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A CONCEPTUAL FRAMEWORK OF DESIGN OPTIMISATION OBJECTIVES FOR ALIGNING LOWER-LIMB EXOSKELETONS TO INDUSTRIAL REVOLUTION 5.0

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Graphical abstract

Abstract

Lower-limb exoskeletons can be used extensively in manufacturing, medical, rehabilitation, and the military. The design optimisation for each exoskeleton is vary depending on its intended use. Improving the design of the lower-limb exoskeletons encompasses objectives, attributes, and methods for fulfilling various application. This paper aims to establish a conceptual framework for developing most optimum design for lower-limb exoskeletons for industrial use. Additionally, this paper offers a critical review of design optimization for lower-limb exoskeletons with the aim of enhancing the ergonomics of workers in the industrial sector. To achieve this, this paper delves into an overview of both original research papers and review articles to extract valuable methodologies and design considerations for optimising lower-limb exoskeletons specifically for industrial use. The key outcomes of this paper include recommendedmethods, mechanical design considerations, and a conceptual framework specifically tailored for the design optimization of lower-limb exoskeletons in industrial environments. By offering a comprehensive overview of existing research, this review paper not only aids researchers and designers in the field but also benefits end-users, manufacturers, and the environment. The proposed conceptual framework serves as a valuable tool to guide the development of future lower-limb exoskeletons, ensuring a harmonious integration of technology, user needs, and industrial requirements.

Keywords: Design Sustainability, CAD/CAE, Sustainable Development Goals (SDGs), Wearable Technology, Manufacturing Process

Abstrak

Eksoskeleton anggota bawah digunakan secara meluas dalam industri pembuatan, perubatan, pemulihan dan ketenteraan. Pengoptimuman reka bentuk untuk setiap exoskeleton adalah berlainan bergantung pada penggunaan yang diinginkan. Penambahbaikan reka bentuk eksoskeleton anggota bawah merangkumi objektif, sifat exoskeleton dan kaedah untuk memenuhi pelbagai keperluan. Kajian ini bertujuan untuk membangunkan satu rangka kerja konsep untuk penambahbaikan reka bentuk yang paling optimum untuk eksoskeleton anggota bawah untuk kegunaan industri. Selain itu, kajian ini memberi ulasan kritikal tentang pengoptimuman reka bentuk untuk eksoskeleton anggota bawah dengan tujuan mempertingkatkan ergonomik pekerja dalam sektor perindustrian. Untuk mencapai matlamat ini, kajian ini mengkaji penemuan kajian lepas dan kertas ulasan untuk memperolehi metodologi dan pertimbangan reka bentuk untuk mengoptimumkan eksoskeleton anggota bawah khusus untuk kegunaan industri. Hasil utama kajian ini adalah kaedah yang disyorkan, pertimbangan reka bentuk mekanikal, dan rangka kerja konsep yang disesuaikan secara khusus untuk pengoptimuman reka bentuk eksoskeleton anggota bawah dalam persekitaran industri. Dengan memberi gambaran menyeluruh tentang penyelidikan sedia ada, kertas ulasan ini bukan sahaja membantu penyelidik dan pereka bentuk dalam bidang exoskeleton anggota bawah, malah mampu memberi manfaat kepada pengguna, pengeluar dan alam sekitar. Rangka kerja konsep ini berfungsi sebagai rujukan yang berguna untuk pembangunan eksoskeleton anggota bawah untuk memastikan penyepaduan harmoni teknologi, keperluan pengguna dan keperluan industri.

Kata kunci: Kelestarian Reka Bentuk, CAD/CAE, Matlamat Pembangunan Mampan, Teknologi Boleh Dipakai, Proses Pembuatan

1.0 INTRODUCTION

The Industrial Revolution refers to a worldwide shift in industrial practices characterised by increased prevalence, improved efficiency, and enhanced stability in the manufacturing sector. The global landscape is transitioning from the fourth industrial revolution (IR 4.0) to the fifth industrial revolution (IR 5.0). The current trajectory has shifted towards fostering a more cohesive and synergistic relationship among humans, machines, and artificial intelligence (AI). In addition, the field of Industrial Revolution 5.0 is shifting its attention towards a more human-centric approach, placing greater emphasis on sustainability. The Industrial Revolution 5.0 will need to consider the Sustainable Development Goals established by the United Nations to fulfil the objective of IR 5.0. For the sake of the people and the planet in the future, the United Nations has devised a plan that applies to all nations and aims to promote peace and prosperity. This is a critical request for the entirety of the nation [1]. The United Nations has included “excellent health and well-being” as one of their 17 sustainable development goals. A healthy lifestyle involves engaging in activities that leave a positive impression on the body. One of the many advantages of leading a healthy lifestyle is that it can reduce the risk of developing disease, increase longevity, and improve the overall quality of one's life. Adopting a healthy way of life will bring you closer to meeting one of the sustainability development goals, which is to improve your health and well-being.

