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Численное проектирование механизмов замкнутой кинематики: синтез эргономичного модуля экзоскелета для поддержки спины

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Статья посвящена задаче со-дизайна исполнительных механизмов робототехнических систем, назначение которых заключается в контактном адаптивном взаимодействии с неструктурированным окружением, в том числе человеком. Со-дизайн заключается в одновременной оптимизации механики и системы управления механизмом, обеспечивающих оптимальное поведение и производительность системы. Под оптимизацией механики понимается поиск оптимальных структуры, геометрических параметров, распределения массы среди звеньев и их податливости; под управлением понимается поиск траекторий движения сочленений механизмов. В работе представлен обобщенный метод структурно-параметрического синтеза неполноприводных механизмов замкнутой кинематики, применимый для создания механизмов для робототехнических систем разного назначения; например, ранее он был апробирован для со-дизайна механизмов пальцев антропоморфных захватов и механизмов ног галопирующих роботов. Метод реализует концепцию морфологического расчета законов управления за счет особенностей механической конструкции, минимизируя управляющее воздействие со стороны алгоритмической составляющей системы управления, что позволяет снизить требования к уровню технического оснащения и понизить энергопотребление. В данной работе предложенный метод апробирован для оптимизации структуры и геометрических параметров пассивного механизма модуля поддержки спины промышленного экзокостюма. Движения человека разнообразны и недетерминированы, если сравнивать с движениями автономных роботов, что усложняет проектирование носимых робототехнических устройств. Для снижения травматизма, усталости и повышения производительности рабочих синтезируемый промышленный экзокостюм должен не только компенсировать нагрузки, но и не мешать естественным движениям человека. Для проверки разработанного экзокостюма были использованы кинематические данные захвата движения всего тела человека при выполнении промышленных операций. Предложенный метод структурно-параметрического синтеза был использован для повышения эргономичности носимого робототехнического устройства. Верификация синтезированного механизма произведена с помощью имитационного моделирования: пассивный модуль спины прикреплен к двум геометрическим примитивам, осуществляющим движение грудной клетки и таза оператора экзокостюма в соответствии с данными захвата движения. Эргономичность модуля спины количественно измерена расстоянием между сочленениями, соединяющими верхнюю и нижнюю части экзокостюма; минимизация отклонения от среднего значения соответствует меньшей степени ограниченности движения оператора, т. е. большей эргономичности. В статье приведены подробное изложение метода структурно-параметрического синтеза, пример апробации метода для создания модуля экзокостюма и результаты имитационного моделирования.

Ключевые слова: со-дизайн, морфологический расчет, экзокостюм, носимые роботы

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Computational design of closed-chain linkages: synthesis of ergonomic spine support module of exosuit

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The article focuses on the problem of mechanisms' co-design for robotic systems to perform adaptive physical interaction with an unstructured environment, including physical human robot interaction. The co-design means simultaneous optimization of mechanics and control system, ensuring optimal behavior and performance of the system. Mechanics optimization refers to the search for optimal structure, geometric parameters, mass distribution among the links and their compliance; control refers to the search for motion trajectories for mechanism's joints. The paper presents a generalized method of structural-parametric synthesis of underactuated mechanisms with closed kinematics for robotic systems for various purposes, e. g., it was previously used for the co-design of fingers' mechanisms for anthropomorphic gripper and legs' mechanisms for galloping robots. The method implements the concept of morphological computation of control laws due to the features of mechanical design, minimizing the control effort from the algorithmic component of the control system, which reduces the requirements for the level of technical equipment and reduces energy consumption. In this paper, the proposed method is used to optimize the structure and geometric parameters of the passive mechanism of the back support module of an industrial exosuit. Human movements are diverse and non-deterministic when compared with the movements of autonomous robots, which complicates the design of wearable robotic devices. To reduce injuries, fatigue and increase the productivity of workers, the synthesized industrial exosuit should not only compensate for loads, but also not interfere with the natural human motions. To test the developed exosuit, kinematic datasets from motion capture of an entire human body during industrial operations were used. The proposed method of structural-parametric synthesis was used to improve the ergonomics of a wearable robotic device. Verification of the synthesized mechanism was carried out using simulation: the passive module of the back is attached to two geometric primitives that move the chest and pelvis of the exosuit operator in accordance with the motion capture data. The ergonomics of the back module is quantified by the distance between the joints connecting the upper and bottom parts of the exosuit; minimizing deviation from the average value corresponds to a lesser limitation of the operator's movement, i. e. greater ergonomics. The article provides a detailed description of the method of structural-parametric synthesis, an example of synthesis of an exosuit module and the results of simulation.

