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Critical Factors Influencing User Experience on Passive Exoskeleton Application: A Review

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Abstract: Wearable assistive devices such as passive exoskeleton have been recognized as one of the effective solutions to assist people in industrial work, rehabilitation, elderly care, military and sports. The design and development of a passive exoskeleton that emphasizes on satisfying and fulfilling users' requirements and users' experience are essential to ensure the device remains competitive in the global market. A good user experience of using an exoskeleton stimulates users' satisfaction, as contemporary users are not only considering basic functional features but also fascinated by perception values such as aesthetics and enjoyment. The main purpose of this article is to review the critical factors that are influencing user experience before, during and after utilizing a passive exoskeleton. The authors had searched relevant articles from academic databases such as Google Scholar, Scopus and Web of Science as well as free Google search for the publication period from 2001 to 2021. Several search keywords were used such as 'passive exoskeleton + user experience', 'passive exoskeleton + industry', 'passive exoskeleton + rehabilitation', 'passive exoskeleton + military', 'passive exoskeleton + sports', 'passive exoskeleton + sit-stand', and passive exoskeleton + walking'. This online search found that a total of 236 articles related to the application of passive exoskeleton in the area of industry, rehabilitation, military and sports. Out of this, 81 articles were identified as significant references and examined thoroughly to prepare the essence of this paper. Based on these articles, the authors revealed that the engineering design, usability, flexibility, safety and ergonomics, aesthetics, accessibility, purchase cost, after-sales service and sustainability are the critical factors that are influencing user experience when employing passive exoskeleton.

Keywords: Wearable assistive device, engineering design, exoskeleton fabrication, materials selection, user acceptance

1. Introduction

In the era of Industrial Revolution 4.0, the application of wearable assistive devices such as exoskeleton become popular to ease people in performing daily living activities and industrial operations. It is vital to ensure every product or device developed for human use must consider users' or customers' needs and expectations to remain competitive in the market [1]. In the advancement of robotics technology, human-use products should not only provide functionality and usability but also should be fashionable and fascinating [2]. As the number of workers in industrial workforce with musculoskeletal system problems increased [3], consequently the attention toward exoskeleton technologies as a human

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assistive devices are also growing. An exoskeleton can be defined as a wearable device designed with external mechanical structure that can enhance human physical strength or provide extra support to the human body [4]. Exoskeleton technology can be classified into two types, active and passive. An active exoskeleton comprises one or more actuators that augment the human's power and helps in actuating the human joints. These actuators may be electric motors, hydraulic actuators, pneumatic muscles, or other types [5]. On the other hand, a passive exoskeleton system does not require any actuator and external power source or battery.

The passive exoskeleton is designed and developed through a fully mechanical mechanism such as springs, cables, pulleys and dampers [6]. A simple example is a worker lifting a box manually from the floor to a shelf to demonstrate how a passive exoskeleton operates. The exoskeleton stores energy when the worker bends forward. While in the bending posture, the energy stored by the exoskeleton supports the worker to maintain that posture or to erect the body during the lifting process. Classification of exoskeletons can be distinguished by the supported body region(s): lower body exoskeletons - providing support to lower extremities, upper body exoskeletons - providing support to upper limbs, and full-body exoskeletons - giving support to the whole body [7], [8]. Usually, exoskeletons are used to support the following activities, but not limited to manual lifting, walking, sitting and standing, carrying heavy loads and rehabilitation. Fig. 1 shows three prototypes of passive lower limb exoskeleton developed by authors to support body in seated and standing tasks. The prototypes shown in Fig. 1 (a) and Fig. 1 (b) are two-leg exoskeletons, meanwhile the single leg exoskeleton is illustrated in Fig. 1 (c). A two-leg exoskeleton has two lower limb supports which are attached to user's legs or ankles. With a greater number of supports, the two-leg exoskeleton is heavier than the single leg with a same material.

(a) (b) (c)

Fig. 1 - Three prototypes of passive sit-stand exoskeleton developed by authors

One of the significant achievements in developing a passive exoskeleton is compliance with the users' requirements or fulfills the users' expectations. To achieve this, a designer or developer must contemplate the user experience - how an individual feels when utilizing the exoskeleton. The importance of user experience is to ensure the developed exoskeleton performs its function strictly follows the user requirements, easy to use, consistent performance and sense of satisfaction. According to the International Standard ISO 9241-210 [9], the user experience is defined as the *"person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service. It includes user's perceptions and responses that result from the use and/or anticipated use of a system, product or service" and where "users' perceptions and responses include the users' emotions, beliefs, preferences, perceptions, comfort, behaviors, and accomplishments that occur before, during and after use"*. A latest study pointed that user experience is one of important elements in product design to enhance users' acceptance level towards the developed products [10]. Recent studies on the SPEXOR passive exoskeleton revealed that the exoskeleton provides substantial support for rehabilitation of patients with low back pain and industrial workers who are performing manual lifting tasks. This exoskeleton does not hinder functional movements and well accepted by the users [11], [12], [13].

Based on two decades of published review articles in the exoskeleton (Table 1), the authors realized that a clear lack of detail information on the critical factors which is influencing user experience, and this was largely overlooked by previous reviews. A considerable amount of published literature was focusing on the algorithm, mechanical design and application of the exoskeletons. However, far too little attention has been paid to review the critical factors that can influence users' experience and satisfaction. This article aimed to examine the critical factors that influence user experience before, during and after utilizing a passive exoskeleton. Information presented in this article will certainly guide designers and developers to develop passive exoskeletons that satisfy users' requirements.

