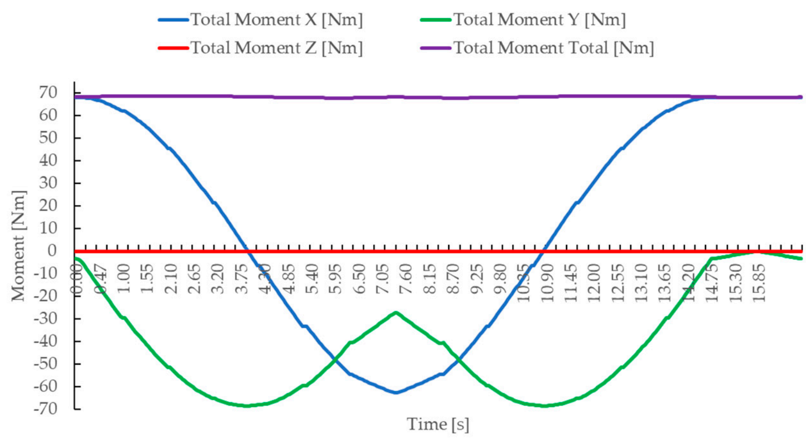

Figure 8. Graphs of torques in the X-, Y-, and Z-axes in C' kinematics pair in a range of motion.

Figure 9 shows the results of determining the values of the torques in the X, Y, and Z axes of the D' kinematic pair. Through these tests, the following maximum values were determined during the movement of the mechanism, i.e., in the X-axis, the maximum torque is 65.596 Nm; in the Y-axis, it is 54.671 Nm; and in the Z-axis, it is 7.2349×10^{-14} Nm. In this case, the maximum value of the total torque is 66.023 Nm. The knowledge about these torques is in addition to optimising the links of the CPM motion apparatus. It also makes it possible to determine the parameters of the pins connecting links 2, 3, and 4, which were omitted from the analysis when simplifying the geometry prepared for the numerical analysis.

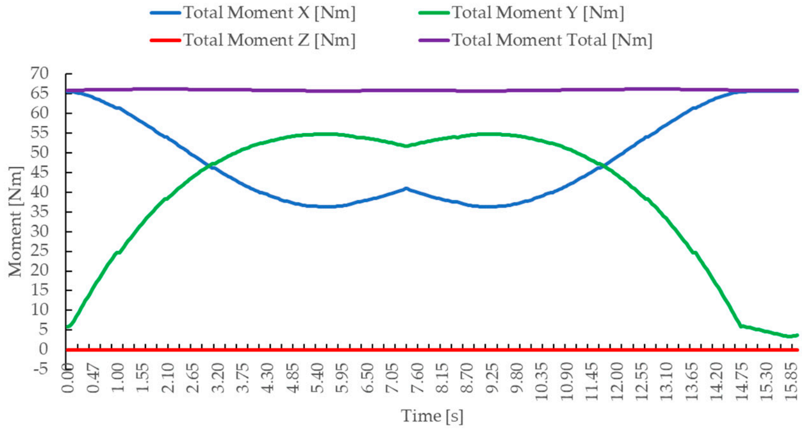

Figure 9. Graphs of torques in the X-, Y-, and Z- axes in D' kinematics pair in a range of motion.

Figure 10 shows the results of determining the torque values in the X-, Y-, and Z-axes of the kinematic pair E'. Through these tests, the following maximum values were determined: in the X-axis, the maximum torque is 8.4168×10^{-14} Nm; in the Y-axis, it is 8.6849×10^{-14} Nm; in the Z-axis, it is 4.3682×10^{-8} Nm. The maximum value of the total moment, in this case, is 4.3682×10^{-8} Nm. As in the case of kinematic pair A', the results indicate that this pair does not practically transfer the moments induced by drive link motion.