Keywords: co-design, morphological computation, exosuit, wearable robots

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1. Introduction

Design of mechatronic and robotic systems is a non-trivial creative activity, which is often not formalized. Results of such activity strongly depend on experience, creativity and engineering insights of a particular designer. Manual design results' can be compared with a local optimum in a vast space of potential solutions. Algorithms and methods for mechanisms' generation of mechatronic and robotic systems can potentially allow to do better exploration of vast space of potential solutions to find *better* sub-optimal solution. Automation of the design process makes it possible to effectively search for a global optimum in the space of solutions [Chen, Wang, 2020].

State of the art of exosuits

Industrial exosuits are designed to support a person in performing physically exhausting routine operations. Over the past two decades, researchers have demonstrated that industrial exoskeletons can reduce overall labor intensities, fatigue and workload while simultaneously improving productivity and quality of work [Looze et al., 2015; Marin et al., 2018].

The main source of injuries and aches is the combination of lifting and relocating heavy loads, and the resulting injuries are not only difficult to recover but also have a high risk of relapse even after successful treatment [Budihardjo, 2002], since workers are constantly exposed to the same environmental factors and perform the same tasks. A significant part of the employees who often have to perform hard work in manufacturing and industrial conditions suffer from lower spine pain or related injuries, which lead to significant losses for the industry [Looze et al., 2015].

Many exosuits have been developed to assist laborers in the industrial sector: to reduce their fatigue during assembly and technological operations, to prevent potential disorders of the musculoskeletal system, in particular, in lifting heavy objects, laying on pallets and assembling overhead. For most of them, the electric motor is directly connected to the joint via a rigid gearbox, such as a harmonic gear, to create the high torques necessary for lifting, while keeping the actuator as light and compact as possible [Yu et al., 2015; Toxiri et al., 2017]. Pneumatic and hydraulic drives are used [Zoss, Kazerooni, Chu, 2006; Tsagarakis, Caldwell, Medrano-Cerda, 1999] as an alternative to the gear motor. However, they are heavy and bulky, since the compressor or pump must be installed on the exosuit. Another option is to put the compressor stationary, which adds undesired external restrictions that can disturb the work and cause discomfort.

One of the studies suggests using a twisted string actuator to support a spine lower part [Seong et al., 2020]. The researchers have developed a device that uses the variable nature of the gear ratio of twisted strings: high when untwisting and decreasing when twisting, which corresponds to the profile of the connection torque required to lift the load. In [Toxiri et al., 2018], an electric exoskeleton for spine support is presented, which reduces muscle activity in the lumbar vertebral by 30 %. As an alternative, a passive exoskeleton for the spine is proposed with an increase in the range of movement of the torso in the sagittal plane by 25 % compared to the rigid power design [Naf et al., 2018b].

Computational design approach

For the industrial exosuits, motion transformation and load compensation are mainly provided by linkage mechanisms with integrated elastic elements, variable stiffness joints, and actuators. Automatic synthesis of generation of linkage mechanisms is a way to speed up the design process and at the same time to better explore a vast space of potential solutions. However, topology generation, optimization of geometric, kinematic, and dynamic parameters, choice of actuation and joints' trajectories generation are challenging.