2. Methodology

The authors had searched relevant research articles from electronic databases such as Google Scholar, Scopus and Web of Science (n = 327), taking into account the date of publication from 2001 until present. Relevant articles were also searched from Google search (n = 86). The following keywords were typed throughout the search: 'passive exoskeleton + user experience', 'passive exoskeleton + industry', 'passive exoskeleton + rehabilitation', 'passive exoskeleton + military', 'passive exoskeleton + sports', 'passive exoskeleton + sit-stand', and passive exoskeleton +

walking'. Then the full texts of journal articles consisted of original research and review articles written in English were downloaded. Additionally, the authors examined the reference lists of all articles to collect additional relevant articles.

Table 1 - Published review articles and focuses of the review related to lower limb exoskeleton

Published articles	Focuses of review	Passive exoskeleton	Active exoskeleton
[14]	Identify the methods, metrics and experimental procedures to assess robotic-assisted motor skills of lower limb exoskeletons for gait assistance and rehabilitation.	√	√
[15]	The mechanical design and controls of rehabilitation exoskeleton.	√	√
[16]	The mechanical design such as actuation, structure, and interface attachment.	√	√
[17]	The problems and future trends of lower limb exoskeleton.	√	√
[18]	Risk management and regulations of exoskeletons that enable users to ambulate over-ground.		√
[19]	Users' perspectives on exoskeleton for rehabilitation of individuals with neurological impairment.		√
[20]	The current development of lower limb exoskeletons for walking assistance.	√	√
[21]	Compliant joint mechanisms to ensure user's safety and comfort.	√	√
[22]	Application of wearable lower limb exoskeletons for rehabilitation of patients with gait disorders.		√
[23]	Control algorithms, mechanical architecture, sensors, control systems and validation with users of exoskeleton for people with lower-limb muscular weakness and disabilities.		√
[24]	The selection of actuators, power supply, mechanical design, interfaces and control method of rehabilitation exoskeleton.		√
[25]	The mechanical design, actuation systems and controls of exoskeletons for rehabilitation therapy.		√
[26]	Motion recognition algorithms, walking conditions adaptation, gait phase identification and walking patterns generation of active and semi-active ankle exoskeleton for rehabilitation purposes.	√	√
[27]	Application of lower limb exoskeletons for therapy activities and rehabilitation treatment of stroke patients.		√

The questions explored through this literature review are:

1) What are the requirements from the users regarding passive exoskeleton?
2) What are the factors influencing the user experience on passive exoskeleton?
3) What are the applications of passive exoskeleton?

After screening articles with similar or overlapping contents, there were 236 articles remained. The title of the articles were then examined and comprehend. Next, the abstracts of 193 articles were read. Any article with unclear objectives and results in the abstract was removed (n = 62). The subsequent step was to read the full text of the 131 articles. In order to justify the relevancy of studies, these articles will be contained within the final review if they meet the following inclusion criteria: reporting findings on passive exoskeleton studies with regards to engineering design, usability, flexibility, safety and ergonomics, aesthetics, accessibility, purchase cost, after-sales service and sustainability. The journal name, authors, and institution were not considered as criteria to minimize bias in the selection of the articles. Finally, 81 articles were selected and reviewed to extract information on engineering design, usability, flexibility, safety and ergonomics, aesthetics, accessibility, purchase cost, after-sales service and sustainability. Additional information on the passive exoskeleton (e.g. manufacturer, price and materials properties) were searched from the relevant websites, standards and handbooks. Fig. 2 provides a flow chart of processes involved in collecting, filtering and reviewing the articles.

3. Results

This section provides three main outcomes from the review namely the users' requirements on passive exoskeleton design, factors influencing the user experience and passive exoskeleton applications.

3.1 Users Requirements on Passive Exoskeleton

Users can be categorized into two categories, primary and secondary users. Primary users of the exoskeleton represent the end-users such as industrial workers, spinal cord injury patients and soldiers who are directly wearing the exoskeleton. The secondary users include healthcare professionals and caregivers who support primary users. Investigating user's requirements is a crucial step in the early development of passive exoskeleton to determine their needs and desires with regards to design of the device. Table 2 tabulates seven main requirements from the users' perspective with regards to the design of exoskeleton. Later, these requirements can be classified into two major groups, technical requirements and subjective requirements. The technical requirements represent the basic purpose or functional features of the exoskeleton such as assisting or supporting daily activities or physical limitations of users, usability of the exoskeleton such as easy to use, maneuver and don/ doff, the strength of the exoskeleton, ergonomics (e.g., comfort) and low maintenance. Meanwhile, the subjective requirements stimulate the perception of users that drive to user acceptance. This includes aesthetics and purchase cost.

