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Design optimization of a wearable chair using The Bees Algorithm

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Abstract

A wearable chair is designed to reduce musculoskeletal disorders in workers. Two-staged optimization process using The Bees Algorithm is conducted to determine the lowest operable height of the chair and minimize the maximum force among the three supports. Geometric, dimensional, and rotational angle constraints are defined accordingly. A CAD model of the chair is imported into ADAMS software for simulation. The simulation results identified the most stressed rod in the chair. A spring is selected and implemented in ADAMS to counteract the applied force on this rod. A comparison between the force on the most stressed support and the spring force through a defined motion revealed minimal differences, indicating that the spring effectively counteracted the applied force. The results demonstrated the successful application of The Bees Algorithm to wearable chairs and the successful implementation of a spring to counteract applied force, thereby achieving the objectives of this study.

Keywords

Wearable chair, passive exoskeleton, posture support, the bees algorithm, optimization

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Introduction

Due to improved living standards and developing medical technology, life expectancy has increased around the globe. However, this has also led to an aging workforce, which is at a higher risk of back, shoulder, lower limb, and upper back pain, especially for those who stand for long periods of time.[1] Work-related musculoskeletal disorders (WRMSDs) are caused primarily by workers assuming unhealthy postures in their jobs.[2,3]

To prevent WRMSDs, various exoskeletons have been studied and manufactured by researchers and companies. These exoskeletons help to reduce the load on the human body part to an external mechanism.[4] Exoskeletons are generally divided into two types based on their power requirements: passive and active. Active exoskeletons have motors or actuators that aid the wearer. This additional power increases the weight and volume of the exoskeleton and shortens the operating time due to the limited battery capacity. Passive exoskeletons do not have motors or actuators, and instead use springs or other elastic elements to help the wearer. This makes passive exoskeletons lighter and more compact than active exoskeletons, and they also have a longer operating time since there is no battery to recharge.[5,6] For example, passive wearable chairs help to reduce the back pain of the human body by transferring the load carried by lower limbs to the ground.[7] The wearable chair was also the first concept identified in the literature that allowed the workers in industrial sector to work with proper posture in a dynamic work environment by providing sitting assistance.[8] To assure stability and relief on human body when designing a wearable chair, the designer must consider the following factors: the location of the mass center when sitting and the joint location of support rods to the limbs of the exoskeleton. These factors can best be provided by optimizing the knee angle for sitting and the magnitude of forces applied to the support rods, respectively. The main purpose of this work is to enhance the mentioned factors through the application of The Bees Algorithm and a simulation software that is ADAMS. The goal is to effectively implement a spring onto the most stressed support rod of the mechanism, ensuring optimal support for the wearer without compromising ease of use. To achieve this, an initial step involves a comprehensive review of literature on wearable chairs, providing valuable

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insights to better contextualize and understand the current research endeavor. While existing literature offers numerous studies on wearable chairs, these primarily focus on four key aspects: material selection for lightweight yet robust mechanisms capable of supporting the wearer, minimizing production costs through optimized functionality, and enhancing user-friendliness through intuitive design and efficient operation. To provide a deeper context for this work, several of these relevant studies on wearable chair design are given below.

Bijalwan and Misra[9] designed a flexible wearable chair. They also performed finite element method analysis on the chair with ANSYS software. As a result of the analysis, they stated that, under the loading condition of the chair, stress, and deformation are within the permissible value and the structure is stable. After the analysis they manufactured the flexible wearable chair by using pure aluminum and its alloy 6061-T6. They also stated that, the flexible wearable chair is lightweight as the gross weight of the mechanism for both legs is 3 kg.

Bhagat et al.[10] designed a wearable chair with pneumatic support. They stated that, the designed wearable chair reduced fatigue on human body and increased the working efficiency and the chair weighted only 1 kg. Zhu et al.[11] designed a wearable chair using a 6 bar mechanism. To be used in different working environments they designed the support rod as a slider mechanism with adjustable angle of rotation. They also made experiments to verify if the designed exoskeleton can reduce the load on legs. After the experiments they stated that, the activity of leg muscles with the exoskeleton is decreased.

Zurina et al.[12] designed and manufactured a basic wearable chair. They stated that, the designed wearable chair angle can be adjusted to 45° and 90°. They also made an experiment to verify the adjustability of the chair. Also, Magdum and Jadhav[13] designed a similar wearable chair. They used hydraulic piston for the support of the chair. They stated that, the stress analysis on the chair is performed and the values are in acceptable range. They also manufactured the designed chair and stated that, the wearable chair is performing well.

Basha et al.[14] designed, analyzed, and manufactured a simple wearable chair that can't be adjusted for different sitting positions and/or body heights. They used FEM for the analysis of the designed wearable chair. To reduce the weight of the chair, they chose Aluminum Alloy 6082(T6). Similarly, Irawan et al.[15] designed, analyzed, and manufactured a wearable chair. They stated that, the materials of the chair are cheap and easy to obtain in the market. But as a disadvantage, the chair is too heavy to not let the wearer walk properly. They also tested the wearable chair and verified that; the chair can function as desired without walking. Delicia et al.[16] designed and manufactured a wearable chair in a similar way. They used a hydraulic piston for the support of the chair. The materials of the chair are taken from scraps. As a disadvantage, because of using too many straps, the wearer should give physical pressure on the chair.

Choi et al.[17] designed a wearable chair with a cam-drive implemented to the ankle and connected to the knee joint with wires. They stated that, the feature of this design is to allow the wearer concave swing motion in chair mode while joints passively follow the motion of the legs in normal gait mode. They also performed stress analysis on the chair and manufactured. Hadirah et al.[18]designed a wearable chair and focused on the motion analysis and the stress analysis. Unlike other wearable chairs, they used a cam to transfer motion from upper part to lower part of the mechanism. After the motion and stress analysis, they stated that, the design of the wearable chair performs satisfying.

Hasegawa et al.[19] designed and manufactured a wearable chair to reduce the physical load of a caregiver when transferring elderly or a physically challenged person. They also conducted experiments with healthy subjects and discussed the feasibility of the designed chair. They stated that, the manufactured chair reduced the physical load of caregiver and functioning smoothly.