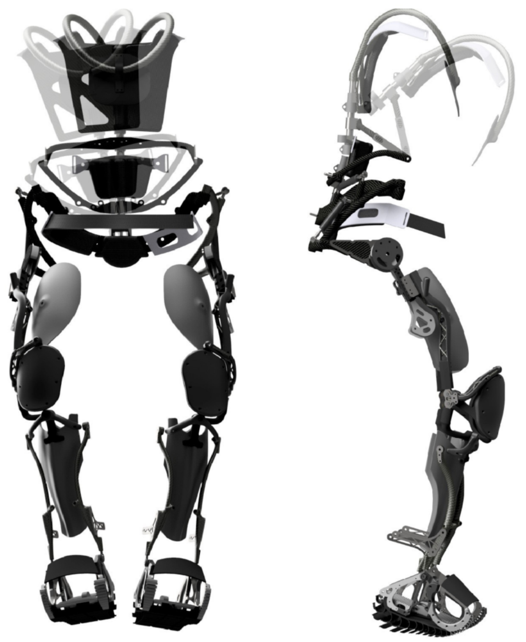
For parametric optimization, some studies suggest using evolutionary algorithms, for instance, to synthesize a linkage mechanism [Lin, 2010] by combining differential evolution with a real-valued genetic algorithm. Or, in [Penunuri et al., 2011], the optimal dimensional synthesis is used in the case of planar mechanisms using also differential evolution, wherein path generation, function generation and motion generation are taken into account. In [Ben Abdallah, Khemili, Aifaoui, 2020] optimal design parameters of a mechanism with flexible elements been found by a combined optimization process using Genetic Algorithm, Imperialist Competitive Algorithm, Artificial Bee Colony, Ant Colony, Differential Evolution, and Simulating Annealing techniques. In addition to parametric optimization, a more challenging task is the problem of topology generation. For example, [Zhao et al., 2020] presents a fully automated approach for generating optimized robot structures to traverse given terrains; however, the generation of physically reproducible robots remains a problem here.

Contribution and Structure

Within this paper, we propose a general method for automatic structural-parametric synthesis of closed-chain linkage mechanisms and give an example how to use it to ensure ergonomics of a designed industrial exosuit. The paper is organized as follows. The section 2 presents a designed industrial exosuit, whose ergonomics should be improved. The section 3 presents general method for the structural-parametric synthesis of closed kinematics mechanisms, and the section 4 presents the results of the synthesis of the exosuit spine module as an example of validation of the developed method regarding a field of wearable robots

2. Exosuit design

Renders of a CAD model of a designed industrial exosuit, whose ergonomics should be improved, are shown in Fig. 1. Sequences of pictures show which movements the exosuit allows to perform for a torso unit. Within this study, we consider a spine support module only.



(a) (b)

Figure 1. Render of a CAD model of an original industrial exosuit. Sequences of pictures show which movements the exosuit allows to perform for the torso unit

The kinematic scheme of the exosuit is shown in Fig. 2. The upper part 1 consists of connected links of the shoulder girdle, resting on the shoulders of a person at points N and P and on the chest

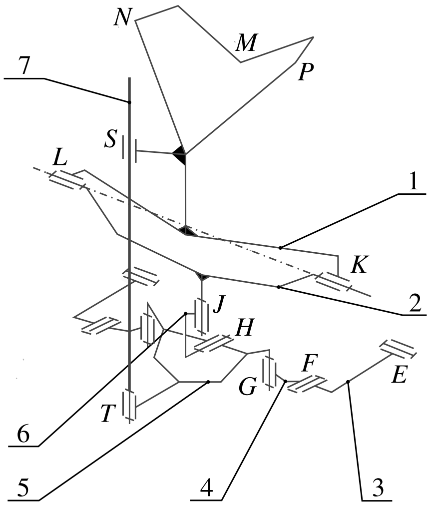


Figure 2. Kinematic diagram of an original exosuit's torso unit: 1 is the upper part of the exosuit module that attaches on shoulders at points N and P and on the chest at point M; the bottom part of the exosuit module consists of an arc 2 and a number of passive hinges of the pelvic region 3–6; an elastic rod 7 generates force when deflected, it is attached to the upper and bottom part is the hinges S and T respectively

at point M. The bottom part is an arc 2 and a number of passive hinges of the pelvic region 3–6. The upper part can rotate around the bottom part by means of a pair of hinges K and L. An elastic rod 7 is used to apply support when the back is bent, which is fixed in the hinge T, associated with the bottom part. The rod bends and has the ability to slide along its axis using guide S. The base of the back 2 is attached to link 6 with the help of hinge J, which has a lock with the ability to change the position on the vertical rod — in this way it is possible to adjust the position of the upper shoulder girdle of the suit relative to the pelvic part.