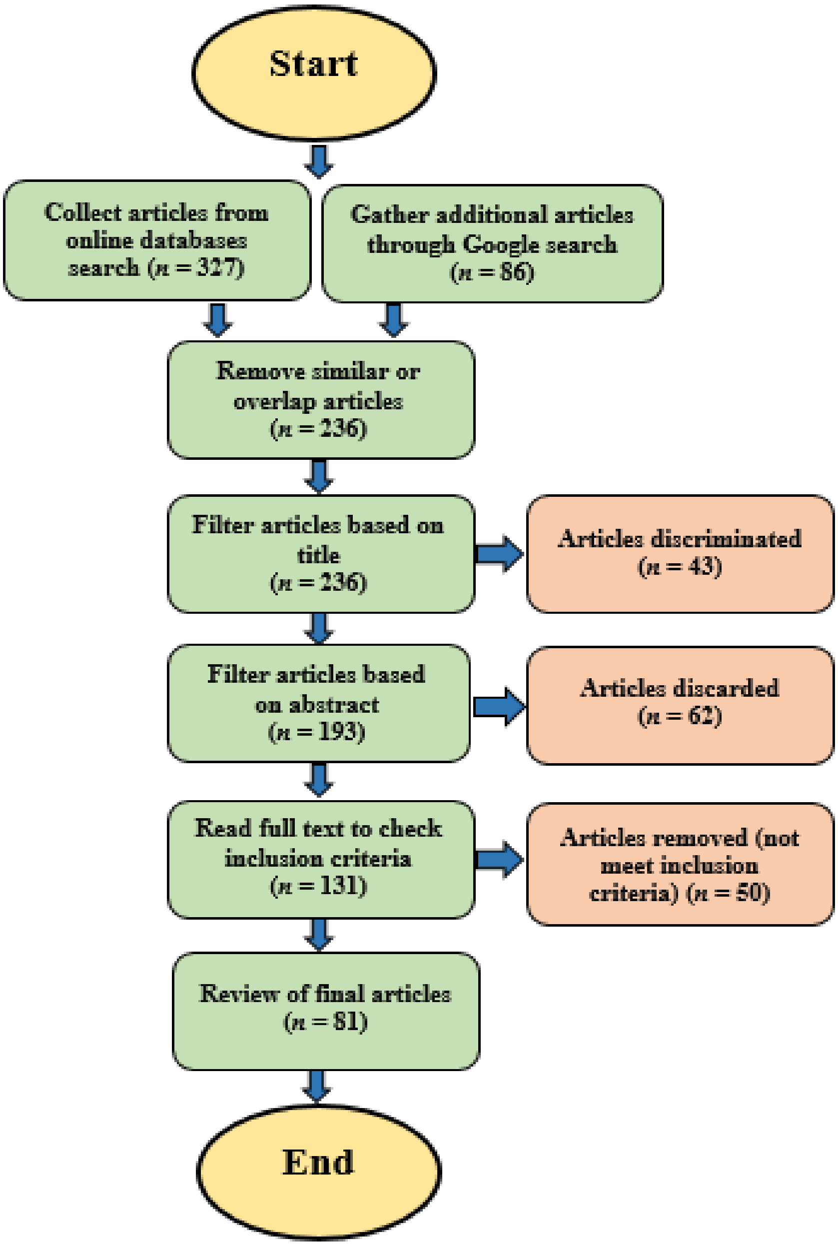

Fig. 2 - Flow of process in collecting, filtering and reviewing the articles

Table 2 - User's requirements on the exoskeleton design

Requirements	Description	References
Benefits and functions	The exoskeleton improves mobility or walking quality, provide adaptable support for lower body joints, provide help and support with bending activities, hands-free solution.	[28]
Practicability	Easy to maneuver, easy to store, lightweight, robust and easy to don and doff.	
Training and support	Easy to learn and easy to use.	
Design and aesthetics	Has a good appearance, not too bulky and compatible with clothing and footwear.	
Costs	Affordable or purchases at a low cost.	
Comfort	The exoskeleton does not cause discomfort or pain.	[29]
Durability	The longevity of the exoskeleton.	
Low maintenance	Minimal maintenance.	

3.2 Factors Influencing User Experience on Passive Exoskeleton

The following sections describe nine critical factors that influencing user experience before, during and after utilizing a passive exoskeleton.

3.2.1 Engineering Design

The engineering design is a core element in the development of passive exoskeleton. Table 3 provides the details of the engineering design factors. Based on Table 3, the authors summarized that the engineering design factors focus on the technical aspects such as materials, structure design and specifications to achieve the fundamental purpose of the exoskeleton. For example, the application of body balance and stability principles [30] in the design of exoskeleton are mandatory to ensure the safety of users or wearers when performing their daily living activities such as standing and walking. Balance is the ability of the body to maintain equilibrium (either in static or dynamic) in relation to gravity. Meanwhile, stability is the ability of the body to resist external force and acceleration during static or moving. In the design and development of an exoskeleton, these two principles are considered necessary as they influence the body posture, muscle strength, coordination and control of users when using the exoskeleton.

Table 3 - Engineering design factors in exoskeleton development

Engineering design factors	Research findings	Sources
Materials	Commonly aluminum alloy is used to fabricate the exoskeleton links. For the exoskeleton frame, titanium is ideal in terms of strength and lightweight. An alternative material is a fiber-reinforced plastic (e.g. as carbon fiber) which is lighter than aluminum.	[31]
	Pure aluminum and its alloy 6061-T6 was used to fabricate a flexible wearable chair.	[32]
	Smart materials for sensing and actuation of soft lower-limb exoskeleton to help individuals with mobility deficiencies.	[33]
	Aluminum with a density of 2.70 g/cm^3 and Young's modulus of 68.9 GPa was used to design a lower limb exoskeleton for enabling elderly citizens to walk.	[34]
	Carbon-fiber composite was used to construct the leg's structure of exoskeleton. This material is significantly reducing the overall weight of the exoskeleton.	[35]
	ATLAS – a lower limbs exoskeleton, made of duraluminium and stainless steel at the joints.	[36]
	Mild steel was used to design a chair-less chair for prolonged standing tasks.	[37]
	Aluminum Alloy 6082 (T6) was applied in designing a chairless chair for people exposed to stand for long hours.	[38]
Lightweight	Flexible wearable chair has weights 3 kg for industrial workers in assembly lines.	[32]