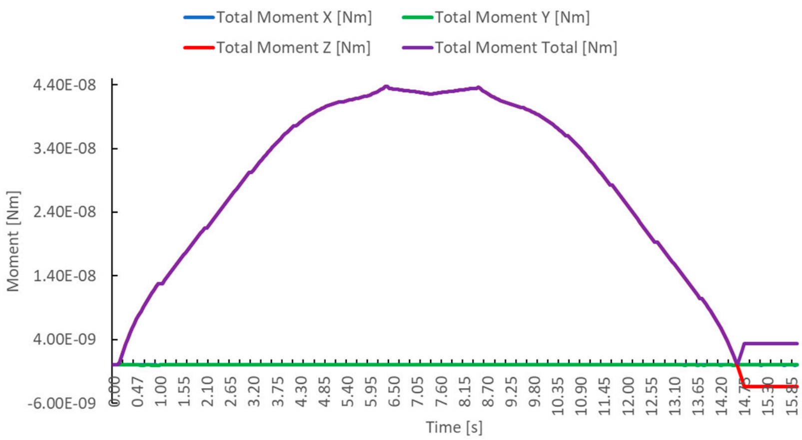

Figure 10. Graphs of torques in the X-, Y-, and Z- axes in E' kinematics pair in a range of motion.

The results of the torque analysis obtained in this way in each of the defined kinematic pairs are the necessary input parameters for the optimisation of the structure using the Generative Design method, with the aim of reducing the mass, assuming in the study the maximum stiffness of the links, on which the accuracy of the movements of the CPM positioner will mainly depend.

3.3. Results of the Optimisation of the CPM Mechanism Links

This section will present the results of the optimisation of the design of the main positioner mechanism links of the CPM device. They concern the analysis of the main links 3 and 4, which provide the main support for the rehabilitated lower limb, and the driving kinematic pair of the positioner mechanism, consisting of links 1 and 2. The choice of test materials from which new link structures were generated concerned the material used in the base structure based on commercial aluminium structural profiles, made from AL 6061. Structures were also generated using Generative Design methods made from MG-AL-ZN ALLOY and MG-AL ALLOY alloys. During preliminary research, attempts were also made to use plastics, ABS and PEEK, which due to their lower material density and stiffness could not realistically contribute to reducing the mass of the solution while maintaining an acceptable level of deformation. The first attempts to generate structures showed that the mass of the links was significantly lower in relation to the initial mass, but the deformations of the links forming the kinematic pairs studied disqualified the results obtained from the practical application. Among the other metallic materials initially selected for numerical analysis, titanium was also chosen. This material, with its very good mechanical properties, offered the hope of obtaining a generated structure which, although much denser than aluminium and its alloys, could ultimately form a high-strength, low-mass structure. In the case of titanium, the initial tests showed that the high density of the material led to a rejection of the results, as the final mass of the solution exceeded the initial mass of the positioner links. However, for the optimisation (creation of a new design) of links 1 and 2, only one material was selected—316 Stainless Steel, analogous to the basic solution of the CPM device. The results of the optimisation of each link with the Creo Parametric Generative Design tool will be presented later in this chapter.

3.3.1. Results of Optimising Link 3 of the CPM Main Positioner

The input parameters for the optimisation were the moment values previously determined using the Rigid Dynamics toolbox of ANSYS Workbench. The analysis looked at each of the positioner links of the CPM separately. It is not possible to create a new structure for the entire kinematic chain. The Generative Design synthesis required the additional definition of boundary conditions in the form of surfaces that had to be excluded from the optimisation, as their shape and purpose were necessary to maintain the full functionality of the original solution. In the case of link 3, these were the hinge surfaces by which the link was attached to the other moving and fixed links of the mechanism. In addition, for the purposes of the research, an additional area of $5 \times 4 \times 1$ cm was defined in the structure of the link, which in a real solution would replace the area used to fix the support of the femoral part of the limb. An important assumption in the research was to define the plane of symmetry for the optimised solution and to identify max stiffness as a complementary parameter. Most structures cannot be generated correctly without this parameter. Results were generated assuming a volume limit of between 20% and 50%. Values below and above these assumptions did not satisfy the mass and displacement conditions of link 3 and were therefore not included in the results. For the AL 6061 material, the mass of link 3 before optimisation was 0.81712 kg. Preliminary strength tests in Creo Parametric showed that the von Mises stress for link 3 was 121.4 MPa, and displacement was 5.43 mm. Such a high value of the displacement parameter is due to the fact that the simulations have neglected the influence of the stiffness of the shaft connections 3 and 4, which in the real solution ensures sufficient stiffness of the connection in the kinematic pair 3–4. The initial results, to which we will relate the obtained results of the generated structures, will allow us to select the optimum solution in terms of minimum mass and least deformation. For each of the newly generated structures, additional numerical analyses are carried out to verify the result obtained, consisting of the determination of the strength parameters: von Mises stress and displacement. The results of the optimisation of link 3 of the positioner mechanism are summarised in Tables 4–6. The number of finite elements used in the numerical study was 23,012. A single finite element had a size of 0.003 m.