Spine module supports a user thanks to an elastic element integrated into the structure in accordance with studies of [Naf et al., 2018a; Naf et al., 2018b; Koopman et al., 2020]. To use an elastic element of a spine module, the upper and bottom parts of an exosuit do not have to be connected to each other, besides to the elastic element itself. However, in order to remove loads from the shoulder girdle and arms and redistribute them between the torso, pelvis and legs, the upper and bottom parts of the exosuit must be mechanically connected. Thus, the task is to search for a topology and geometric parameters of the mechanisms that connect the upper and bottom parts of the spine support module. Within this study, we have considered only kinematics and ergonomics of an exosuit's spine module.

3. Synthesis method

The proposed method for structural-parametric synthesis of linkages with closed kinematic chains is general and can be utilized for different kinds of robotic and mechatronic systems. We have applied the developed method for synthesis of closed-chain linkage mechanisms for a number of mechatronic systems: (a) anthropomorphic gripping devices [Borisov et al., 2021; Borisov et al., 2022], (b) galloping and jumping robots [Borisov et al., 2019; Zashchitin et al., 2020], and (c) wearable exosuits.

In [Borisov et al., 2021] a general method of structural-parametric synthesis of closed-chain linkage mechanisms is proposed. In particular, the paper considers examples of finger mechanisms synthesis for versatile adaptive grippers capable of performing both fundamental types of gripping: precise pinching and force encompassing, thanks to the use of variable-length links and mechanical decomposition of control channels.

The method of structural-parametric synthesis of closed-chain linkage mechanisms consists of three steps: (1) synthesis of fully actuated open-chain kinematics, (2) synthesis of fully actuated closed-chain kinematics, and (3) introduction of underactuation.

3.1. Fully actuated open-chain kinematics

At the first step we need to set a topology of the open-chain mechanism, set geometric parameters, set trajectories profiles for mechanism's joints to provide the required motion. Each of the indicated parameters can be set in advance or found as a result of the optimization task.

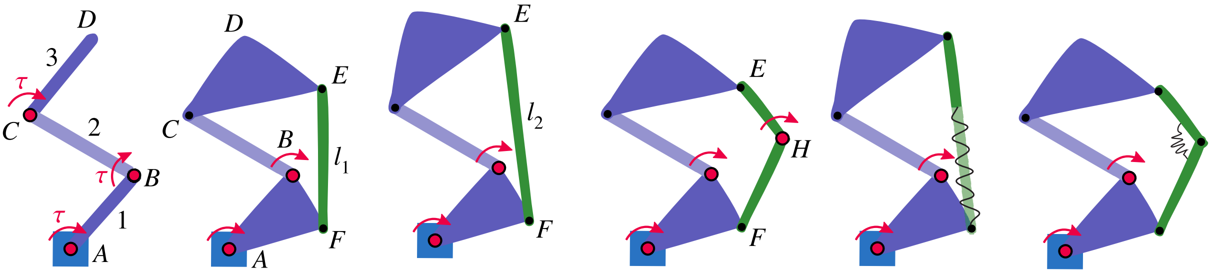


Figure 3. General design procedure's stages: (a) defining a fully-actuated open-chain mechanism; (b) linkage closure for some cyclic trajectory t_1; (c) another cyclic trajectory t_2; (d) linkage closure to ensure both trajectories t_1, t_2, and a smooth transition between them; (e) introduction of under-actuation as a prismatic joint; (f) revolute joint within a passive variable length link structure. Red dots indicate motors, black dots mean passive revolute joints

As a result of the first stage of synthesis, a fully actuated open-chain mechanism should be obtained that performs the required movement. For clarity, the Fig. 3, *a* shows an abstract fully actuated open-chain mechanism with three degrees of freedom; red circles represent drives.

3.2. Fully actuated closed-chain kinematics

At the second stage we need to find a topology for groups of links to be attached, to set a search for points of connection to the open-chain kinematics mechanism and set an optimization task to find geometric parameters. We have to obtain a fully actuated closed-chain mechanism with the required number of motors at this stage.