	Weight less than 8 kg of a lower limb exoskeleton for lower limb rehabilitation training.	[39]
	The weight of the actuation module is 1.4 kg in the construction of TWIICE, a lower limb exoskeleton for people suffering from complete paraplegia.	[35]
	ATLAS – a lower limb exoskeleton weighed 6.5 kg providing stability for walking.	[36]
Dimension and size (bulkiness avoidance)	At a point over 70 mm of a length away from the leg in the lateral plane of the ATLAS exoskeleton, its actuator causes a hindrance when the users in sitting, walking and passing through a door.	[40]
	Links of the lower limb exoskeleton for sit-to-stand and stand-to-sit movements were fabricated with dimension of 31 cm for the thigh, 34 cm for the shank, 64 cm for the back and 20 cm for the foot. The exoskeleton is capable of supporting users' weight during different movement stages.	[41]
Strength/ Endurance	The strength of the KUEX-R exoskeleton structure was analyzed using stress analysis. The exoskeleton can withstand the load of 1000N in a static condition.	[42]
	Mechanical stress analysis on Chairless Chair Exoskeleton found that the maximum deflection of the upper link of the exoskeleton is 0.2 mm. The stresses developed in the structure are lower than the ultimate tensile strength of the material used (aluminum). Hence, the exoskeleton is considered safe for users.	[43]
	Exoskeleton Based Hydraulic Support was fabricated and tested. It is safe under fluctuating and static loads of 116 kg.	[44]
	A load of 100 N (~ 100 kg) vertical downward force was applied to a lower limb exoskeleton. The maximum stress is 15MPa, less than the yield strength of the material used (62.05 MPa).	[45]
	The maximum stress of a wearable chair part is 317.9 MPa, less than the yield strength of the material used, iron (811 MPa).	[46]
Equilibrium and stability	An exoskeleton called as flexible wearable chair satisfies equilibrium and stability criteria, the summation of force and moment are zero.	[32]
	Testing on the lower body exoskeleton prototype (EXO) found that wearing EXO resulted in greater short term postural instability compared to without wearing EXO. The load held by the user (participant) significantly influenced this result.	[47]
Pressure distribution	Analysis of pressure distribution on the contact area between the user's body and exoskeleton. For example, a peak pressure (50 kPa) on the front pad of LOPES lower limb exoskeleton [48].	[49]
	An exoskeleton for lifting and lowering tasks is worn by the user like a backpack. The contact pressure is highest on the trunk (91.7 kPa-93.8 kPa) and least on shoulders (47.6 kPa-51.7 kPa).	[50]
Spring stiffness	Spring stiffness in the range between 5 – 12 N/mm is recommended for a passive ankle exoskeleton.	[51]
	The stiffness of the series spring decreases when the walking speed increases from 0.8 to 1.2 m/s. However, the stiffness of parallel spring is proportionate to the walking speed.	[52]
	The maximum amount of energy that can be stored by a fixed stiffness spring is circumscribed by user geometry.	[53]
	The undeformed length of spring is zero. When spring length is zero, the spring force is zero.	[54]

3.2.2 Usability

Usability can be linked-to simplicity, functionality and experience in using the exoskeleton. The ISO DIS 9241-11 [55] defines usability as "the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use". The word usability also refers to “usefulness” and “ease of use” that drive users’ satisfaction and frequency of use of a product [56]. In the design and development of an exoskeleton, feedbacks or constructive comments on usability that are voiced by the users are important to motivate designers or developers to develop exoskeletons that function as intended. This includes less cognitive and physical efforts (low complexity) in donning and doffing of the exoskeleton, compatibility of the exoskeleton with the footwear and clothing, functionality achieved while using the exoskeleton, maintain a safe body posture and flexible body movement while operating the exoskeleton, and feeling of comfort and confidence while using the exoskeleton. Additionally, the designers or developers may evaluate the perceived value, whether the user enjoyed or frustrated when using the exoskeleton.

Some examples of usability concerns rose by the users related to exoskeleton application at the workplace include:

- *The usability of lower limb exoskeletons is higher if they are designed with adjustable and fit to the user body* [57].
- *The use of passive exoskeleton “Chairless Chair” during screwing and assembly work is perceived as beneficial* [58].
- *An exoskeleton may not be usable with other personal protective equipment such as powered respirators and fall-arrest harnesses* [59].
- *Application of a wearable back-support exoskeleton during the static assembly task is moderately helpful* [60].
- *The Levitate Technology passive exoskeleton is useful to perform precision tasks such as sealing operation* [61].