Table 4. Results of Generative Design optimisation of link 3—material AL 6061.

Parameter	**Limit Volume 20%**	**Limit Volume 30%**	**Limit Volume 40%**	**Limit Volume 50%**
Starting mass, [kg]		2.153		
Valid value, [%]	14.9	26.9	38.3	50.2
Parameters of link 3 after Generative Design optimisation				
Displacement, [mm]	6.038	2.48	1.7284	1.0884
Von Mises Stress, [MPa]	279.76	112.74	101.01	87.06
Final mass, [kg]	0.3210	0.5800	0.8240	1.0800

Table 5. Results of Generative Design optimisation of link 3—material MG-AL-ZN ALLOY.

Parameter	**Limit Volume 20%**	**Limit Volume 30%**	**Limit Volume 40%**	**Limit Volume 50%**
Starting mass, [kg]		1.43		
Valid value, [%]	Not generated	26.4	38.1	50.0
Parameters of link 3 after Generative Design optimisation				
Displacement, [mm]	-	4.27	2.63	1.66
Von Misses Stress, [MPa]	-	100.83	100.94	86.97
Final mass, [kg]	-	0.3770	0.5440	0.7150

Table 6. Results of Generative Design optimisation of link 3—material MG-AL ALLOY.

Parameter	**Limit Volume 20%**	**Limit Volume 30%**	**Limit Volume 40%**	**Limit Volume 50%**
Starting mass, [kg]		1.43		
Valid value, [%]	15	27	37.6	50.0
Parameters of link 3 after Generative Design optimisation				
Displacement, [mm]	7.3908	3.9095	2.336	1.662
Von Mises Stress, [MPa]	277.50	99.79	99.97	86.97
Final mass, [kg]	0.2140	0.3860	0.5380	0.7140

A prominent feature of the Generative Design numerical study is the mass of the optimised object and the associated output geometry that the object adopts for optimisation in Creo Parametric. This is clearly higher for the same material, as can be seen in Table 4. For the AL 6061 material, the initial mass of the link is approx. 2.64 times higher (was 2.153 kg) than the original link (0.81712 kg) in the same material. This is because when analysing and generating the new object structure, the software takes the entire volume of the object as the initial mass.

The main problem identified when attempting to use other digital engineering tools that offered the ability to perform optimisation using generative design techniques (Fusion 360 and Autodesk Inventor, among others, were used) was that it was not possible to confirm by additional strength testing that the structure under test actually met the assumed strength constraints. This was only possible by applying CAD modelling techniques that used the generated geometry to manually model a new solid object with a spatial shape similar to the optimisation result. This is a very labour-intensive and time-consuming activity when it comes to achieving quite complex spatial forms, and the end result is nevertheless an approximation of the result achieved. The Creo Parametric programme allowed such studies to be carried out without modifying the optimised shape, which is a major advantage of the tool and hence its selection.

The results of the strength analyses of the generated link 3 structures showed that the most favourable result was obtained when using AL 6061 material for optimisation at the 30% volume limit. The final object mass was 0.58 kg. Displacement was also improved by 2.48 mm compared to the original design's 5.43 mm, which in practice improved the value of this parameter by 2.1 times. The von Mises stress for the tested design was 112.74 MPa, a slight change from the initial pre-optimisation value of 121.4 MPa, with no major effect on the optimised positioner link. The accumulation of von Mises stresses and the highest value of displacement in the case studied relate to the area of the link that forms the rotational connection to links 4 and 2 of the positioner.

In the case of design tests assuming the MG-AL-ZN ALLOY material, the most favourable result was obtained for the Generative Design test at a limit volume of 50%. Although the final mass of the object was the highest of the structures generated (0.715 kg), the von Mises stress value was the lowest (86.97 MPa) and the displacement level was the lowest at only 1.66 mm. For this structure, the mass reduction was 0.10212 kg.