Work activities that are prolonged and physically demanding, such as constant exposure to overhead drilling and heavy lifting, are lowering the quality of life for those who perform them in industrial environments. The use of an engineering solution known as exoskeletons is one way in which certain work practices can be made more efficient. An exoskeleton can give support for posture, function as a prosthetic for an amputee, and even provide strength augmentation in the lower limb area, such as the knees and the leg [2]. A mechanical device that helps with the movements of the lower limbs is known as an exoskeleton for the lower-limbs [3]. An exoskeleton is not only allows for the enhancement of physical activities or movement, but it also has the potential to improve human lifestyle by reducing the risk of severe injuries. Previous research by Yan [4] demostrated that the average muscle activity used when wearing an exoskeleton has decreased by 46.3%. Additionally, a case study conducted at Shizuoka Hospital by Michihito Nagakawa [5] found that surgeons reported reduced fatigue the day after utilizing an exoskeleton during surgical procedures. Rehabilitative and medical applications of exoskeletons are some examples of their uses [6–20], as well as applications in the industrial sector [21–35].

Moreover, exoskeletons have been applied in the military [36-37]. The application of lower-limb exoskeletons in stroke therapy has been observed in persons experiencing stroke. The development of an exoskeleton is designed to assist those who have experienced a stroke recover lower limb strength. A lower-limb exoskeleton has the potential to offer ergonomic assistance to surgeons engaged in prolonged surgical procedures. Moreover, in the context of industrial applications, a lower-limb exoskeleton is commonly employed as a means of augmenting physical capabilities, particularly in tasks such as involving the carrying of heavy objects. Finally, within the military context, the utilization of lower-limb exoskeletons can be regarded as a means of assisting in transporting substantial cargo across extended distances. Figure 1 illustrates an example of exoskeleton application in rehabilitation, industry and the surgical procedure.

(a) Rewalk Exoskeleton (b) Nonee chairless chair

(c) Alkeris Exoskeleton

Figure 1 (a) ReWALK exoskeleton [19] for rehabilitation, (b) Nonee chairless chair exoskeleton [29] for tasks in industry, and (c) Alkeris exoskeleton [5] for surgical procedures

Applying the engineering design approach to develop an exoskeleton closely mirrors its application in creating other assistive devices. The conceptual design phase is an essential component of the engineering design process. During this phase, a number of different design concepts are created in order to build a design that satisfies all of the necessary objectives that were established by the designers. Design optimization is a technology that can speed up the design cycle and produce better outcomes rather than using an iterative design process to fulfil its objective in terms of effectiveness, satisfaction, and performance within the limit of the constraints [38]. Employing computational tools, mathematical models, and design criteria to optimise the design variables to achieve the intended goals specified by the designers in the most efficient manner possible is what is meant by the term "design optimization." Design optimization tools are creation tools that systematically build and assess design alternatives by employing parametric modelling, performance simulation, and mathematical optimization [39]. This design process is the best possible solution from among a number of options that are practicable on the basis of a criterion, or more specifically, a set of criteria [40]. In computational design optimization, the decision-maker is the one who is responsible for selecting the problem formulation, the modelled relationships, and the optimization technique [41]. The process of formulating the problem includes figuring out the decision factors, objectives, and constraints associated with the products that need to be developed.

Usually, the decision is informed by the feasibility of an optimization algorithm in mathematically addressing the problem.It has been demonstrated that design optimization through the use of computational tools and mathematical models can shorten the amount of time required to decide on the most optimal design to achieve its aim while adhering to the constraints that have been established. The various definitions of design optimization that can be found in earlier publications are presented in Table 1. After examining these definitions, this article summarized that design optimization is an effort to search for the optimum design to achieve single or multiple objectives by using the iteration process while also fulfilling the constraint that has been set.

Once the most optimal design is obtained, validation becomes necessary to assess whether the design aligns with the established criteria. These criteria are subject to variation, but the safety of the users are the most crucial criteria. The study of how different loads and situations affect the behaviour of a structure's design and the components that make it up is the focus of the engineering discipline known as structural analysis. The calculation of the structure's internal forces, stress, and deformations, as well as its safety factor, are all part of this aspect of structural engineering. The computational approach, often known as computer-aided engineering (CAE), is one of the instruments that are used for structural analysis.

For interdisciplinary design activities, such as performing structural analysis to confirm the safety factor and structural stability of the building structure [42]. An example of this is design organisations in China, which purchase a variety of commercial computer - aided design (CAD) /CAE software. Aside from that, the CAE technology is possible to develop methods of body parts force displacement calculations on a metal cutting machine, which helps to improve the design in terms of the user's safety and helps to prevent defects on the workpiece of the cutting machine [43]. CAE software has also been utilised in Formula 1 racing cars in order to increase the safety features and the cassis's stability when the car is being raced [44].

This demonstrates how crucial structural analysis is in the design of engineering projects in order to guarantee that structures can accomplish their goals while retaining their safety and stability throughout time. Although the application of structural analysis is most frequently seen in buildings, it is also possible for it to be utilised in other types of structures. An example of this would be an exoskeleton for the lower limbs.