The existing exoskeletons, either passive or active mechanisms are far away from the natural human body in terms of movement precision and motor controls. There are abundant research and development in human assistive technology nowadays; however, the exoskeletons still have limitation to function as the natural ones. This includes the limited number of degrees of freedom of the exoskeleton plus with the structure is heavy, huge and not flexible [62]. Other challenges that need to address include user movements such as from sitting to standing as well as ascending and descending staircases [63], [64]. A well-accepted design of a passive lower limb exoskeleton centers upon a research and development process that closely integrates the end-users and exoskeleton’s designers and developers. The design process emphasizes the usability and acceptance of the exoskeleton which is driven by the users' requirements rather than the technological possibilities. This method is known as the user-centered or anthropocentric approach [65], [66], [67], [68]. Qualitative and quantitative approaches can be applied to study the usability of a passive exoskeleton. The selection of the approach is subjected to usability attributes that need to be assessed, such as ease of use, user’s satisfaction, task and time performances [69]. Table 4 tabulates several tools used by previous studies to assess the usability of exoskeletons.

Table 4 - Tools used in the usability study of passive exoskeleton

Tools	Application examples	Sources
Usability Metric for User Experience [70]	Usability study of a passive low-back support exoskeleton among workers in automotive manufacturing workplaces.	[71]
System Usability Scale [72], [73]	Study the usability of an industrial exoskeleton for dynamic lifting and lowering manual handling tasks.	[74]
	To compare the usability aspects of the lower limb exoskeleton for paraplegic users.	[75], [76]
	Usability study of exoskeleton arm to support activities of daily life.	[77]
Questionnaire	Usability of a rehabilitation device for lower limb. Obtains general feedbacks on effectiveness, efficiency, attractiveness and satisfaction. In addition, feedbacks on device-specific parts such as footrest and footplate were captured.	[78]
	Study of preparation and ease of use of exoskeleton for activities of daily living.	[79]
Interview	Usability study of a lower-limb exoskeleton (crutches) for paraplegic individuals.	[80]
Interview with video show	Usability of lower limb exoskeletons for individuals with spinal cord injury.	[81]

3.2.3 Flexibility

Flexibility feature in the passive exoskeleton design means the exoskeleton provides multi-functions, as opposed to an exoskeleton with a specialized design. However, an exoskeleton with a flexible design is more complex than the specialized design. Figure 3 illustrates an example of flexible design of a passive sit-stand exoskeleton. The exoskeleton provides several functions that increase its flexibility. It can support gravitational force from the body and provides sitting and standing positions to the user. Additionally, it allows users to walk, ascent and descent a staircase. These functions (sit, stand, walk, ascent and descent) if combined together are considered as low usability and less efficient than an exoskeleton with a specialized function (e.g. standing only). On the other hand, when the exoskeleton just provides one function only (e.g. standing), it gains the usability. Here there is a clear flexibility-usability trade-off that exists. This is due to the designer of the exoskeleton trying to apply flexibility to satisfy a broader set of users' requirements. However, the designer needs to understand the trade-off and to make an intelligent decision aligned with the priorities of the exoskeleton design. Users might be able to tolerate with a minor usability issue if they found the flexibility feature is more appealing. Examples of flexible design of lower limb exoskeletons that support multiple functions are standing, walking, ascending and descending [82]; walking and sitting [83]; sitting, walking and swinging [84] and dorsiflexion and plantarflexion of ankle joint, eversion and inversion of ankle motion [85].

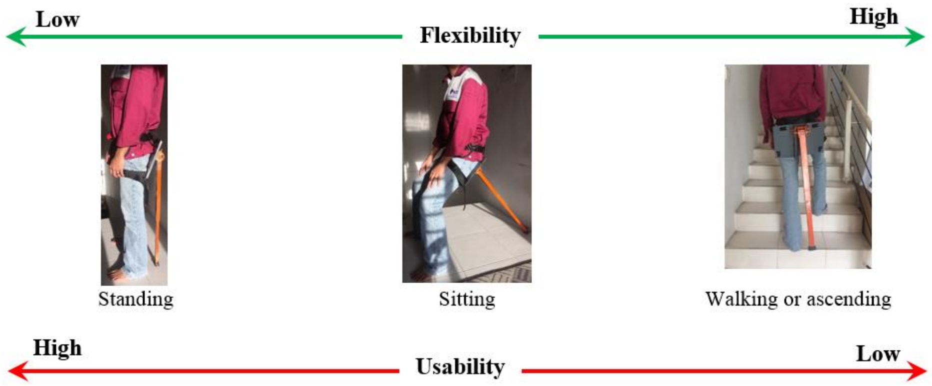

Fig. 3 - Flexibility versus usability of a sit-stand exoskeleton

3.2.4 Safety and Ergonomics

Compliance with the safety requirement is mandatory in the design of a passive lower limb exoskeleton. The safety aspect should be taken into account in the design and development stages so that it would not trigger a hazard (e.g. entanglement) and cause serious injuries to the users. Furthermore, the exoskeleton should be easily and safely removable when the users are facing hazards such as pinch, trip, and snag [57]. A study suggested that an exoskeleton should be designed compactly and form-fitting so that it can be utilized without compromising with users' safety and practicality during their daily activities [82]. To design the exoskeleton mechanism, compliant actuators have been recommended to ensure a safe interaction between the exoskeleton and the users [86].

In addition to the safety aspect, an ergonomically designed passive lower limb exoskeleton has a potential in improving user experience. The ISO 9241-210 [9] defines ergonomics as *'scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance'.* The goal of ergonomics is to ensure the developed products (e.g. exoskeleton) match or fit to human physical (e.g. joint range of motion), physiological (e.g. muscle activity) and psychological or cognitive (feeling and perception). Ergonomics assessment tools such as electromyography, ergo spirometry, heart rate monitor, energy consumption, postural balance, near-infrared spectroscopy and Borg rating of perceived exertion can be used to study the effects of exoskeleton design on the physical, physiological and psychological of the user [87], [88], [89], [90], [91].