The essence of the synthesis stage is as follows: we consider the links n_i and n_{i+2} are connected to each other through the intermediary link n_{i+1} or connected through a group of intermediary links, and look for a pair of points p_i and p_{i+2} belonging to them, respectively. If the distance between points is constant throughout the entire cycle of movement, then the points p_i and p_{i+2} can be connected by a fixed length link. An addition of holonomic constraints allow to remove redundant motors. The Fig. 3, *b* shows the closed-chain linkage mechanism obtained by attaching the link *EF* to the links 3 and 1 at points p_3 and p_1, which coincide with joints *E* and *F*. As a result, a closed-chain kinematics mechanism with a reduced number of motors was obtained: only two motors are needed to follow the same trajectory instead of three.

If a mechanism has to perform not a single cyclic trajectory t_1, but a range of cyclic trajectories $t \in \{t_1, t_2, \ldots, t_n\}$, then such points p_i and p_{i+2} can be found to which links with lengths l_1, $l_2, \ldots, l_n$ can be attached to execute trajectories $t_1, t_2, \ldots, t_n$ respectively. The figure 3, *b* shows a closed-chain kinematics mechanism with $l_2 > l_1$ to ensure motion along a different cyclic trajectory t_2.

If all trajectories $t \in \{t_1, t_2, \ldots, t_n\}$ are required, then instead of a link of fixed length, a group of links can be attached, imposing a similar number of connection conditions, but allowing reconfiguring the length between the found points p_i and p_{i+2}. In the Fig. 3, *d*, instead of a fixed-length link, a group of two links EHF is attached (in [Borisov et al., 2021] alternative variants of the attached groups are presented) with a motor in the joint H. As a result, a mechanism was obtained with the original number of motors, but relocated to a different position.

Following the second stage of synthesis, a closed-chain kinematics mechanism should be obtained which can perform the required movement (possibly partially reproducing only the required kinematics) using the necessary number of motors. Besides the topology and geometric parameters, the joints' trajectory profiles must be found; thus, all steps of optimization focus on co-design problems of mechanics and control. This step can be performed to relocate motors, for example, closer to a body to minimize mechanism's inertia, and/or reduce a number of motors. The operation can be repeated recursively several times.

3.3. Introduction of underactuation

The linkages' joints can be both active and passive. In the case of passive joints, the mechanism is treated as underactuated. Underactuation can enhance the mechanism's performance. It is possible to introduce underactuation with the help of passive elastic elements: tension or compression springs, including as part of variable length links (Fig. 3, *e*), or rotation springs (Fig. 3, *f*).

This operation allows to get a mechanically adaptive mechanism, passively generate torque, and/or ensure energy recuperation. As a result of the third stage of synthesis, an underactuated closed-chain linkage mechanism has to be synthesized that performs the required motion fully.

4. Synthesis of the exosuit spine module mechanisms

We have tested the proposed method to synthesize mechanics of the torso unit for an exosuit. The method allows to search for the optimal topology of a mechanism and perform parametric optimization of the geometric parameters of linkage mechanisms. The criteria of optimally is to ensure ergonomics.