Table 1 Definitions of design optimisation reported by past studies

References	Definitions	Product/ Application
[39]	Design optimisation entails using computational tools, mathematical models, and design criteria to optimize the design variables to achieve the desired objectives set by designers as effectively as possible. Design optimisation tools are creation tools that systematically develop and assess design alternatives using parametric modelling, performance simulation, and mathematical optimisation	General
[45]	Design optimisation tools are creation tools that use parametric modelling, performance simulation and mathematical optimisation to generate and evaluate design alternatives systematically.	General
[41]	In computational design optimisation, the decision-maker must decide upon the problem formulation, the modelled relationships, and the optimisation algorithm that should be employed. The problem formulation involves defining the decision variables, objectives, and constraints of the problem. Modelling involves choosing appropriate mathematical relationships that model each objective as a function of the decision variable. An optimisation algorithm is typically chosen. Based on its appropriateness to mathematically solve the problem	Concrete Mixture
[38]	Design optimisation is a technology that can speed up the design cycle and produce better outcomes instead of using an iterative design process to fulfil its objective in terms of effectiveness, satisfaction, and performance within the limit of the constraint.	General
[46]	The design optimisation aims to determine the optimal shape of a structure to maximize or minimize a given criterion, such as minimize the weight, maximize the stiffness, subjected to the stress or displacement constraint condition	Building structural design

Prior studies [47–59] have analysed and discussed the design optimisation of lower-limb exoskeletons for a variety of applications. The past studies on the review paper of design optimisation of the lower-limb exoskeleton are presented in Table 2, and the area highlighted in green represents the research gap. The applications mentioned in Table 2 pertain to the applications of lower-limb exoskeletons. The applications of these lower-limb exoskeletons encompass various domains, including general (usage in daily tasks, such as enhancing ergonomic posture), medical (usage for rehabilitative purposes), and industry (utilization of lower-limb exoskeletons to assist with daily tasks in industrial settings). More recent attention and trends have been more focused on the provision of stability in the control system of the exoskeleton, which primarily focuses on a method to achieve stability of the motors and actuators. The relatively recent invention of the lower-limb exoskeletons has also increased the necessity of considering the addition of AI to the lower-limb exoskeletons [60–62].

Unfortunately, for lower-limb exoskeletons application in the industrial sector, far too little attention has been paid to the interaction between design optimisation objectives such as manufacturability and cost, functionality and dependability, weight and size, and energy efficiency. The contemporary design of exoskeletons lacks consideration for their applicability in industrial settings. Notably, there is an absence of frameworks or guidelines delineating design optimisation objectives aimed at the development of exoskeletons tailored for industrial use, aligning with the tenets of Industrial Revolution 5.0. Neglecting to address the existing research gap poses a significant challenge for industrial designers and engineers, hindering their ability to achieve the intended goals, criteria, and methodologies for the development of lower-limb exoskeletons. Consequently, the acquisition of state-of-the-art technology and design considerations essential for the construction of an optimal and effective lower-limb exoskeleton, while adhering to specified parameters, becomes unattainable. The ramifications extend to jeopardizing user safety, as improper alignment of the exoskeleton may lead to severe injuries, rendering it a potential hazard [63]. This, in turn, impairs industry productivity and may result in diminished output. This paper aims to address a notable research gap by establishing a conceptual framework for the development of an optimal design for lower-limb exoskeletons tailored for industrial use. Additionally, this paper provides a critical review of design optimisation objectives for lower-limb exoskeletons, with the specific goal of enhancing ergonomic requirements for industrial workers. Besides, the authors identified challenges encountered by industrial designers and engineers in aligning lower-limb exoskeletons with the requirements of Industrial Revolution 5.0. Furthermore, this paper presents essential design considerations pertaining to lower-limb exoskeletons. The significance of this work lies in its contribution to informing policymakers about safety factors and mechanical design considerations, which are crucial for the development of effective lower-limb exoskeletons.

Table 2 Published review papers on design optimisation and the research gap

Application of lower-limb exoskeleton	References	Functionality and Reliability	Manufacturing Process	Cost	Energy Efficiency	Weight and size	Durability
General	[47]	√	-	-	√	√	-
	[48]	√	-	√	√	√	√
	[49]	-	-	-	-	-	-
	[50]	√	√	√	-	√	√
	[51]	√	-	-	-	√	-
	[52]	√	-	-	-	√	-
	[53]	√	-	-	√	√	-
	[54]	√	-	-	-	-	-
	[55]	√	-	-	-	-	-
Medical	[56]	√	-	-	-	-	-
	[57]	-	√	√	-	√	-
	[58]	√	-	√	-	√	-
	[59]	√	-	√	√	√	-
Industry		-	-	-	-	-	-

*Green highlight indicates the research gap

2.0 DESIGN OPTIMISATION OBJECTIVES FOR LOWER-LIMB EXOSKELETON

The goal of design optimization is to achieve the targets set by designers for developing and enhancing a product.The goal of design optimisation might change from project to project and is directly related to the final use of the product. Following an extensive review of the relevant literature [47–59], the objective that can be established for a lower-limb exoskeletons are as follows: functionality and reliability; manufacturability and cost; weight and size; energy efficiency; durability; and weight and size.

2.1 Functionality and Reliability

The term "functionality" encompasses a product's or prototype's intended performance across a wide range of capabilities and functions. According to the Oxford Dictionary, engineering functionality is defined as the purpose for which something is designed or expected to perform[64], while engineering reliability is defined as the quality of being trustworthy to fulfill desired purposes[65]. Both definitions are relevant to engineering. Functionality collectively refers to the capabilities and functions that a product or prototype is designed to fulfill. Reliability, on the other hand, pertains to the effectiveness of a product or design, encompassing its trustworthiness and ability to meet specific requirements and performance standards. Functionality is a crucial aspect of the engineering design process as it directly influences both the effectiveness and dependability of a product. Designers of lower-limb exoskeletons face an additional responsibility beyond meeting mandatory safety, performance, or environmental regulations. They must also consider the comprehensive spectrum of functionality required to meet the user's needs.