Specifically, ergonomics studies on contact pressure or stress between the human body and the exoskeleton as well as the compatibility between the anthropometry or size of user and dimension of the exoskeleton, should be taken into account. Anthropometry is depending on age, gender, ethnic group, countries and occupations [92]. Due to this fact, exoskeletons which are developed based on male users would not match to females because in general, the male is bigger than female. Furthermore, an exoskeleton made in the USA might not be suitable for Asian. This incompatibility issue can be resolved if the exoskeletons are designed and fabricated for multi-size and adjustable to accommodate large target users. The exoskeleton's designer or manufacturer needs to consider and apply ergonomics requirements in their products such as anthropometry of human limbs, muscle strength and biomechanics of joint to ensure matching and fitness of the exoskeleton to users' body [93]. A study pointed out that matching of the exoskeleton and user can be classified into two requirements: structure matching, and driven matching which involving joint and muscle biomechanics [62]. It was found in the literature, passive industrial exoskeletons are successfully supporting the lower back in lifting activities, but the exoskeletons caused negative effects such as increasing leg muscle activity, high levels of discomfort and muscle deconditioning [8]. Table 5 shows some benefits and concerns on safety and ergonomics with regards to the application of passive exoskeleton.

Table 5 - Benefits and concerns on safety and ergonomics with regards to the passive exoskeleton

Exoskeleton	Benefits and concerns on safety and ergonomics	Sources
Leg support exoskeleton (legX)	The legX was significantly reduced the muscle activity of the rectus femoris (knee region) and may minimize pain and discomfort associated with squatted tasks.	[94]
Passive exoskeleton "Chairless Chair"	The exoskeleton was perceived as useful for screwing and assembly tasks; however, it received negative ratings with regard to posture and feeling of safety.	[58]
Lower limb exoskeleton	Based on a comparative study of wearing the exoskeleton and without the exoskeleton, the users (participants) reported low physical demands. Still, high mental demands during performing sustained attention to response test in static semi squatting posture.	[95]
Passive exoskeleton "Chairless Chair"	A vital parameter is the percentage of the user's weight that can be supported by the exoskeleton. If the percentage is high, the user's lower limbs will experience less strain. Follows the 70:30 ratio (70 is the percentage of body weight supported by the exoskeleton and 30 is the percentage of body weight sustained by the user's feet)	[96]
Passive exoskeleton	The exoskeleton reduced the discomfort and muscle activity in the lower back by 35 – 38 %. However, it led to discomfort in the chest region.	[97]
Modular lower limb exoskeleton	The size of the exoskeleton should be adjustable to fit different sizes of users. The recommended size range is between the 5th percentile female to 95th percentile male.	[98]
Modular lower limb exoskeleton	The exoskeleton frame allows length adjustment to fit different users' heights, ranging from 1.50 m to 1.90 m.	[99]
Passive trunk exoskeleton	The exoskeleton reduced 17 % of metabolic costs during lifting, but the metabolic costs increased by up to 17 % during walking.	[100]
Passive upper-limb exoskeletons	The application of the exoskeleton reduced 34 % and 18 % of deltoid and trapezius muscles activities respectively. This in turn minimizes discomfort and fatigue in these muscles.	[101]
Passive 'back pack' exoskeleton	The exoskeleton reduced up to 15 % and 5 % of erector spinae and biceps femoris muscle activities respectively. However, contact pressure was highest on the trunk (91.7 kPa - 93.8 kPa).	[50]
Passive upper body exoskeleton for static overhead tasks	The exoskeleton reduced muscle activity on the trunk and lower body, and capable of minimizing localized discomfort.	[74]
Upper limb exoskeleton	The exoskeleton reduced shoulder flexor muscle activity. However, it increased the antagonist muscle activity, postural strain and heart rate.	[89]
Passive Spexo back support exoskeleton	The range of motion of lateral bending decreased by 10% (13°) compared to not wearing an exoskeleton.	[102]
Exoskeletal vest	The exoskeleton decreased 45% of the shoulder muscle activity levels. However, the exoskeleton had minimal influences on the trip or slip related fall risks during level walking.	[103], [104]

3.2.5 Aesthetics

Aesthetics reflects visual attributes of the exoskeleton including appearance, stylistic design, unique shape, color, weight, size, materials and textures that are perceptually meeting the user experience [105], [106], [107]. Aesthetics is an important factor to consider in the design of exoskeleton because it was recognized as one of the most valuable attributes to attract and stimulate the end-users [28], [108], [109], [110]. Earlier studies have shown aesthetically designed product is capable of acquiring users' attention to purchase the product [111], [112]. Within the literature there are examples of aesthetics consideration in the exoskeleton design such as the drives are compact and lightweight [113], and small sized actuators so that not to bother the user [114]. An aesthetically designed exoskeleton makes it attractive and pleasant to the users. A study pointed out that increasing the aesthetic value in the rehabilitation exoskeleton can make patients feel relax and happy to use the device [115].