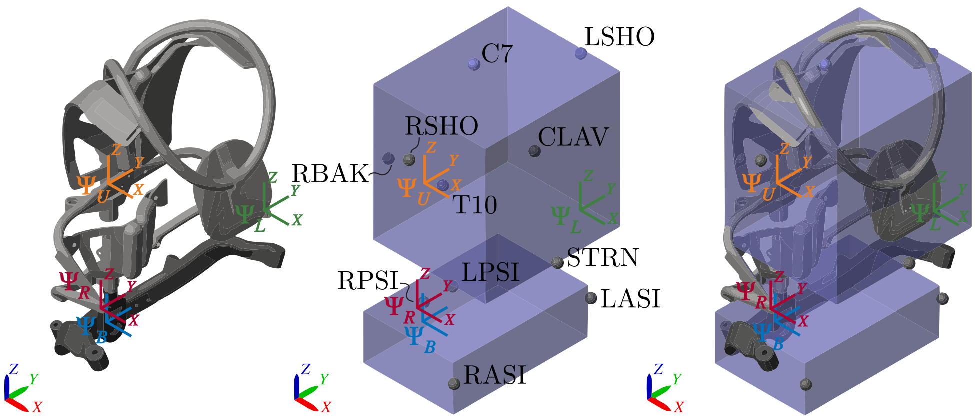
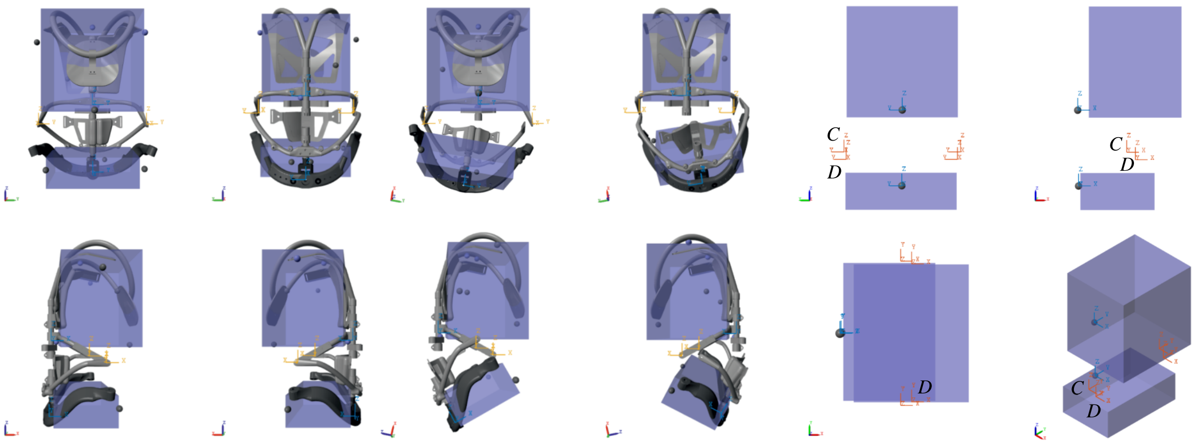


Figure 4. An original Exosuit provided for verification (a), motion capture markers together with primitives representing an upper and bottom torso parts (b), and the Exosuit with the markers and primitives (c)

A three-dimensional model of the spine module of the exosuit being developed is shown in Fig. 4, *a*. The spine module consists of upper part with frame Ψ_U and bottom part with frame Ψ_B. The upper and bottom parts are connected by rotational joints on right Ψ_R and left Ψ_L sides. For an upper body we consider that Ψ_U, Ψ_R, and Ψ_L belongs to a rigid body. The revolute joints give rotational mobility along the $\widehat{y}$ axis, while mobility along the $\widehat{z}$ and $\widehat{x}$ axis is carried out by joints of the bottom part. Here we are interested in points of connection of upper and bottom parts, that are depicted red Ψ_R and green Ψ_L frames (Fig. 4, *a*).

The dataset [Maurice et al., 2019] was used to verify ergonomics numerically. Fig. 4, *b* shows motion capture markers that move along trajectories from the dataset, and cubic primitives indicating an upper and bottom parts of torso[1]. Fig. 4, *c* shows the exosuit model, primitives and markers all together. The [Human Motion Database, 2022] provides a description of a default marker's attachment pattern.

4.1. Initial state of original design



(a) (b) (c)

Figure 5. A sequence of images of exosuit before and after optimization: initial "T" pose before optimization (a), intermediate pose before optimization (b), initial pose after optimization (c)

The initial position corresponding to the "T" pose is shown in Fig. 5, *a*. We can notice the proper location of the markers relative to the box primitives and spine module of the exosuit. Also, we can see that the connection points are coincide (highlighted with a pink circle). However, during the animation sequence the connection points moves away from each other (Fig. 5, *e*–*i*). Fig. 6, *a* shows the distance between the joints for the left rotational joint l_l^* and the right rotational joint l_r^*

$$l_l = \sqrt{\left(x_l^b - x_l^u\right)^2 + \left(y_l^b - y_l^u\right)^2 + \left(z_l^b - z_l^u\right)^2},$$
$$l_r = \sqrt{\left(x_r^b - x_r^u\right)^2 + \left(y_r^b - y_r^u\right)^2 + \left(z_r^b - z_r^u\right)^2},$$

where x_l^b is x coordinate for the left bottom frame, x_l^u is x coordinate for the left upper frame, both expressed in the frame fixed in space. It can be seen that the distance between the joints for both the left and right parts are located in the proximity of zero only in the initial position. At the peak, the difference between the joints corresponds to greater than 8 cm (Fig. 5, *b*). Throughout the recorded movement from the dataset of 100 sec, the joints never returned to their original position. The designed structure, due to engineering insight, is not optimal in accordance with the ergonomics criterion.