Before beginning the process of design optimisation with functionality and reliability as its objective, the functional requirements of the design or product must be determined. These functional requirements can differ and vary for the lower-limb exoskeleton. During this step, it is also necessary to determine the activity or process for which the design or product was developed. Other than that. It is also crucial to determine the obstacles that must be overcome in order to complete these duties. One of the most typical functional requirements for the lower-limb exoskeleton is to reduce the metabolic cost. The term "metabolic cost" refers to the amount of energy that must be expended by the body in order to reach its goal [66]. Researchers have used a wide array of methodologies to achieve these objectives[47-48], [50–56], [58-59]. Many recent studies that have been published on optimizing the exoskeleton's functionality and reliability pay special attention to the characteristics reducing metabolic cost increase the functionality and reliability of the lower-limb exoskeleton.

The relationship between the user and the exoskeleton can be conceptualized as the interection between the two entities. When the user and the exoskeleton have a positive interaction, it will lead to harmonious communication between the two. An example of these interactions are the kinematic compatibility of the exoskeleton and the communication method between the user, and the exoskeleton. In more recent times, effort has been concentrated on the topic of improving the interaction between the user and the computer for the lower-limb exoskeletons [67–69]. Other than increasing the interaction between the user and the lower-limb exoskeleton, human performance augmentation can be consider as improving the functionality of the lower-limb exoskeleton. Human performance augmentation is improving human capabilities, skills, and productivity. The purpose is to equip people with the skills necessary to perform their tasks in a manner that is both more efficient and effective. According to report from Singla [70], the functionality of an exoskeleton has been improved by effectively creating optimal torque in order to provide physical aid. Aside from that, Beil [71] have built the structure of the exoskeleton so that it has the capability to attach the motor and the actuator in order to provide human performance augmentation and maximize the functionality of the lower-limb exoskeletons. Furthermore, improving the gait movement of the exoskeleton can also increase the functionality of the lower-limb exoskeleton. The pattern of walking that human limb movements make is referred to as gait movement. In order to correct an incorrect gait movement, a patient might require medical treatment, physical therapy, or even technology like an exoskeleton. Several studies have been published on the subject of increasing the exoskeleton's gait movement in order to enhance the usefulness of the exoskeleton [72–76]. The increase of gait movement is not an essential requirement for the industrial sector. Yet, a high degree of freedom is essential so as not to limit the user's gait movement when carrying out a task. Doing so will have an effect on the performance of the user while they are working and will put the user's safety at a lower priority. Also, users in the industrial sector may benefit from human performance enhancement, particularly when the work at hand requires lifting, pushing, or tugging. When it comes to user interaction, having a harmonious interaction between the user and the exoskeleton can be beneficial to the user because it will boost the user's performance on the tasks they are assigned.

2.2 Manufacturability and Cost

The term "manufacturability" refers to a design's ability to be efficiently and effectively produced using available resources, cutting-edge technology, and manufacturing processes. When designing lower-limb exoskeletons, it is crucial to consider both cost and manufacturability. A product that is either excessively expensive or challenging to assemble may face reduced profitability or may become impractical to produce. Optimising for manufacturability involves considering various factors such as materials, tooling, assembly, and the manufacturing process. A well-designed framework not only minimizes waste and maximizes efficiency but also reduces manufacturing costs, leading to cost savings. To align with the 17 sustainability goals set by the United Nations [1], manufacturability and cost must both be optimized, taking into account environmental and economic aspects. The design of lower-limb exoskeletons heavily relies on the selection of appropriate manufacturing materials, and the development of these exoskeletons is closely tied to production methods [57]. Recent studies, summarized in Table 4, have employed diverse approaches to enhance the manufacturability and affordability of lower-limb exoskeletons. The majority of these studies highlight the following approaches:

One of the method that can help improve the manufacturability of a lower-limb exoskeletons is the process of selecting the material that will be used for the lower-limb exoskeletons. To make sure the exoskeleton is profitable and achieves the desired levels of sustainability, it is essential to choose the materials that offer the highest possible level of performance in terms of factors such as cost, durability, environment, usage, and the ability to be manufactured. In the industrial sector, it is crucial to emphasize the use of a material that is both very durable and capable of adjusting to the rigorous environment that characterizes industrial settings.

Table 4 Method to optimize the manufacturability and cost of lower-limb exoskeletons

No.	Method to optimize the manufacturability and cost	References
1	Using simulation	[23]
2	Optimum framework	[71–73]
3	Reducing cost	[77–82]
4	Reduce the difficulty to fabricate complex designs by using 3D printing	[83–86]

Incorporating a contemporary aesthetic into the overall design of the exoskeleton is crucial, as it plays a vital role in fostering user acceptance within the community. Nonetheless, if the design is too complicated, it might be difficult to fabricate. The conventional methods have trouble machining complicated designs because of the complexity of the shapes involved.