In the case of design tests assuming the MG-AL ALLOY material, the most favourable result was obtained for the Generative Design test at a limit volume of 40%. The final object mass was 0.5380 kg. Strength tests showed that the von Mises stress value was 99.97 MPa and the displacement was 2.336 mm. In the case of the structure generated from the material in question, the weight reduction was as high as 0.27912 kg; hence, it represented the best of the results achieved.

3.3.2. Results of Optimising Link 4 of the CPM Main Positioner

The same methodology was used to optimise link 4 using Generative Design techniques as was used to generate the structures for link 3. The mass of link 4 before optimisation after inflicting AL 6061 material was 0.89385 kg. Strength tests in the Creo Parametric programme showed that the von Mises stress for primary link 4 was 255.53 MPa, and displacement was 5.87 mm. The high value of displacement analogous to link 3 is due to the failure to take into account the stiffness of the shaft connecting links 3 to 4, which in a real-world solution provides adequate stiffness to the connection in kinematic pair 3–4. The above results will be the baseline to which we will refer to the results obtained from the new structures generated. The results of the optimisation of link 4 of the positioner mechanism are summarised in Tables 7–9.

Table 7. Results of Generative Design optimisation of link 4—material AL 6061.

Parameter	Limit Volume 20%	Limit Volume 30%	Limit Volume 40%	Limit Volume 50%
Starting mass, [kg]	2.35			
Valid value, [%]	14.2	25.1	36.5	49.3
Parameters of link 4 after Generative Design optimisation				
Displacement, [mm]	4.0465	4.049	2.245	1.44
Von Mises Stress, [MPa]	318.18	201.21	202.60	203.03
Final mass, [kg]	0.3330	0.5900	0.8570	1.1550

Table 8. Results of Generative Design optimisation of link 4—material MG-AL-ZN ALLOY.

Parameter	Limit Volume 20%	Limit Volume 30%	Limit Volume 40%	Limit Volume 50%
Starting mass, [kg]	1.561			
Valid value, [%]	14.2	25.3	35.9	49.2
Parameters of link 4 after Generative Design optimisation				
Displacement, [mm]	4.4611	5.14	3.24	2.21
Von Mises Stress, [MPa]	240.42	201.80	202.49	202.97
Final mass, [kg]	0.2210	0.3950	0.5600	0.7690

The results distinguish between the generated structures by the material used. The number of finite elements used in the numerical study was 23,011. A single finite element had a size of 0.003353 m. When using the AL 6061 material, the most favourable result was obtained after optimising the Generative Design at a limit volume of 30%. The final object mass was 0.59 kg. A better displacement value was also obtained relative to the original design, as it was 4.049 mm, relative to the original 5.87 mm. The von Mises stress for the tested structure was 201.21 MPa, giving a reduction from its initial pre-optimisation value of 255.53 MPa. An even greater reduction in mass is obtained for a limit volume value of 20%, although in this case, the von Mises stress after testing was as high as 318.18 MPa, despite a similar displacement value to the optimisation at a limit volume of 30%; hence, this result was rejected. Results above the 30% volume limit were discarded due to the mass of the objects obtained, which would not translate into a reduction in the value of the actuator torques in the CPM positioner design studied.

Table 9. Results of Generative Design optimisation of link 4—material MG-AL ALLOY.

Parameter	Limit Volume 20%	Limit Volume 30%	Limit Volume 40%	Limit Volume 50%
Starting mass, [kg]		1.5611		
Valid value, [%]	14.2	25.1	36.3	49.3
Parameters of link 4 after Generative Design optimisation				
Displacement, [mm]	4.7928	6.1504	3.7318	2.1634
Von Mises Stress, [MPa]	249.96	201.12	202.90	203.02
Final mass, [kg]	0.2210	0.3910	0.5670	0.7696

When MG-AL-ZN ALLOY material was used to generate the structures, the most favourable result was obtained after optimisation at a limit volume of 50%. Although the mass of the object was not significantly reduced compared to the original solution, at 0.7690 kg (0.12458 kg less than the original), this solution was selected for its lowest displacement parameter value of 2.21 mm. It is worth noting that the von Mises stress values do not differ significantly when different volume limits are chosen. Thus, the factor of choosing the best solution mainly concerned the lowest mass, with a minimum displacement value.