Du et al.[20] designed, analyzed with FEM method, and manufactured a wearable chair named as HUST-EC. They used golden-division method to optimize the chair angle for operating mode with the lowest chair height. They stated that, another optimization technique is used to evaluate the most stressed support out of three by optimizing the dimensions and the rotation angles of the supports. They also conducted a walking simulation for the designed chair with OpenSim software by implementing the weight of the designed chair to a human model. And they performed experiments with 10 healthy subjects for static and dynamic tasks. After experiments, the authors stated that, the designed chair can effectively relieve muscle burden, and improve working posture.

Lovrenovic and Doumit[21] designed a walking assistive exoskeleton. The design consisted of a seating mechanism to produce an upward force to the wearer's pelvis. With this, the felt weight of the user has reduced. They also stated that, to match the anatomical needs of a single participant, a human-scale prototype was fabricated. As a result, the designed walking assistive exoskeleton reduced the felt weight of the user when standing and walking. With the same purpose, Farahani et al.[22] designed and analyzed a walking assistive exoskeleton. The design objective of their study was to reduce the user's foot reaction force to make the wearers feel less weight on the sole of their foot. Designed mechanism had two active prismatic joints. After the design, they performed force analysis on the mechanism. At the results, they stated that, the support force is almost in the same direction of foot reaction force, meaning the design objective is achieved.

Raut and Raut[23] designed and manufactured an upper body exoskeleton and a wearable chair. They stated that, the upper body exoskeleton can increase the capacity of weightlifting of a human up to 20–45 kg and the designed wearable chair can be locked at 90°, 120°, and 150° with using a ratchet gear. After the manufacture process they stated that, the designed upper body exoskeleton and the wearable chair are working well.

In the studies given above on the wearable chairs, most of them focused on the mechanism configuration of the chair. Only one of the studies given above, Du et al.[20] used a technique for the mechanism to be suited to the wearer that is the golden division method. But the golden division method, being a mathematical concept, may not necessarily yield the optimal solution. In contrast, in this study, The Bees Algorithm is a metaheuristic optimization algorithm capable of providing optimal solutions. This characteristic distinguishes this study from others in the existing literature. Furthermore, the study acknowledges rigidity in its mechanism, anticipating potential variations in results based on future experiments and material selection. This aspect offers a valuable opportunity to compare experimental studies with theoretical ones.

In this study, the mechanism configuration of a wearable chair, as outlined in Du et al.,[20] has been selected deliberately. The choice was driven by the inherent advantages of this particular configuration, which notably facilitates the clear formulation of equations and constraints. This inherent clarity not only streamlines the mathematical representation of the mechanism but also renders it more amenable to optimization processes when compared to alternative configurations explored in prior studies. Du et al.[20] stands out for its meticulous design and articulate representation, providing a solid foundation for the subsequent optimization endeavors undertaken in this study. The deliberate consideration of the ease of expressing mathematical relationships and constraints within this chosen mechanism configuration lays a robust groundwork for a more effective application of optimization techniques. This selection ensures that the performing analyses and enhancements are built upon a sound and comprehensible mechanical foundation, thereby contributing to the overall success and validity of the study. After choosing the mechanism, a global optimization technique that is The Bees Algorithm was used to optimize the lowest operating chair height and forces of the support rods. The detailed explanation for the choice of The Bees Algorithm in this study is provided in sub-section 3.1. A spring was also used for the most stressed support out of three, and the stiffness corresponding to the force on the support was determined. This study aims to assess the applicability of The Bees Algorithm in optimizing wearable chairs and to investigate the efficacy of incorporating a spring onto a support rod. The objective is to determine if the spring can effectively mitigate the applied force on the rod, thereby enhancing the overall functionality and comfort of the chair.

To ensure a comprehensive understanding of optimization techniques, applications from diverse fields that utilize a range of algorithms, apart from The Bees Algorithm are given below.

To improve automated driving by handling uncertainties in sensor data, He et al.[24] proposed a new decision-making technique in their study. In their study, models of the car's longitudinal (speed) and lateral (lane changing) choices as a coordinated system that can adapt to unexpected sensor noise are made. The authors stated that, they achieved significant improvements in both traffic efficiency (25–30%) and safety (81–91%) compared to traditional methods, demonstrating the effectiveness of their approach in real-world scenarios. Gad and Jabeen[25] worked on a neural network-based approach to system controller design, with a specific emphasis on preview control for vehicle suspension in both deterministic and stochastic settings. By establishing system dynamics and formulating a cost function, they derived an optimal control law using the linear-quadratic regulator (LQR) methodology. Through comprehensive evaluation, the authors stated that, a specific model emerges as a standout, showcasing superior ride comfort and dynamic stability, while the integration of a PID-fuzzy T-2 control system significantly enhances vibration isolation in seat suspension applications, underscoring its practical efficacy and robustness.

Shi and Zhang[26] addressed the lack of a comprehensive control-oriented tire model adaptable to diverse road conditions, despite the influence of tire characteristics on vehicle dynamics and control performances in their study. To fill this gap, they proposed a general control-oriented tire model, accounting for friction coefficient, vertical force, and combined slip, structured in linear parameter varying (LPV) form for simplified stability analysis and controller design. Through parameter minimization and utilization of the Grey Wolf Optimizer (GWO) method for identification, they stated that, the proposed model's accuracy is validated against CarSim tire test data, with introduced methods for lateral stability analysis and path-following controller design, demonstrating its effectiveness compared to benchmark models. Also, they made a study[27] that aimed to bolster the safety of automated vehicles by exploring fault diagnosis techniques, recognizing their pivotal role in ensuring vehicle safety. To streamline the process and overcome complexities associated with observer design, the authors investigated steering actuator fault diagnosis for automated vehicles using a model-based Support Vector Machine (SVM) classification approach. By implementing a procedure with Linear Discriminant Analysis (LDA) and threshold adjustment using Grey Wolf Optimizer (GWO), the authors stated that, the study significantly improved fault classification and diagnosis performance, as validated through comparative analyses on widely used datasets and experimental results on an automated vehicle.