Complex geometries and structures can be manufactured by a rapid prototyping method known as 3D printing, which is a type of additive manufacturing (AM). The use of 3D printing as a production method for intricate lower-limb exoskeleton designs has been increasingly popular in recent years [83–86]. This method uses the data from 3D models as its source. The procedure entails printing successive layers of material on top of the previously printed layers. The printing of various metallic and non-metallic materials is possible using this technology. Also, the weight of the product can be reduced with 3D printing, and the production time can be reduced compared to traditional methods when designing something that is intricate, modern, or appealing. This procedure is, in theory, the best method to use when working on complicated designs. Yet, the expense of manufacturing it in huge quantities might be rather significant. For large production, conventional manufacturing techniques such as computer numerical control, also known as CNC, as well as metal casting, and extrusion may be the best option. Using both approaches that is, the traditional approach as well as the 3D printing approach, is the strategy that will yield the best results. In general, it is recommended to use a traditional approach for a part with a simple design, while the technique of 3D printing should be used for a part with a complex design. In a later step, these components can be put together with the help of joining techniques such as metal welding and thermal bonding.

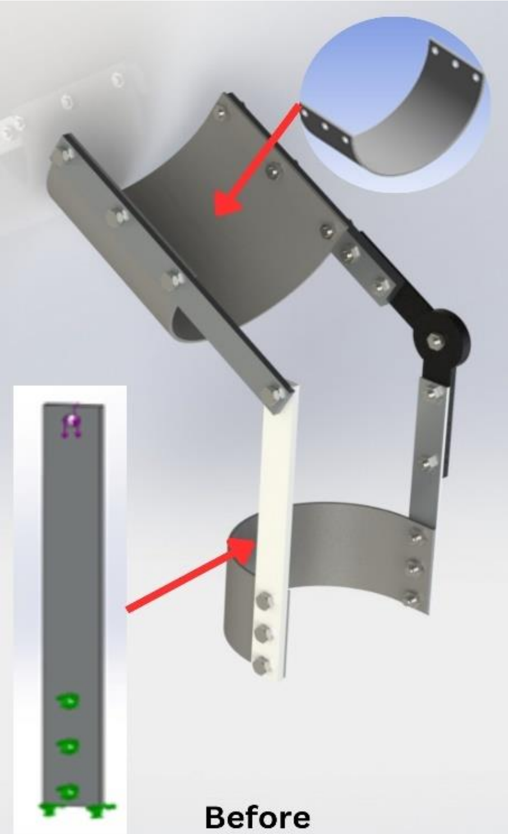
The use of simulation is one of the approaches that may be utilized to determine which process is the most suited and the most cost-effective. For the purpose of simulating the manufacturing process, numerous simulation programmes such as ANSYS [87], Solidworks [88], CATIA [89], and Autodesk Inventor [90] are available for use. This piece of software may estimate the amount of time required to make an item, as well as the flow of production and the process.Futhermore, these software able to identify appropriate tools and parameters to employ and potential flaws. By performing simulations, it is possible to lower the likelihood of catastrophic events as well as the cost of potential damage and faults that may occur during manufacturing.

2.3 Weight and Size

Weight and size are of the utmost importance in the design of the lower-limb exoskeletons. Exoskeletons should not be excessively large and cumbersome, and they should be designed to be compatible with the clothing and footwear worn by the user. In order to fulfil the requirements of the user, the exoskeleton needs to be lightweight [91]. A lightweight lower-limb exoskeleton is essential because it is a wearable device, and a heavy lower-limb exoskeleton will put additional strain on the legs, which can lead to musculoskeletal diseases. Several attempts have been made to optimize the design with regard to size and weight as the primary focus. There are a few different approaches that can be taken in order to accomplish the goal of making the lower-limb exoskeletons lighter and smaller. The first one is choosing the appropriate materials. In the research presented in [69], [92–94], the material selection was used to either replace or employ an appropriate material that satisfies the requirement that had been imposed. While choosing materials for a lower-limb exoskeletons designed for industrial application, qualities such as hardness and stiffness of the materials must be prioritised. Two further factors that need to be taken into consideration are the machinability and corrosion resistance of the materials. These specific characteristics of the material must be able to resist load with a minimum amount of distortion. When a load is applied to a material that cannot sustain this, the material will deform, and the user's safety will be compromised as a result. Titanium and carbon fibre have the best strength-to-weight ratio of any material, which makes them the ideal material for decreasing the weight of the lower-limb exoskeletons while yet maintaining its strength. Yet, because of the high price of these materials, utilising them is not the best option. When compared to titanium and carbon fibre, aluminium alloy is superior as a replacement for these materials due to its lower cost.

Other than that, methods to reduce the weight of the lower-limb exoskeleton is to minimise component count. Hu [95] have decreased the number of components that make up the lower-limb exoskeleton in order to lessen the overall weight of the lower-limb exoskeletons. Nevertheless, because certain components have been taken away, this technique needs to find a way to make up for the functionality that has been lost.