When MG-AL ALLOY material was used to generate the structures, the most favourable result was obtained after optimisation of link 4 at a limit volume of 40%. The mass of the resulting structure was 0.5670 kg, being 0.32685 kg lower than the original mass. The displacement parameter value was 3.7318 mm, with the von Mises stress set at 202.90 MPa (originally 255.53 MPa). The result obtained at the 50% limit volume is less favourable from a mass point of view, although there is a significant improvement in the displacement parameter, which has been reduced to a value of 2.1634 mm. It can therefore be concluded that the search for an optimum solution should be limited to carrying out further retail simulations in the 40% to 50% range, where more favourable results can be obtained in terms of further mass reduction and improvement of the displacement parameter.

3.3.3. Results of Optimising Links 1 and 2 of the CPM Main Positioner

As with the methods described above for optimising links 3 and 4 of the CPM motion apparatus, drive links 1 and 2 were also optimised. The tool used was also the Creo Parametric software. Optimisation studies using Generative Design methods focused on the selection of a single structural material, 316 Stainless steel. Loading moments on the structure were determined in ANSYS Workbench in previous studies. The mass of link 1 before optimisation was 0.61516 kg. Strength tests in the Creo Parametric programme showed that the von Mises stress for link 1 was 0.0934 MPa, and the displacement magnitude was 2.8600×10^{-7} mm. The number of finite elements used in the numerical study was 23,012. A single finite element had a size of 0.001498 m. Table 10 summarises the results of the Generative Design optimisation of link 1.

The most favourable optimisation result was achieved for the limit volume of 75%. The mass of the optimised link 1 was 0.452 kg, resulting in a mass reduction of 0.16316 kg. It is worth noting that the values of the displacement parameter and the von Mises stress are practically the same in the assumed boundary volume ranges from 75% to 85%. Thus, the only parameter determining the optimum solution was the mass of the object after optimisation. Below the 75% volume, the Creo Parametric software was unable to generate the optimum structure because there was not enough material to create the correct link structure.

Table 10. Results of Generative Design optimisation of link 1—material 316 Stainless Steel.

Parameter	Limit Volume <75%	Limit Volume 75%	Limit Volume 80%	Limit Volume 85%
Starting mass, [kg]		0.61516		
Valid value, [%]	Not generated	74.8	78.6	83.2
Parameters of link 1 after Generative Design optimisation				
Displacement, [mm]	-	8.3405×10^{-4}	8.3404×10^{-4}	8.3400×10^{-4}
Von Mises Stress, [MPa]	-	0.0285831	0.0285827	0.0285812
Final mass, [kg]	-	0.452	0.476	0.504

For the Generative Design optimisation of link 2, the mass of the object before optimisation was 0.63436 kg. Strength tests in Creo Parametric software showed that the von Mises stress for link 2 was 87.9776 MPa, and the displacement magnitude was 2.8833×10^{-3} mm. The number of finite elements used in the numerical study was 10,650. A single finite element had a size of 0.002 m. Table 11 summarises the results of the Generative Design optimisation of link 2.

Table 11. Results of Generative Design optimisation of links 2—material 316 Stainless Steel.

Parameter	Limit Volume <90%	Limit Volume 90%
Starting mass, [kg]	0.63436	
Valid value, [%]	Not generated	86.2
Parameters of link 2 after Generative Design optimisation		
Displacement, [mm]	-	1.45×10^{-3}
Von Mises Stress, [MPa]	-	52.3150
Final mass, [kg]	-	0.538

In the case of the link 2 optimisation study, the Creo Parametric only allowed the optimisation to be performed with a maximum volume limit of 90%. In this case, the mass of the link was reduced from 0.63436 kg to 0.538 kg (17.9% reduction). The values of the displacement parameter and the von Mises stress, due to their low value, do not affect the accuracy of the positioner movement in the practical implementation of CPM. Below the limit value, 90% of Creo Parametric was unable to generate a valid structure.

3.4. Selection of an Optimal Solution for the Generation of Structures

The geometric results of optimising the CPM positioner's links 3 and 4 are shown in Figure 11. The results show the geometric shape before and after optimisation using the Generative Design method.