Material and methods

Passive wearable chairs

There are many wearable chairs in commercial area. Some of the passive ones are Noonee Chairless Chair,[28] LEX Wearable Chair,[29] Ofrees Wearable Chair,[30] and H-CEX Hyundai chairless chair.[31] Some of the active ones are Honda Bodyweight support system[32] and ExoChair Exoskeleton.[33] There are many more commercial wearable chairs. But most of them focused on passive wearable chairs.

When designing a passive wearable chair, the designer must know which muscles on human body are affected and select or configurate the mechanism accordingly. One of the main muscle groups affected by wearable chairs is the quadriceps femoris, which is composed of four muscles located at the front of the thigh. The four muscles are the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius. The quadriceps are responsible for extending the knee joint and are continuously engaged when using a wearable chair to maintain an upright posture. Prolonged use of the device can cause fatigue and discomfort in the quadriceps, leading to a condition known as quadriceps strain. Another muscle group that can be affected by wearable chairs is the gluteus maximus, which is the largest muscle in the buttocks. The glutes are responsible for extending the hip joint and maintaining proper posture while standing. However, prolonged use of wearable chairs can cause the glutes to become weakened or fatigued, leading to a condition known as gluteal strain. The gastrocnemius and soleus muscles located in the calf may also be affected by wearable chairs. These muscles are responsible for plantar flexion, or pointing the foot downward, and are continuously engaged when standing or walking. Prolonged use of a wearable chair can cause fatigue and discomfort in these muscles, leading to a condition known as calf strain.[34] Finally, the erector spinae are another muscle group that can be affected by wearable chairs. This group of muscles runs along the length of the spine and is responsible for extending and stabilizing the back.[35] However, when using a wearable chair, the erector spinae muscles may become strained due to the prolonged upright posture required by the device. By knowing the muscles affected by wearable chairs, the configuration of the mechanism can be performed accordingly, and it is given in the next sub-section.

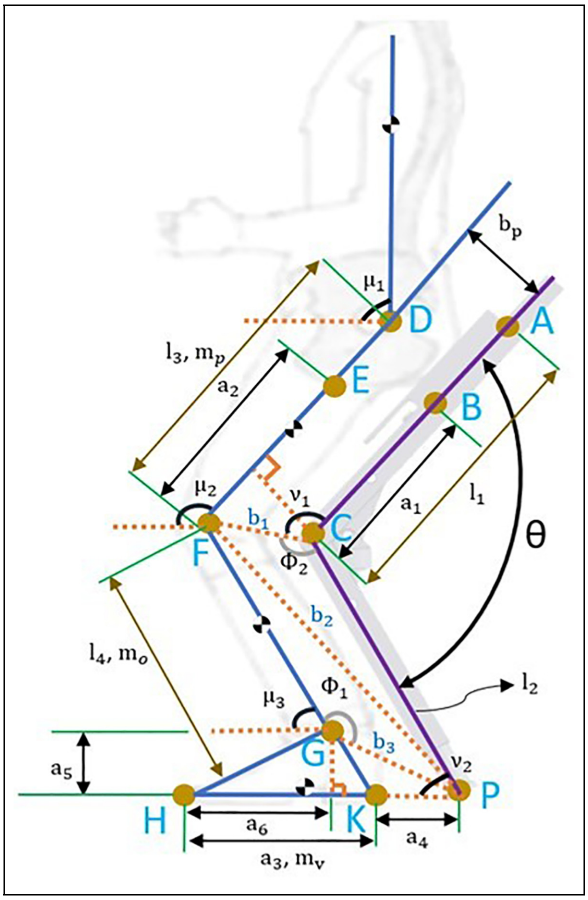

Figure 1. Configuration of wearable chair in relation to the human body's posture and positioning.

Configuration of the mechanism

This sub-section describes the mechanism configuration in two parts. In the first part, we examine the chair and human body contact to design the chair for the wearer. Then, in the second part, we write the forces on the chair accordingly. The configurations of the wearable chair mechanism are given below.

Chair movement of upper body. The mechanism configuration of the wearable chair is taken from the Du et al.[20] The configuration is same but some of the equations are changed for better understanding. This also includes the objective functions for optimization works.

An important factor in the configuration of the mechanism is that the wearer must keep their upper body vertical when using the wearable chair due to the change in their center of gravity (COG). This parameter is assumed in this configuration.

Points, link lengths and rotation angles of the mechanism from Figure 1 are as follows; E is the strap point, D is the hip joint of human body, P is the point of contact of the chair with the ground, $l_{1,2}$ are the lengths of upper and lower part of the chair, a_1 is the length between strap point and chair joint, a_2 is

Table 1. Design parameters of the configuration.

Variable	Subscript	Value
A	1, 2, 3, 4, 5, 6	240, 430, 275, 220, 94, 225 mm
B	*p*	220 mm
L	1, 2, 3, 4, *g*	520, 415, 460, 450, 1814 mm
M	*k, p, o, v*	90 kg, %14.16m_k, %4.33m_k, %1.37m_k

the length between knee joint and interaction point of the chair and human body, b_p is the length between chair and human body, a_3 is the foot length of the human body, a_5 is the foot height of the human body, θ is the angle between upper and lower part of the chair, $\mu_{1,2,3}$ are the rotation angles between human body and coordinate system, the $\nu_{1,2}$ are the rotation angles between the chair and coordinate system, and $\Phi_{1,2}$, $b_{1,2,3}$ are the parameters of CFGD rectangle. The human body used in this study has a weight m_k and height l_g

Known values of the design parameters are given in Table 1.