Last but not least, there have been a number of studies that have used topology optimisation to find ways to lessen the burden that the lower-limb exoskeletons place on the user [28], [96–98]. Topology optimisation is an advanced method of structural design that can provide the optimal structure through a reasonable material distribution that satisfies the required load conditions, performance, and constraints [99]. Topology optimisation can provide the optimal structure through these means. The aim of topology optimisations is to cut down on the amount of unnecessary material by removing it. In addition, topology optimisation was able to cut down on the amount of material used and the amount of waste produced. Using the computer-aided design (CAD) program Solidworks, Figure 2 shows an example of topology optimisation for a structure component. This structure component is the frame and the calf support of a lower-limb exoskeletons. When optimising in order to reduce weight and size, the load that is applied to the lower-limb exoskeletons must not be overlooked, and it must be kept within the safety factor that has been defined. It is essential to do this in order to guarantee that the lower-limb exoskeletons is capable of supporting the load that is being applied, such as the user's body weight.



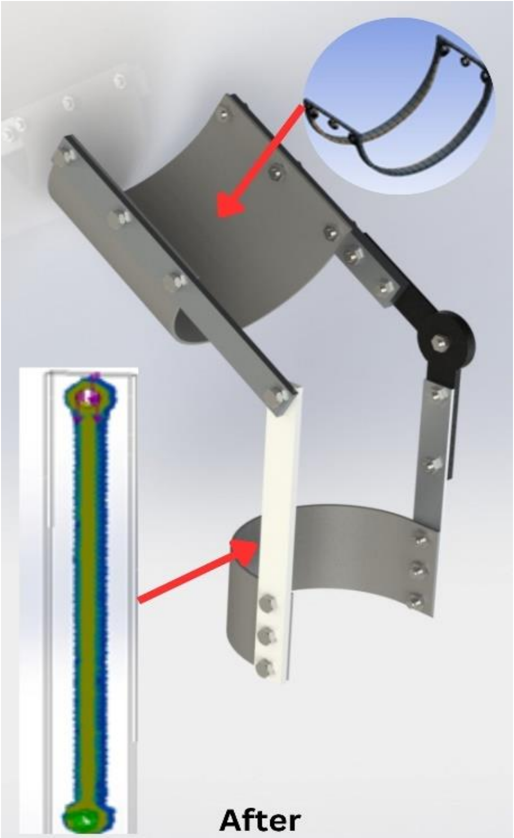


Figure 2 Topology optimisation of a lower-limb exoskeleton structure

2.4 Material Selection, Process Selection and Eco-audit

From the design to actual prototype fabrication of exoskeletons, the material selection for the exoskeleton is relatively important for manufacturing the exoskeleton. Not to mention, the process selection is also important for the exoskeleton in order reducing the waste and production cost while improving various properties such as weight to frame strength distribution, durability, aesthetic appearance and even prevent allergic reaction to certain material. Combined with computer aided engineering software, it will produce near-realistic simulation to prevent precedented failures and catastrophic failures in using the exoskeleton. There are cases that using material selection methods to select suitable material to be used in Waist-Supportive Exoskeleton. Using Ashby charts, the author select Al 7075 or carbon fiber composite as the best candidate material for their exoskeleton using material performance index based on the load applied on the exoskeleton frame[100]. The study could be refined to define the specification of the exoskeleton using ANSYS Granta Edupack such as carbon footprint, energy, and CO2 emission in manufacturing, moving and using the exoskeleton [101]. Furthermore, as for process selection, it can be divided into three main process which is Shaping, Joining and Finishing that can be further analyze such as in term of batch production quantity, initial capital, overhead cost, tooling cost that can be break down for each component [102].

2.5 Energy Efficiency

Energy efficiency is the ability of a system or product to use less energy to perform the same task or achieve the same level of output. A product or system is considered to have good energy efficiency when able to deliver the desired result while minimizing energy waste. In most cases, optimising a design for energy efficiency is only relevant when the system being designed is an active exoskeleton equipped with a power source to supply energy to its components. A passive exoskeleton would not apply to design optimization with energy efficiency for its objective because a passive exoskeleton only uses mechanical components and parts. The lower-limb exoskeletons can benefit from energy efficiency in a number of ways, including reduced power usage, cost savings, and a positive impact on the environment. There have been multiple studies conducted to maximise the energy efficiency of the lower-limb exoskeleton in order to reduce the amount of power that is consumed and to increase the amount of time that it can be used [71], [103]–[106].

2.6 Durability

Durability is the ability to last for a long time without breaking or getting weaker [107]. The capacity of a product or material to withstand wear, pressure, or damage over time and with continued usage is the definition of durability in lower-limb exoskeletons. When referring to a product or material, something is considered to be durable if it is able to keep its original function, look, and quality over an extended length of time. Given that the resistance to wear and tear significantly influences the lifespan of lower-limb exoskeletons, the manufacturing industry places considerable emphasis on ensuring their durability. A lower-durability exoskeleton may incur high maintenance costs, necessitating frequent replacement. The constant wear and tear on the lower-limb exoskeletons contribute to their relatively short lifespan. In addition to this, a lower-limb exoskeletons with a high level of durability can have a positive effect on the environment by reducing the amount of carbon footprint produced. There have been a number of studies [108]–[113] that have looked into the possibility of strengthening the durability of the actuator, motor, and other components in order to lengthen the lifetime of the lower-limb exoskeletons.