4.2. Intermediate state of original design

Before using the proposed method of synthesis for closed-chain linkage mechanisms, an attempt was made to carry out parametric optimization with the topology given initially. Figure 6, *b* shows the

[1] The materials below are presented for the file *Participant_541_Setup_A_Seq_5_Trial_5.qualisys*.

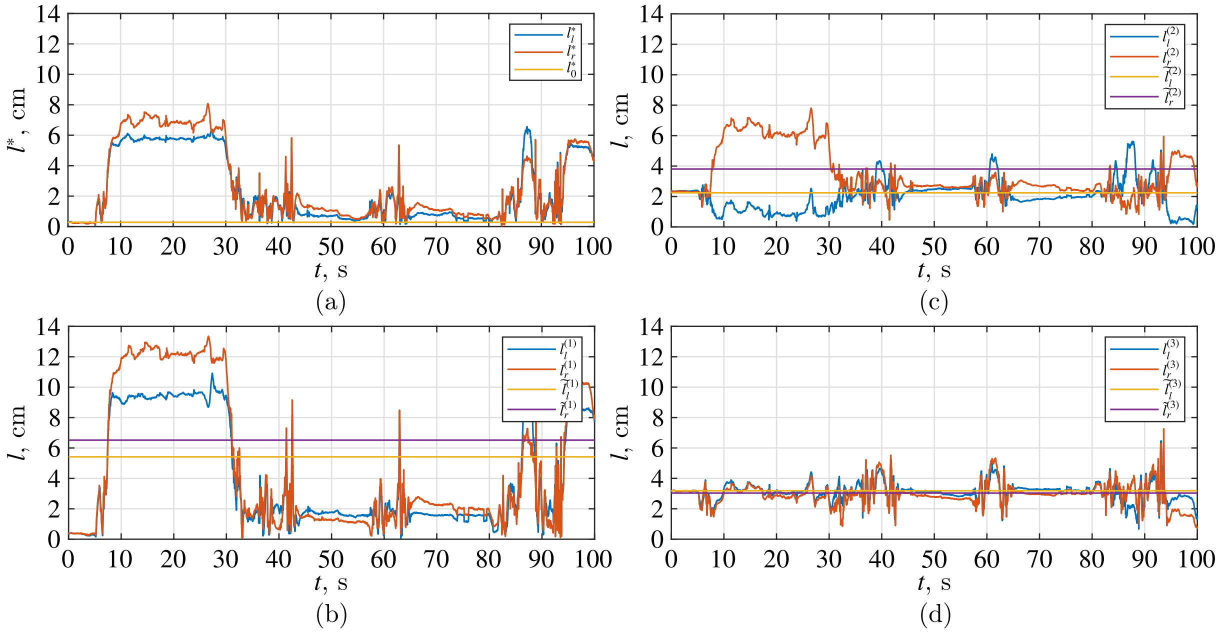


Figure 6. A comparison of the distances between the attachment points of the upper and bottom parts of the exosuit spine module: for the left l_l^* and right l_r^* sides before optimization, and for the left l_l and right l_r sides after optimization; the upper superscript number in brackets indicates the optimization attempt, $\widetilde{l}$ indicates a mean value of distance between the attachments points. Initially (a), the points were aligned only at the beginning for the rest pose, but after 6 seconds, when motion started, the points were disconnected. Parametric optimization of frames' positions works only for the initial rest pose (b), and does not provide the solution for the whole sequence of motion (c). According to the proposed method of structural-parametric synthesis, an intermediate link CD is added between the attachment points, since the distance between the points fluctuates around $l_0 = 3$ cm throughout the entire movement

results of minimization of the following fitness function

$$F = -\frac{1}{1 + l_l \cdot l_r}.$$

The right and left frames have the same geometric parameters, the only difference is the sign for distance along $\widehat{y}$ axis. The idea is to find parameters such that $l_l \cdot l_r = 0$. The optimization been set up for the first 4 seconds of simulation, when an operator stands still. This been done to verify the fitness function, since we know for sure that an optimal solution exists for a stance pose. We have used genetic algorithms from Global Optimization Toolbox of MATLAB. The program has found parameters that provides the distances between the frames in the proximity of zero. However, we can see that for the rest of animation sequence the deviation has increased up to almost 14 cm.