The percentages of the masses are taken from Wong et al.[36] Using these values, the equations for this configuration of the mechanism can be written.

$$\Phi_2 = 270 - \theta - \arctan((a_2 - a_1)/b_p) \quad (1)$$

$$b_2 = \sqrt{(a_2 - a_1)^2 + b_p{}^2 + l_2{}^2 - 2 l_2 cos\, \Phi_2 \sqrt{(a_2 - a_1)^2 + b_p{}^2}} \quad (2)$$

$$b_3 = \sqrt{(a_4 + a_3 - a_6)^2 + a_5{}^2} \quad (3)$$

$$\Phi_1 = \arccos\left(\frac{b_3{}^2 + l_4{}^2 - b_2{}^2}{2 b_3 l_4}\right) \quad (4)$$

$$\mu_3 = 270 - \Phi_1 - \arctan((a_4 - a_3 + a_6)/a_5) \quad (5)$$

$$\nu_2 = \arcsin\left(\frac{\sin\Phi_2 \sqrt{(a_2 - a_1)^2 + b_p{}^2}}{b_2}\right) + \arccos\left(\frac{a_4 + a_3 - a_6}{b_3}\right) + \arcsin\left(\frac{l_4 \sin\Phi_1}{b_2}\right) \quad (6)$$

$$\mu_2 = 180 - \theta + \nu_2 \quad (7)$$

$$b_2 = \arctan\left(\frac{a_2 - a_1}{b_p}\right) + 90 \quad (8)$$

As previously stated, the user of the chair must maintain a relatively upright posture. Assuming this, to reduce the load on the lower part of the human body when using the chair, the COG must stay between points K and P. Closer to the point P means increased force on the chair. Taking the point K as the origin, the x coordinates of the centroids are given below.

$$x_1 = a_3/2 \quad (9)$$

$$x_2 = a_3 - a_6 + \frac{l_4}{2}\cos\mu_3 \quad (10)$$

$$x_3 = a_3 - a_6 + l_4 \cos\mu_3 + \frac{l_3}{2}\cos\mu_2 \quad (11)$$

After these, first we need to express the x coordinate and the rotation angle of upper body. Equations are formed below when the COG is at points P and K, respectively.

$$x_{4.P} = -\frac{(m_v(x_1 + a_4) + m_o(x_2 + a_4) + m_p(x_3 + a_4))}{m_k - 2(m_p + m_v + m_o)} \quad (12)$$

$$\mu_{1.P} = \arccos\left(\frac{x_{4.P} - (a_4 + a_3 - a_6 + l_4 \cos\mu_3 + l_3 \cos\mu_2)}{(h - l_3 - l_4 - a_5)/2}\right) \quad (13)$$

$$x_{4.K} = -\frac{(m_v x_1 + m_o x_2 + m_p x_3)}{m_k - 2(m_v + m_o + m_p)} \quad (14)$$

$$\mu_{1.K} = \arccos\left(\frac{x_{4.K} - (a_3 - a_6 + l_4 \cos\mu_3 + l_3 \cos\mu_2)}{(h - l_3 - l_4 - a_5)/2}\right) \quad (15)$$

Now that we have written these equations for the chair movement, we can form the equations on the forces of the designed chair. These equations are given in the next subsection.

Forces on the chair. For the wearable chair to be stable and withstand the human body weight, the supports play an important role. Three support rods are defined as shown in Figure 2. Supposing the chair is lightweight, the weights of the supports are taken as $G_1 = 10N$ and $G_2 = 10N$. Thinking the worst case as the wearer puts his whole weight on one leg of chair, the force value at the interaction point B is taken equal to human weight. The three-support rod structure can be treated as a planar link mechanism. When sitting down, the RN link is the shortest and when stood up RN link is the longest. The shortest and the longest length of RN link are taken as d_a and $2d_a$ respectively.

All the support forces in Figure 2 must be written in equation form. The equations are given below accordingly.

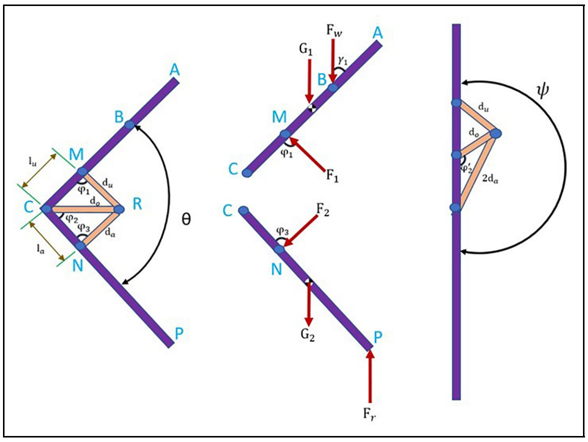

Figure 2. Free body diagram of the wearable chair when sitting and standing.

$$\gamma_1 = \mu_2 - 90 \tag{16}$$

$$\gamma_2 = 90 - \nu_2 \tag{17}$$

$$F_1 = \frac{\left(F_w a_1 \sin\gamma_1 + \frac{G_2 l_1 \sin\gamma_1}{2}\right)\sqrt{l_u^2 + l_o^2 - 2 l_u l_o \cos(\theta - \varphi_2)}}{l_o l_u \sin(\theta - \varphi_2)} \tag{18}$$

$$\varphi_1 = \arcsin\left(\frac{F_w a_1 \sin\gamma_1 + \frac{G_2 l_1 \sin\gamma_1}{2}}{F_1 l_u}\right) \tag{19}$$

$$d_u = \frac{d_o \sin(\theta - \varphi_2)}{\sin\varphi_1} \tag{20}$$

$$F_2 = \frac{\left(F_r l_2 \sin\gamma_2 - \frac{G_1 l_2 \sin\gamma_2}{2}\right)\sqrt{l_a^2 + l_o^2 - 2 l_a l_o \cos\varphi_2}}{l_o l_a \sin\varphi_2} \tag{21}$$

$$\varphi_3 = \arcsin\left(\frac{F_r l_2 \sin\gamma_2 - \frac{G_1 l_2 \sin\gamma_2}{2}}{F_2 l_a}\right) \tag{22}$$

$$d_o = \frac{d_o \sin\varphi_2}{sin\varphi_3} \tag{23}$$

To obtain the force equation for CR link, vector method can be used as follows:

$$F_3 = \sqrt{F_1^2 + F_2^2 + 2F_1F_2\cos(360 - \theta - \varphi_1 - \varphi_3)} \tag{24}$$

For CMR and CNR triangles, considering the d_a and $2d_a$ situations, geometric constraints can now be defined and given below.