3.0 DISCUSSION

3.1 Challenges and Issues

It can be difficult to perfect the design of lower-limb exoskeletons while simultaneously meeting the requirements of the user. Fabricating a complicated design is one of the hurdles that must be overcome in order to optimized the lower-limb exoskeletons. A more contemporary modern appearance is required for the lower-limb exoskeletons if it is to gain wider user acceptance in society. People will be encouraged to wear the lower-limb. A contemporary and stylish appearance, will make the design more challenging to produce and complicated, which will drive up the cost. Moreover, developing a harmonious relationship between humans, exoskeletons, and computers can be an extremely difficult task. It is difficult to develop harmonic interaction between human body parts because of the intricate flexibility of human body parts, which have a lot of freedom. As a computer is included into the active exoskeleton, the interface will become far more complicated. There may be complications that arise when the processing time between humans, computers, and exoskeletons is shortened. As a consequence of this, the command sent from the human to the exoskeleton will be sent with a tiny delay, which will result in the breakdown of the harmonious interaction. The stability of the control system in the lower-limb exoskeletons is one of the issues that must be overcome in order to achieve optimal performance from the lower-limb exoskeletons. If it is not possible to achieve stability in the control system, the motion that is produced by the motor and the actuator will be jerky rather than smooth.

3.2 Future Direction and Research Opportunities

Industrial Revolution 4.0 is currently in the process of shifting to Industry Revolution 5.0, which is transitioning from an emphasis on economic value to one that places greater emphasis on societal value [114]. The collaborative efforts of humans and machines are given a greater priority in the fifth stage of the Industrial Revolution (also known as Industrial Revolution 5.0). Prioritizing the 17 sustainable development objectives [1] for future research is essential to ensuring that people and the earth can live in harmony and prosperity in the years to come. Figure 3 illustrates the shifts in focus and trend that have occurred in lower-limb exoskeletons design. The development of the exoskeleton has shifted its emphasis from the environment and sustainability to a user-centered design as it has moved from IR4.0 to IR5.0. This shift comes about as a result of the addition of AI technologies, the internet of things (IoT), and automation. The development of the lower-limb exoskeletons in IR 5.0 takes into consideration the societal value of the community by adhering to the 17 sustainability development goals [1]. Although the development of AI, the internet of things (IoT), and automation are still the primary areas of emphasis, these areas of development now take into account the societal value of the community.

One of the strategies that may be used to attain sustainability is the design of a modular structure that is capable of enduring for an extended length of time. Research from H. Koch and K. Mombaur [72], [115] have established a way to lessen the carbon footprint that is left behind during the manufacturing process of the lower-limb exoskeletons. This is one of the measures that needs to be taken in order to transition to an environment that is more sustainable. Not only has technology such as AI and the internet of things (IOT), but it has also revolutionised other fields, such as industry. It is impossible for an exoskeleton to take advantage of certain technologies if they are not embedded on the lower-limb exoskeletons. These technologies can benefit an exoskeleton based on the needs of the exoskeleton. As a result of this change, there will be opportunities to enhance the interaction between humans, computers, and exoskeletons. The data transfer and processing that occurs between humans, computers, and exoskeletons has the potential to become more efficient, which will facilitate a more seamless transition. Last but not least, the fact that the design of the lower-limb exoskeletons needed to be both visually pleasing and up to date increased the complexity of the design, which in turn increased the difficulty of producing the device. The cost of 3D printing is decreasing as the technology advances alongside other developments. 3D printing allows for the use of a wider variety of materials, and the resulting object can have a more intricate pattern. Further research on the production of lower-limb exoskeletons through the use of 3D printing could be beneficial to the fabrication of more complicated designs for the lower-limb exoskeletons.