3.2.6 Accessibility

The expansion of user experience concept in product design and development encourages people to focus on the accessibility of the exoskeleton. Accessibility is about how to ease a user can acquire the exoskeleton (and its replacement parts, if necessary) in the market when he or she needs it. The ISO 9241-171 [116] defines the accessibility as usability of a product, service, environment or facility by people with the widest range of capabilities. It is well known that the exoskeletons are actively developed and manufactured in the USA, Canada, Switzerland, Japan and Korea. A recent review by Voilqué et al. [117] found that the origin of exoskeletons is almost balanced between Europe (37 %), America (34 %) and Asia (29 %). However, not all countries are exoskeleton's manufacturers. This situation can limit the accessibility of the device in the domestic markets. Fortunately, this limitation can be resolved by introducing regional distributors and e-commerce applications for wider accessibility. E-commerce or commonly referred to as online shopping allows users to directly buy a exoskeleton from a manufacturer or a regional distributor through the internet. E-commerce can be enormously helpful to individuals with disabilities, such as mobility impairment and spinal cord injury patients. Additionally, online shopping enables users to access technical information on the exoskeleton and reviews from other users. Table 6 tabulates some commercially available passive and active exoskeletons.

Table 6 - Commercially available exoskeleton [118], [119], [94]

Application	Exoskeleton	Exoskeleton Type
Industrial	Passive Flexible Constructional Exoskeleton Strong Hands PHEL Passive Human Exoskeleton of Lower-limbs Passive Harness Exoskeleton Suit-SOFT Passive Harness Exoskeleton Suit PLESPassive Lower-limb Exoskeleton Passive Upper-limb Carrier Exosuit (PUCE) Noonee, leg support exoskeleton (LegX) FORTIS passive exoskeleton	Passive
	AHESActive Harness Exoskeleton BAE, Boston Dynamics, Equipois, Ekso Bionics Lockheed Martin, Strong arm, B-Temia	Active
Medical and rehabilitation	Ekso Bionics, Myomo, ReWalk, Parker, Rex, Bionics, Cyberdyne, B-Temia, Hocoma Lokomat, ExoAtlet	Active
Military	Barbarian King – Exo military, Harvard Wyss, Ekso Bionics, Otherlab, Boston Dynamics Lockheed Martin, B-Temia, Mawashi	Active
Leisure	LEX Wearable Bionic Chair	Passive

3.2.7 Purchase Cost

Purchase cost can be considered as one of the most influential determinants in users' decision making before buying the exoskeletons. Recent surveys in users' needs on exoskeleton have shown that purchase cost was the second important to users [29], [120]. In an earlier study, users emphasized that cost is one of the potential concerns in deciding to adopt assistive technology [121]. A reputable study in marketing and psychology revealed that users' satisfaction is positively correlated with the reasonable price of the products [122]. The passive exoskeleton has been associated with a high acceptance rate from the end-users due to its low purchase cost [51]. Varghese et al. [44] estimated that the total cost of developing a passive exoskeleton (Exoskeleton Based Hydraulic Support) is USD 126.84, which is considered an affordable price to the public and industrial workers. With a reasonable purchase cost, the passive exoskeletons have a greater chance for successful commercialization and wider use in public and industries. On the other hand, the active exoskeleton is hypothesized as an expensive device due to its high development costs such as expensive frame materials (e.g. Titanium), high-end actuators, active suspension control mechanisms [123], electric motors such as brushless DC flat motor [124], batteries, controllers, gearboxes, service and maintenance. Gardner et al. [125] in a review on commercially available medical active exoskeletons, revealed that the lowest cost is $70,000 which is considered too high for personal use. Studies pointed out that the high cost is considered as one of the key obstacles that are discouraging end-users or patients from having an active exoskeleton [126], [127]. Table 7 provides the estimated price of commercially available wearable passive exoskeletons.

Table 7 - Price of wearable passive lower limb exoskeleton

Exoskeleton	Estimated price	Source
Noonee Chairless Chair	$4,421	[128]
LEX Wearable Bionic Chair	$189	[129]
Ofrees Wearable Chair	$140	[130]
FORTIS	$24,750	[131]
FORTIS Tool Arm	$7,149	
Laevo V2	$2,500	
FLX and V22 ErgoSkeleton	$300-$700	
BackX	$4,000	
ShoulderX	$4,000	
LegX	$6,000	

3.2.8 After-sales Service

After-sales service means to provide supports such as follow up contact, complaints handling, replacement parts and upgrades provided by the manufacturers or sellers after a user has purchased the exoskeleton. One of importance of after-sales service is that a user will be able to replace or upgrade any part of the exoskeleton in the case of malfunction or damage occurs. Additionally, after-sales service includes maintenance, service and repairs [132]. Rahman et al. [133] highlighted that after-sales service (maintenance) is one of the key factors influencing the user acceptance. Basically, a passive exoskeleton uses a spring mechanism or mechanical actuators to activate the exoskeleton. On the contrary, to active exoskeleton, passive exoskeleton requires less maintenance. Moreover, it does not requires an external power supply, such as a battery for providing electric power. This gives an advantage to passive exoskeleton for less maintenance and ease of repair [134], [135]. Example of passive exoskeletons that require less maintenance include the C-Brace which was developed to assist patients with partial lower limb paralysis [136] and the Limpact exoskeleton for stroke rehabilitation [137].