$$cs_1 = d_u + d_o - l_u \tag{25}$$

$$cs_2 = d_u + l_u - d_o \tag{26}$$

$$cs_3 = l_u + d_o - d_u \tag{27}$$

$$cs_4 = d_a + d_o - l_a \tag{28}$$

$$cs_5 = d_o + l_a - d_o \tag{29}$$

$$cs_6 = l_a + d_o - d_a \tag{30}$$

$$cs_7 = d_u + 2d_a - l_u - l_a \tag{31}$$

$$cs_8 = d_u + l_u + l_a - 2d_a \tag{32}$$

$$cs_9 = l_u + l_a + 2d_a - d_u \tag{33}$$

When the length of RN link becomes $2d_a$, φ_2 angle changes as shown in Figure 2. For these changes, the equations (34) and (35) are written as follows:

$$\varphi_2' = \arccos\left(\frac{l_c^2 + l_2^2 - 4l_b^2}{2l_2 l_c}\right) \tag{34}$$

$$\psi = \theta - \varphi_2 + \varphi_2' \tag{35}$$

With this, all the equations are formed from Figures 1 and 2. To design the wearable chair using these configurations, optimization works are implemented. At the below section, the optimization technique is explained, the objective function and the constrains are written for the desired position and the functionality of the chair accordingly.

Results and discussion

Optimization of the wearable chair with the bees algorithm

The Bees Algorithm (BA), proposed by Pham et al.,[37,38] is a population-based search algorithm that mimics the foraging behavior of honeybees. Honeybees share information about the quality of food sources they find by performing a bee dance. Bees that find high-quality sources through this dance share their direction, distance, and food amount information with other bees. This mechanism allows the colony to be directed to sites with high-quality resources. Pham and Kalyoncu used The Bees Algorithm to control a flexible link robot manipulator using PID and The Bees Algorithm based Fuzzy Logic controllers. This was the first experimental and theoretical study to use the BA for controller optimization.[39,40] Şen and Kalyoncu used The Bees Algorithm to design PID and LQR controllers for the optimization of an inverted pendulum system. This study evaluated the suitability of the BA for controller optimization in control engineering.[41,42] As a result of these studies, it is observed that The Bees Algorithm gives appropriate results in the designing of the controller parameters and compared to the traditional methods the position control of the system is improved.

The aforementioned studies aim to explore the versatility of The Bees Algorithm in various domains. However, there are also works that assess the efficacy of The Bees Algorithm by comparing it to other optimization algorithms. Some notable examples include: Ayğahoğlu et al.[43] performed dimension optimization of a polycentric knee prosthesis with The Bees Algorithm and Genetic Algorithm to ensure that the instantaneous center of rotation of the mechanism is as close as possible to the reference curve. At the results, The Bees Algorithm converged to the desired curve much better than Genetic Algorithm; Eser et al.[44] carried out optimization studies to reduce the deviations in the suspension system to achieve better driving ability and comfort of the quarter vehicle suspension system in the road map. They compared the deviations using The Bees Algorithm and Particle Swarm Optimization and stated that The Bees Algorithm gave more successful results; A study by Pham and Castellani[45] compared The Bees Algorithm (BA) to Particle Swarm Optimization (PSO) and a type of Evolutionary Algorithm (EA) on 18 custom-made benchmark functions designed to be diverse and challenging. They found that BA generally outperformed both PSO and EA in terms of convergence speed, solution quality and robustness on diverse benchmark functions, particularly for complex problems. However, EA sometimes achieved slightly better solution quality at the cost of slower convergence; To optimize the Multiple Traveling Salesman Problem (MTSP), Hamza et al.[46] developed a new local search operator called SBESTSO for the Bees Algorithm (BA). This enhanced BA outperformed existing algorithms on various MTSP datasets, finding better solutions with faster execution and balanced tours; Another work by Khalaf et al.[47] made a study on the performance of the Bee Algorithm (BA) compared to the Genetic Algorithm (GA) for sensor coverage optimization. Both algorithms were implemented in MATLAB and evaluated based on coverage percentage, total run time, best response time and number of iterations required for the best response. The results, averaged over 10 runs with identical conditions, demonstrate the BA's superiority in several aspects. The BA achieved a significantly higher maximum coverage (97.87% vs 89.63%) with faster computation time (51.78 s vs 54.20 s), even with fewer iterations. Furthermore, the BA required only 33 sensors to achieve full coverage compared to 40 sensors needed by the GA, indicating its efficiency in sensor deployment optimization. These findings suggest that the BA is a promising approach for sensor network optimization tasks, offering advantages in coverage, computational efficiency, and sensor utilization.

The Bees Algorithm has several parameters that affect its performance, including:

- Number of scout bees (n): The number of bees that explore the search space for new sources.
- Number of sites selected (m): The number of sources that are selected from the n sites visited by the scout bees.
- Number of elite sites (e): The number of sources with the highest quality in the m selected sites.
- Number of bees sent to the best site (nep): The number of bees that are sent to the source with the highest quality (e) sites.
- Number of bees sent to the remaining sites (nsp): The number of bees that are sent to the lower quality (m-e) sites.
- Size of the site (ngh): The size of the neighborhood around each source.
- Stop criterion (iter): The number of iterations or the stop criterion that is used to terminate the algorithm.

This study employs The Bees Algorithm, a population-based search technique inspired by the foraging behavior of honeybees. The Bees Algorithm has gained recognition for its effectiveness in tackling complex optimization problems characterized by large datasets. Unlike traditional optimization methods, The Bees Algorithm incorporates several key functionalities:

- Solution Categorization: It categorizes potential solutions based on pre-defined criteria, allowing for a more focused analysis. This helps prioritize areas within the search space that hold greater promise.
- Prioritization: The algorithm identifies solutions with the highest potential for success based on an evaluation metric. This prioritization guides the search process towards more fruitful areas, improving efficiency.
- Diverse Solution Set Generation: The Bees Algorithm generates a pool of various potential solutions. This diversity ensures that the search doesn't get trapped in local optimum (suboptimal solutions) and increases the likelihood of discovering the global optimum (the absolute best solution).