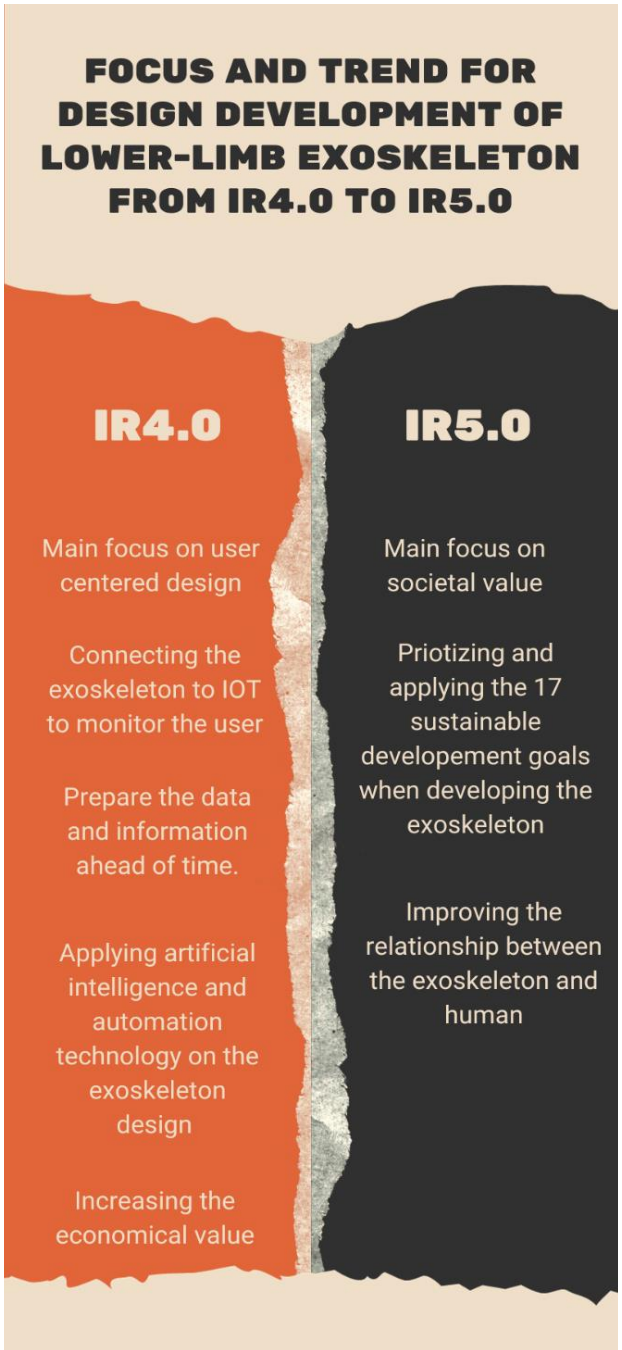


Figure 3 Focus and trend for design development of lower-limb exoskeleton from IR4.0 to IR5.0

3.3 Conceptual Framework of Design Optimisation Objectives for Aligning Lower-limb Exoskeletons to IR 5.0 and Sustainability Development Goals

There is a correlation between the sustainable development goals and the concept of industrial revolution 5.0. The distinction is in the comprehensive scope of the Sustainable Development Goals (SDGs), encompassing a wide range of dimensions pertaining to life and society. In contrast, the concept of Industrial Revolution 5.0 primarily addresses the dynamics between humans and machines, emphasising a human-centric approach that emphasises enhanced resilience and a heightened emphasis on sustainability. The alignment of a lower-limb exoskeleton's development with the industry's requirements, as well as its ability to adapt to the Industrial Revolution 5.0 and the sustainable development goals established by the United Nations, is crucial. Incorporating these elements into the design of a lower-limb exoskeleton is of utmost significance to guarantee the long-term viability and seamless integration of the human-exoskeleton relationship. Figure 4 depicts the conceptual framework outlining the design and development of a lower-limb exoskeleton that is in accordance with the principles of Industrial Revolution 5.0 (IR 5.0), Sustainable Development Goals (SDGs), and user requirements, with potential applications in many industries.

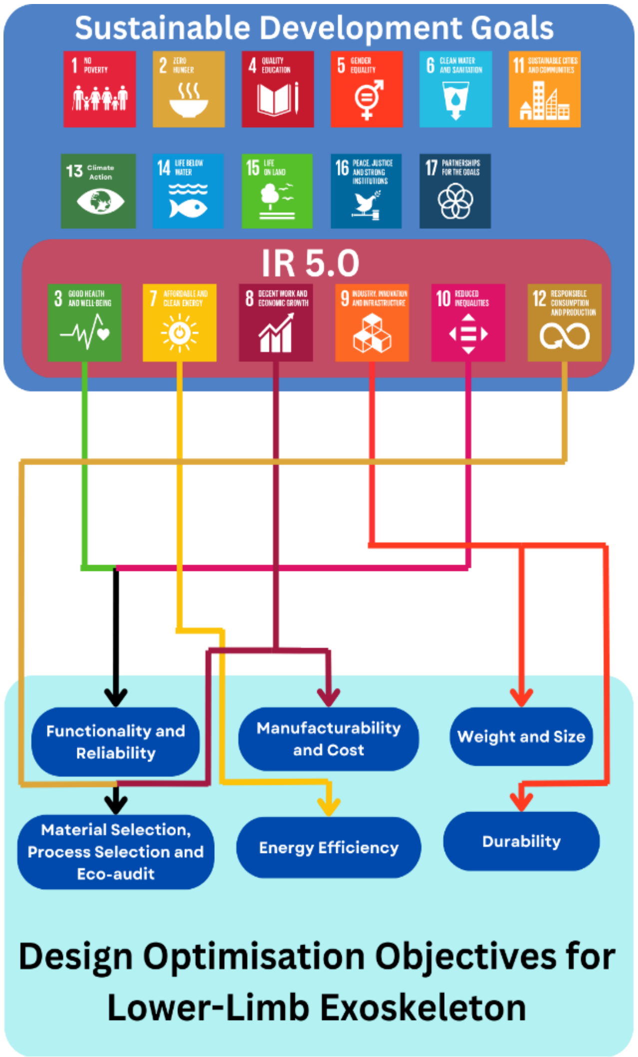


Figure 4 Conceptual framework for developing lower-limb exoskeletons

4.0 CONCLUSION

With the lower-limb exoskeletons, design optimisation is able to unearth the optimal design by utilising a selective strategy that takes into account the presence of constraints, all the while working towards the accomplishment of a single or many goals. Not only has the user of the lower-limb exoskeletons benefited from the functionalities and dependability, as well as the manufacturability and cost, the weight and size, the energy efficiency, and the durability that have been critically discussed above, but the manufacturer and the environment have also benefited from these characteristics. To achieve the 17 sustainable development goals in terms of the economy, environment, health and well-being, industry, and innovation, a conceptual framework that takes into consideration the goals indicated above for design optimisation is necessary. In conclusion, the application of these goals to enhance the performance of the lower-limb exoskeletons will be beneficial to applying these goals to enhance the performance of the lower-limb exoskeletons will benefit society and lead to an improved way of life.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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