The results obtained indicate that it is becoming necessary to change the approach to manufacturing the components (links) of the positioning mechanism. In the original CPM solution, commercially available aluminium structural profiles were used as the basic element for the mechanism. Their use required only the cutting of a specific profile to a defined length. When these profiles are replaced by structures generated by Generative Design methods, it becomes necessary to use profile casting or 3D printing techniques in the manufacturing technology. Traditional manufacturing methods could fail in this case due to the complexity of the geometry that forms the mechanism component. However, the numerical tests carried out indicate that the results obtained concerning the original solution are characterised by a lower mass and better strength parameters, i.e., the level of von Mises stress and displacement under applied moments.

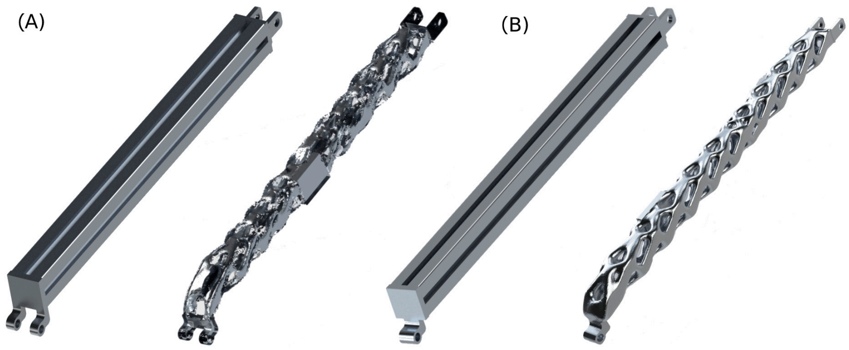

Figure 11. View of the three-dimensional virtual model of links 3 and 4: (**A**) link 3 starting shape and result after Generative Design optimisation; (**B**) link 4 starting shape and result after Generative Design optimisation.

Figure 12 shows the final results of the optimisation of drive members 1 and 2 of the CPM positioner and their original shapes. In the case of optimised links 1 and 2, they can be manufactured using casting techniques or a CNC machine.

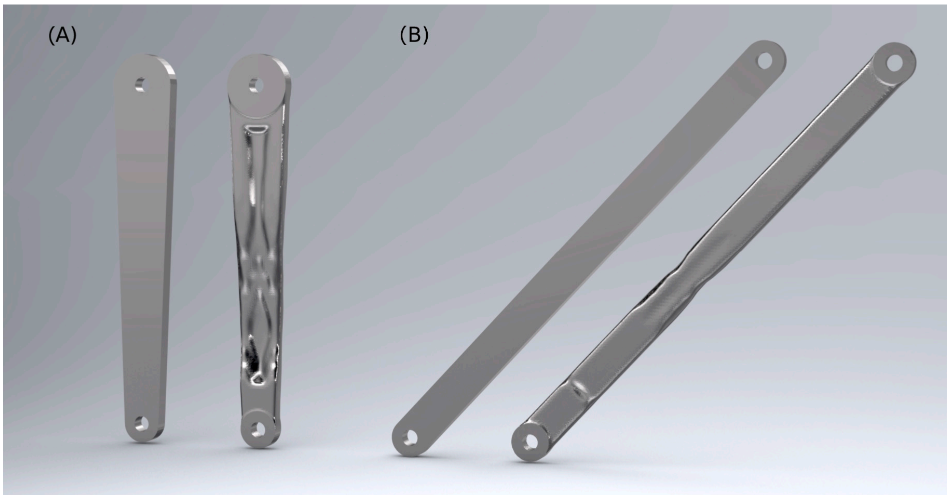

Figure 12. View of the three-dimensional virtual model of links 1 and 2: (**A**) link 1 starting link and result after Generative Design; (**B**) link 2 starting link and result after Generative Design optimisation.

The optimisation of these links slightly altered the original shape of the links, but ultimately reduced the mass of the entire positioner and significantly reduced the von Mises stress.