A crucial advantage of The Bees Algorithm lies in its ability to simultaneously evaluate multiple locations within the search space. This comprehensive assessment significantly enhances the probability of finding the optimal solution. Each solution within the generated set functions independently, visualized as a vector in a multidimensional space. This vector

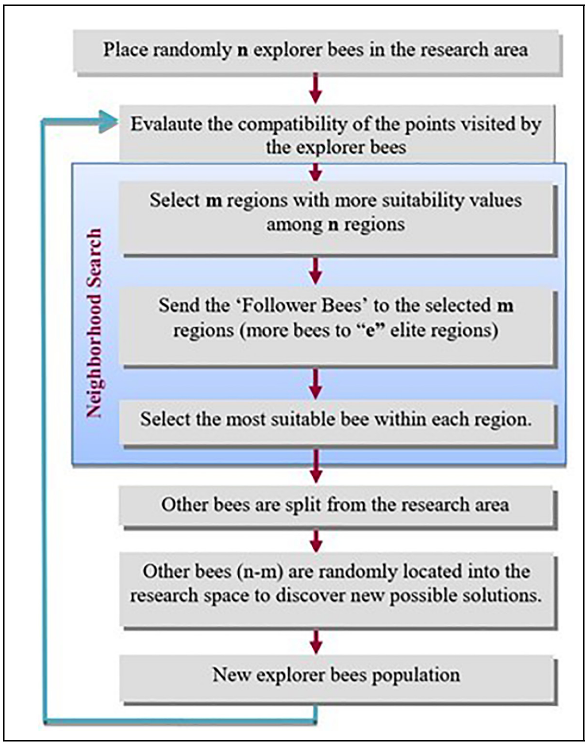

Figure 3. Flowchart of The Bees Algorithm (Ayğahoğlu et al., 2023).

representation highlights the algorithm's versatility in exploring different regions of the problem domain. Furthermore, The Bees Algorithm demonstrates proficiency in both local and global search strategies. This adaptability makes it a valuable tool for a wide range of optimization tasks. Additionally, its user-friendly design fosters seamless integration with other algorithms, potentially expanding its overall capabilities. The selection of The Bees Algorithm underscores this study's commitment to utilizing a robust and versatile optimization technique for achieving the most optimal outcomes.

The flowchart of The Bees Algorithm is given in Figure 3.

In this section, two staged optimization works for the wearable chair mechanism have been performed by using The Bees Algorithm. The parameters of the algorithm are taken as follows: $n = 80, m = 12$, $e = 5$, $nep = 2$, $nsp = 4$, $ngh = 0.01$, $itr = 60$. First optimization work is to find the lowest operatable height of wearable chair by assuming the upper body is vertical. Second one is the dimension optimization of the supports by minimizing the maximum force among the supports. The optimization works are explained in detail in sub-sections below.

Optimization of lowest operable height of chair. For the wearer of the chair to keep their upper body vertical as much as possible when working, an objective function is defined considering μ_1 angle. This means that

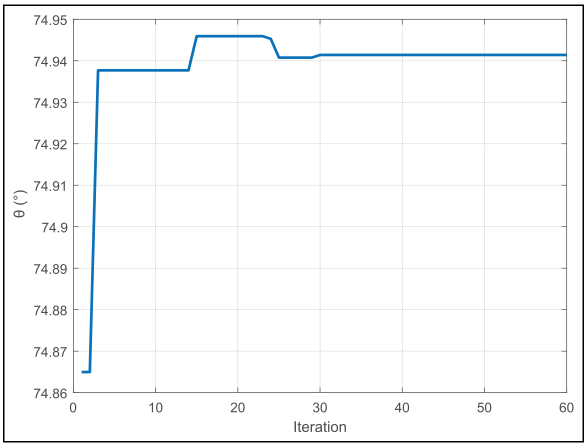

Figure 4. Convergence curve depicting the progress of the first optimization.

when the angle of the upper body is within the range of $\mu_{1.P}$ and $\mu_{1.K}$, the position of the mass center is between the point P and K. The first objective function is defined by using $\mu_{1.P}$, $\mu_{1.K}$ equations given below.

$$s_1 = \mu_{1.P} - 90 \tag{36}$$

$$s_2 = 90 - \mu_{1.K} \tag{37}$$

$$First\ Objective\ Function = s_1 + s_2 \tag{38}$$

As a constraint, the range of chair angle θ is determined as $60 < \theta < 105$. By defining the first objective function and the constraint, using the written equations, the optimization for the best working posture depending on θ can be performed.

In Figure 4 the convergence graph of the optimization with The Bees Algorithm is given for 60 iterations.

After the optimization, the chair angle $\theta = 74.9414^{\circ}$ is found. For implementing easily, it is taken as $\theta = 75^{\circ}$.

When $\theta = 75^{\circ}$, it is assumed the lowest operatable height of the chair.

After this optimization, the second optimization work which is minimizing the maximum force of the supports can be done and it's given in the following sub-section.

Dimension optimization of the support rods. In this sub-section, the force optimization of the supports, depending on the dimensions and the angles are performed. Now that we know $\theta = 75^{\circ}$, the equations can be solved by defining the constraints.

The constraints for the second optimization with The Bees Algorithm are given in Table 2.

Besides these constraints, the geometric constraints given in equations (25)–(33) are defined in the

Table 2. Dimension limits of the wearable chair mechanism.

	l_u	l_a	d_o	φ_2	ψ
Minimum	100	50	40	10	170
Maximum	200	150	50	80	190

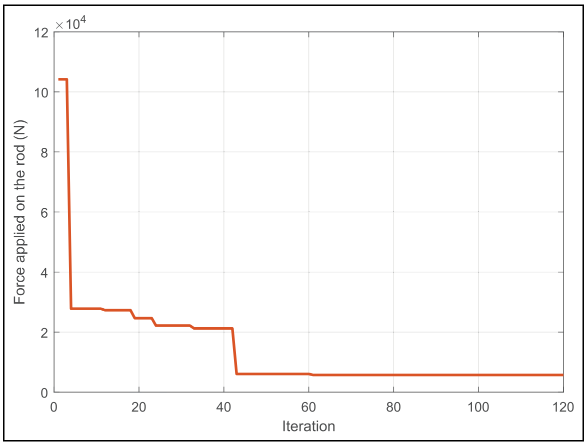

Figure 5. Convergence curve depicting the progress of the second optimization.

algorithm as penalty functions. The value of the function is taken as 100,000.