Then we ran the same optimization task but for the first 30 seconds. Figure 6, *c* shows the result for the whole animation sequence, however the distances between the frames are not in the proximity of zero.

4.3. Optimization of new design

The developed method was used to synthesize the linkage mechanism, i. e., to integrate an intermediate link between the frames that belong to upper and bottom parts of a spine module. Here a human body was considered *as an analogue of the open kinematics mechanism*, in which the bottom (pelvis) primitive was considered as a link n_1, the upper (chest) primitive as a link n_3, which are connected by the a set of intermediate link (loin) n_2. The movement of *open kinematics mechanism* is determined by the data from the dataset.

According to the second stage of synthesis, it is necessary to find the points C and D belonging to the primitives n_1 and n_3, respectively, the variety in the distance between which tends to zero over the entire range of motion. The square of the average distance between points per cycle of movement:

$$\widetilde{l}^2 = \frac{1}{N}\sum_{i}^{N} \|p_C(t) - p_D(t)\|^2,$$

where $\widetilde{l}$ is the scalar value of the mean shortest distance between points, $p_D(t) \in \mathbb{R}^3$ is the position vector of the point D, $p_C(t) \in \mathbb{R}^3$ is the position vector of the point C, N — the number of discrete measurements.

The objective function is the quadratic losses function between the actual distance at the time of measurement i between points with an average value of l

$$\delta = \frac{1}{N}\sum_{i}^{N} \left(\|p_C(t) - p_D(t)\|^2 - \widetilde{l}^2\right)^2.$$

The distance between the points D and C for the left l_l and right l_r sides is shown in Fig. 6, *d*. It can be seen that throughout the entire movement, the distance fluctuates around the initial value of $l_0 = 3.2$ cm. At time points $t \in [5, 10] \cup [30, 44] \cup [58, 65] \cup [82, 95]$, these movements are very noisy due to sudden movements of the actor and fluctuations of markers. The data interval $t \in [0, 30]$ was used for optimization. Genetic algorithms were used to solve the optimization task.

The location of frames C and D in front, side, top, and in isometrical are shown in Fig. 5, *c*. Fig. 5, *c* shows a scheme similar to the Fig. 3, *b*. The link CD can be implemented as a rigid link or a link of variable length.

5. Conclusion

The natural dynamics of mechanical systems should not be canceled by the control system, but rather taken into account when designing a robot. The principles of morphological computation of control laws and the physical intellect embodiment contain the idea that most of the desired behavior and dynamics can be laid at the mechanical level of a robot, and the task of algorithmic control is reduced to augmentation, excitation, and stabilization of movement due to the features of mechanical structures and natural dynamics of a robot. Minimization of control efforts leads to reduction in the requirements for the level of technical equipment and reduces energy consumption.

It is possible to “program” the robot to perform the task at the mechanical level by synthesizing mechanisms of closed kinematics with optimization of structure and geometric parameters, optimization of mass distribution between links and optimization of elasticity distribution. The process of designing such structures is often informal due to the combination of components of different physical nature in a robotic system, a number of topologies and parameters tending to infinity, as well as heterogeneous criteria for optimal solutions, nonlinear objective functions. The result of “programming” strongly depends on the experience and engineering intuition of the designer. Human creative abilities are often insufficient for designing energy-efficient and adaptive robotic systems with morphological computation of control laws and physical embodied artificial intelligence, which is associated with the unlimited space of solutions, the continuous nature of the deformable bodies, the imperfection of the analytical apparatus and simulation tools.

The presented generalized method of structural-parametric synthesis of underactuated mechanisms with closed kinematics could act as a backbone for generative design of robotic systems with morphological computation of control laws and physical intellect embodiment. Within this paper, to verify the method we have synthesized a mechanism for an exosuit spine module that introduces significantly fewer restrictions on the movement of the exosuit user, providing greater ergonomics.

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