3.5. Comparative Analysis of Kinetic, Potential, External, and Total Energy before and after Generative Design Optimisation

The simulation model was rebuilt in ANSYS Workbench to determine how the optimised motion apparatus links changed the dynamic parameters of the CPM device design. Using the Rigid Dynamics toolbox of ANSYS Workbench, a dynamics study was performed to determine how changes in the mass and shape of the positioner members affected the potential, kinetic, total, and external energy of the CPM device's positioning system. The results of the studies, in the form of a graph of the change in energy values over time for the assumed actuator motion pattern, comparing the results before and after Generative Design Optimisation (GDO), are shown in Figure 13.

From Figure 13, we can read that before GDO, the maximum value of potential energy is 286.04 J, kinetic energy is 0.20813 J, external energy is 2.8355 J, and total energy is 148.67 J. Before GDO, the minimum value of potential energy is 145.77 J, kinetic energy is

1.0507×10^{-3} J, external energy is -137.48 J, and total energy is 148.58 J. After GDO, the maximum value of potential energy is 282.57 J, kinetic energy is 0.20565 J, external energy is 2.8016 J, and total energy is 146.63 J. After GDO, the minimum value potential energy is 143.76 J, kinetic energy is 1.0311×10^{-3} J, external energy is -136.04 J, and total energy is 146.54 J. The results obtained confirm that the structure of the kinematic system is preserved and that the optimised links are structurally identical to the pre-optimisation links.

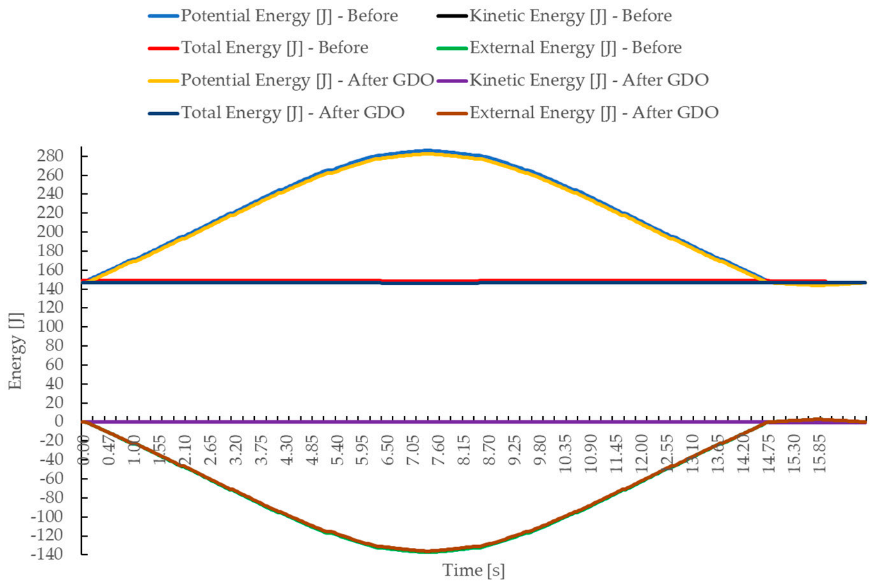

Figure 13. Compare the potential, kinetic, total, and external energy of the positioning system of the CPM device before and after Generative Design optimisation.

The Rigid Dynamics toolbox ANSYS Workbench was again used to determine the effect of the GDO on the change in a total moment in the drive kinematic pair B' of the positioner. The results of these analyses are shown in Figure 14. To better illustrate the changes, they are juxtaposed for comparison with the moments obtained before optimisation, as discussed earlier and shown in Figure 7.