The objective function is defined as the maximum force among three supports and given below. The Bees Algorithm will minimize the second objective function.

$$\textit{Second Objective Function} = \max[F_1, F_2, F_3] + \textit{Penalty} \quad (39)$$

For the same parameters taken for first optimization, the second one is performed by using the above constraints. For this optimization, the iteration is taken 120 and the convergence graph is given in Figure 5.

At the results, the greatest force is on the d_a support and the value of it is $F_3 = 5720.8606N$. For this force the design parameters according to the optimization result is given in Table 3.

After calculating the design parameters of the chair according to optimization with The Bees Algorithm, a spring is implemented to the most stressed support which is RN link in this case. In the following section, the implementation and selection of the spring is explained in detail.

Spring implementation for the support rod

In this sub-section, we selected and implemented a spring and calculated the stiffness of the spring for RN link. The most important factor when selecting a spring is that it should counter the force coming on the RN link. For this reason, we used ADAMS and MATLAB Simulink software to determine and see if the spring can counter the force applied on RN link. Spring stiffness can be calculated from the following known simple equation.

$$P = k\,x \quad (40)$$

Here, the P is the force coming on the RN link which is F_3 in this study. Using ADAMS software, we imported the CAD model of the chair from SOLIDWORKS and implemented a spring to RN link. After that, we calculated the spring stiffness using the F_3 when the chair is in the lowest operatable height and when its value is zero. By doing this, the spring stiffness is found as $k = 197{,}500$ N/m

After calculating the spring parameters in ADAMS software, the model with its spring parameters is imported to MATLAB Simulink software to obtain more realistic spring parameters plots throughout the said motion. The Simulink model of the wearable chair is given in Figure 6.

By using the defined spring stiffness to calculate the spring force, we compared it with the applied force on the link throughout the motion when the chair is at its lowest operable height and when the value of F_3 is 0. The comparison of the force applied on the RN link and the spring reaction force is given in Figure 7.

As shown in Figure 7, the difference between the spring and link forces is low, with a maximum difference value of 200 N. This means that by implementing the defined spring stiffness, the wearable chair can now function as desired without any powered actuators.

Also, the deflection of the spring and the length of spring throughout the said motion are given in Figures 8 and 9 respectively.

Modeling in ADAMS

According to the designed parameters from The Bees Algorithm, the chair is designed in SOLIDWORKS and imported to ADAMS software. Then the spring is implemented to RN link. The designed wearable chair model with the implemented spring is given in Figure 10.

Overall, the proposed wearable chair design, which incorporates The Bees Algorithm and the spring design, has the potential to significantly improve comfort and ease of use for the wearer. The Bees Algorithm can be used to optimize the design of the chair's mechanisms, resulting in a more ergonomic and supportive fit. Additionally, the spring design can be used to reduce the amount of force required to use the chair, making it easier to operate and reducing fatigue. These improvements could lead to a number of benefits for users, such as reduced muscle strain, improved posture, and increased productivity in industrial area.

Table 3. Design parameters after the optimization.

l_u	l_a	d_o	φ_2	ψ
118.6974 mm	108.9625 mm	46.6992 mm	32.0109°	181.4879°

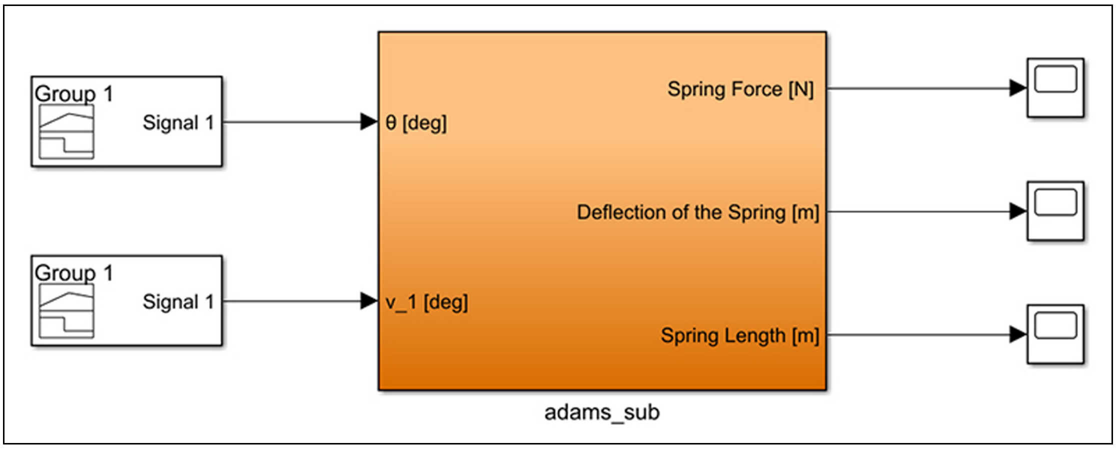

Figure 6. Simulink representation of the wearable chair design incorporating the implemented spring.

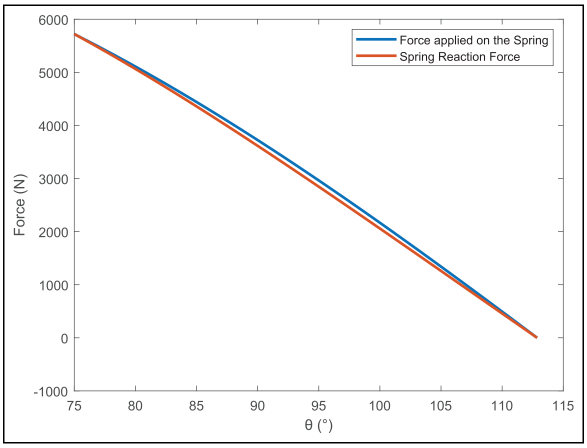

Figure 7. Comparison of applied force on the support rod and corresponding reactive force from the spring.