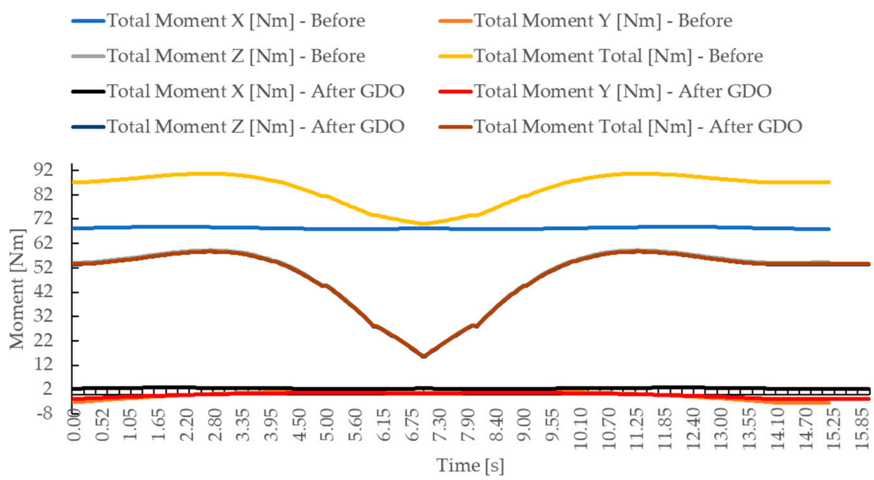

Figure 14. Compare moments in the B' kinematic pair of the positioning system of the CPM device before and after Generative Design optimisation.

The comparison of moment values in the B' kinematic pair of the CPM positioning system is summarised in Table 12. Changing the latter value is the most important thing to consider from the point of view of selecting an actuator system. It is worth noting that the efforts made to optimise the positioner links of the CPM device have reduced the total moment by a value of 32.013 Nm, resulting in a reduction in the final value of approximately 35.31% of the power requirement, given the same loads on the CPM device. Such a result demonstrates the validity of the methodology used to optimise the CPM device positioner links. This allows us to significantly improve the structural performance of the designed device. It should be emphasised that the lower actuator moment is primarily a reduction in the purchase cost of the device itself, which is integrated with the mechanical gearbox to drive the positioner's motion apparatus. Typically, in order to better match the actuator range to the customer's needs, actuator distributors use the power series of the actuators they sell. Therefore, when purchasing the final solution, the achieved reduction in a maximum actuator moment represents a significant price difference. A motor that is tailor-made for the appliance will certainly translate into efficiency and reduce electricity costs during operation.

Table 12. The comparison of moment values in B' kinematic pair of the CPM positioning system.

Moment	Value before GDO [Nm]	Value after GDO [Nm]
X-axis	68.788	2.7136
Y-axis	1.0039	0.5566
Z-axis	59.215	58.587
Total moment	90.661	58.648

4. Conclusions

The use of Generative Design and Topology Optimisation methods for the design and development of modern medical equipment contributes to the improvement of its design parameters according to dimension–mass characteristics and the anthropometric data of patients, thus making it possible to increase its increased ergonomics and reduced energy consumption. It is worth noting that there are limitations to the use of Generative Design techniques in this study. These limitations primarily relate to the designer's restricted influence on the ultimate spatial form of the optimised object. The result obtained, despite meeting the strength conditions assumed by the designer, may not necessarily be accepted in terms of the aesthetics of the form by the consumer. It should be noted too, that the final manufacturing technology for ready-to-use optimised objects may not align with the company's preferred manufacturing technology.

ANSYS Workbench analysis of all structures of a positioning system using the Rigid Dynamics toolbox allows for indicating the position, velocity, and acceleration of all points of the mechanism. When we determine by using the values of forces and torques in the kinematics pair, we obtain complex information about the kinematics and dynamics of the mechanism. The results obtained from such analyses become the basis for conducting research using engineering tools for research using Generative Design methods. The use of modern design methodologies implemented in the CREO Parametric software makes it possible to use design generators based on artificial intelligence. In accordance with the specified boundary conditions, loads, and materials, the optimal design solution for the target cost and sustainability indicators are obtained through countless iterations.

The use of Generative Design methods to optimise the mass of the links in multibody mechanisms allows the actuator torque required to move the positioner to be reduced. In the case of this CPM solution, a reduction of one-third of the torque of the existing drive translates into a lower cost of the actuator (actuators that differ in the type series, in our case instead of ten power/price series, can be from five power/price series). The parallel reduction of the future energy consumption of the actuator is also an added value of the presented optimisation methodology using the Generative Design method. This ensures that the actuator is correctly matched to the specific application of the motion apparatus of the positioning system. In addition to a 0.86549 kg reduction in the total mass of the links, the study also considered the achievement of improved strength parameters as an added value: von Mises stress and thus lower displacement values of the optimised multibody positioner of the CPM machine. As part of future work to develop the design of the CPM device, optimising the platform to support the patient's foot based on a Delta-type parallel robot is planned. The optimisation of this part of the solution can contribute to a further reduction in the mass of the positioner and thus to a reduction in the power of the actuator that moves the whole solution.

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