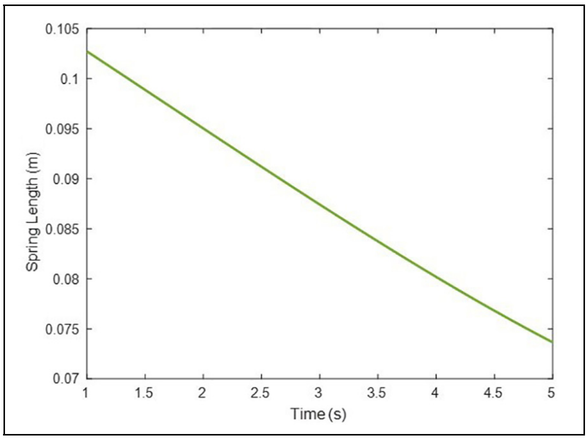

Figure 9. Length of the implemented spring.

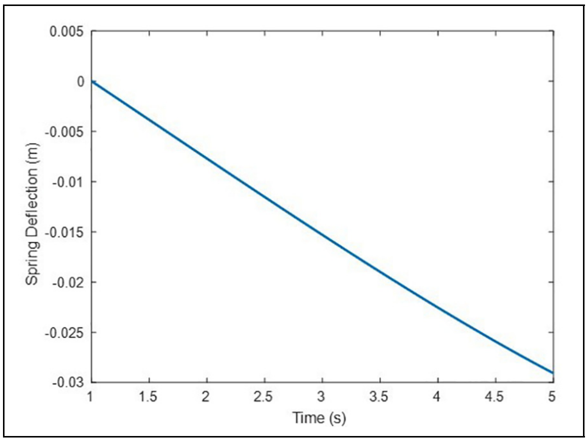

Figure 8. Deflection of the implemented spring.

The decision to solely rely on theoretical and simulation methods in this study was influenced by the prohibitively high manufacturing costs associated with the intricate mechanism and the significant impact of material selection on support rod forces and user-friendliness. Given the assumption of rigid links, calculations and equations were tailored accordingly. This streamlined approach not only facilitated a focused analysis but also provided a controlled environment for exploring the theoretical aspects of the system with precision.

Conclusion

For workers that must do their job in various postures, a wearable chair is designed in this study to

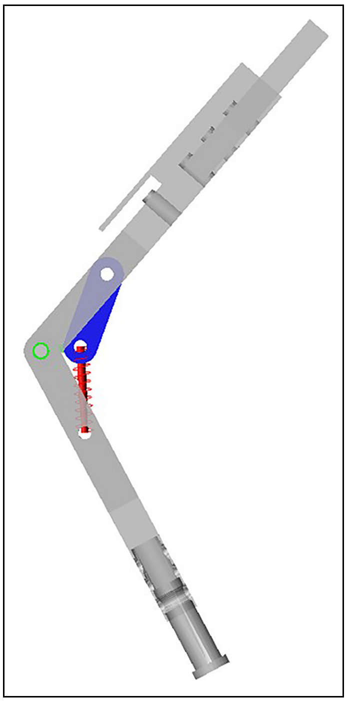

Figure 10. The model of the wearable chair simulated using ADAMS software.

prevent musculoskeletal disorders. Mechanism configuration of the wearable chair is taken from another work and the equations are written in a more understandable way. The mechanism selection was driven by its inherent advantages, particularly in facilitating clear equations and constraints. This clarity streamlines mathematical representation and enhances adaptability for optimization compared to alternative configurations in prior studies. The chosen mechanism's meticulous design and articulate representation provide a solid foundation for subsequent optimization efforts. Deliberate consideration of ease in expressing mathematical relationships ensures a robust groundwork for efficient application of optimization techniques, contributing to the overall success and validity of the study. A two staged optimization work has been performed using The Bees Algorithm by minimizing the defined objective functions and the reason behind. First optimization work was to find the lowest operatable height of the chair when the wearer's upper body is vertical by using the chair angle. Second optimization work was to minimize the maximum force of three supports when the chair is at the lowest operatable height. Constraints for the second optimization work are defined by geometric limits, dimension limits and rotation angle limits of the supports. After the optimization works, the most stressed support is found and the value of it is determined. The wearable chair, using the parameters from the result of optimization works is designed in SOLIDWORKS and the CAD model is imported to ADAMS software. In ADAMS software, a spring is selected and implemented to the most stressed support and spring stiffness is calculated. After that, the spring parameters are calculated in ADAMS software and for more realistic plots the model is imported to MATLAB Simulink software along with its spring parameters. A motion is defined for when the chair is in the lowest operatable height and when its value is zero. Then, to see if the designed spring can function well, a comparison is made between the force coming on the support and the spring force throughout the defined motion. In comparison, the force differences are so low that, the maximum difference value is 200 N. At the results, this study exhibited expertise in two pivotal domains. Firstly, it skillfully employed The Bees Algorithm to optimize wearable chairs, highlighting its capacity to sustain diversity throughout the search process, thus solidifying its position as a fitting choice for this application. Secondly, it innovatively incorporated a spring design into wearable chairs, resulting in a significant enhancement of wearer comfort and usability.

The scope of this study is delimited by its concentration on theoretical frameworks and simulation methodologies. While these methods offer valuable insights, it is imperative to acknowledge their inherent limitations. In our forthcoming research, we aim to modify these constraints by adopting a more expansive and comprehensive approach. This involves moving beyond theoretical confines to practical implementation. Our next steps include manufacturing the designed wearable chair and carefully selecting materials for each part. This material selection process aims to ensure the chair's durability and efficiency along with obtaining close or better results than the current work. Additionally, we plan to conduct experiments to assess the activity of the targeted muscle groups mentioned earlier. These experiments will provide valuable insights into the chair's real-world impact on user physiology during various activities. This shift towards practical implementation and experimentation is aimed at enriching the depth and applicability of our research findings.

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