3.2.9 Sustainability

Among the many definitions of sustainable development, the most frequently quoted definition is from The Brundtland report which defines sustainability as *"the development that fulfills the needs of the present without compromising the capacity of forthcoming generations to fulfill their own requirements"* [138]. The USA commerce department asserts sustainability as 'the making of products from the processes that curtail negative influence on the environment, preserve energy and natural reserves, which is economically sound and safe for all'. This description highlights the importance of products and manufacturing processes in creating sustainable manufacturing goals that safeguard the environment, economy and humanity, which can also be referred to as the planet, profit, and people [139]. Users' behaviors have been influenced by the economic transformation, development of technologies and the damaging environmental issues, and the changing societal needs. Users are growing concern about safeguarding the environment and adopting sustainability as a chosen lifestyle. These user requirements have shifted towards sustainable product and service design [140]. Intrinsic motivation due to environmental climate change and health worries are the renowned reasons, which lead the users to embrace eco-friendly products and services preference. Users are required to change their consumption behavior to reduce the impact on the environment and this influences their preferences for a more eco-friendly and sustainable product [141], [142]. Users are hyper-aware and conscious of sustainability-related issues and this resulted in them changing their shopping list and changing their purchases to products that are shown to be environmentally sound [143]. As per the reports, since 2009, nearly 85 % of consumers in the United States bought a wide range of green products such as fluorescent lamps, natural cleaning products, energy-efficient electronics and appliances, rechargeable batteries, and organic and natural foods (Natural Marketing Institute, 2009 LOHAS Consumer Trends Database as cited in [143]. This establishment shows that manufacturers considering long-term strategies ought to comply with eco-friendliness and sustainability as a factor when pursuing an advantage in today’s marketplace [144]. The majority of firms are concerned about environmental protection and are developing strategies to cope with it [145], [146].

In the context of exoskeleton design, sustainability is the design of exoskeleton with minimum impact on environment, good growth to the economy and positive advantages to the society. The industries must work towards manufacturing products that could be reused, recycled and disposed of safely. In addition, they must strive for minimizing the strong use of materials, energy, and emissions. Companies could and should use the eco-design tools for designers and manufacturers. This will ensure they are aware of the impact of manufacturing processes, and materials used and the life cycle impact of the manufactured goods on the environment. A variety of sustainability design tools is available ranging from simple to intricate, quantitative to qualitative tools. A few of these tools make intensive computations to measure sustainability and provide methods to enhance the sustainability aspect of the product. The simple tools are used to perform primary qualitative analysis from which suggestions are presented to improve the design of the product [147]. Some authors categorized the sustainability and eco-design tools into groups and classifications. Baumann et al. [148] grouped the eco-design tools into six groups: frameworks, checklists and guidelines, rating and ranking approaches, software and expert systems, analytical tools, and organizing methods (Baumann et al., 2002). In contrast, Knight & Jenkins [149] created three classifications: guidelines, checklists and analytical tools (Knight, 2009). Kim and Moon [150] classify them into four groups: guidelines/standards, checklists, comparative tools and analytical methods. Devanathan et al. [151] categorized 30 eco-design tools into three groups: life cycle assessment based tools, checklist-based tools, and quality function deployment based tools. These are all sustainability and eco-design tools that can be used to assess and improvise the exoskeleton design to be more eco-friendly and green.

The one minimal approach is to do it manually using the life cycle impact assessment tool, Eco-indicator 99 to calculate the scores for materials and processes used in making the exoskeletons for product improvement [152]. The Eco-Indicator is categorized into three sections: production of raw materials (e.g., stainless steel), processing, and manufacture (e.g., machining); transportation of product (e.g., shipping), energy in use (e.g., electricity and water), and consumables in use (e.g., spare parts); disposal. All these sections have associated values and scores which can be used to improve the design. Eco-indicator 99 is both a science-based impact assessment method for Life Cycle Analysis (LCA) and a practical eco-design method. It presents a means to quantify a variety of environmental impacts and reveals the final result in a single score. The details of the above tools stated in this section can be found in the respective references, as the discussion of those tools is beyond the scope of this paper. With the use of these tools, manufacturers will ensure that they satisfy user demand for sustainable and eco-friendly products. At the same time, this will improvise user experience while using the exoskeleton. The users know that they are behaving in a sustainable manner while purchasing and using the eco-friendly exoskeletons.

3.3 Application of Passive Exoskeleton

This study observed that passive exoskeletons are widely applied in the industrial settings, healthcare and rehabilitation, military, and sports and recreation. Table 8 presents the application of passive lower limbs exoskeleton in these areas. Based on Table 8, the authors realized that the passive exoskeletons are mainly applied by users from two areas: 1) industry (e.g. workers from manufacturing and construction industries), 2) medical and rehabilitation (e.g. spinal cord injury patients and individual with a physical impairment such as older persons). In manufacturing industry, the exoskeletons are specifically applied to assist workers to perform manual operations such as automotive parts assembly task, lifting and carrying heavy loads, and welding and grinding processes. Meanwhile, for the purposes of medical and rehabilitation, the users utilized the exoskeletons to assist movement of patients such as motor recovery during early stage of rehabilitation, sit-to-stand exercises, and walking.

Table 8 - Application of passive lower limbs exoskeleton in various areas

Application Area	Exoskeleton and Specific Application	Sources
Industrial	Noonee chairless chair – It is useful for (dis)assembling tasks in the automotive industry such as screwing, clip fitting, and cable mounting. This exoskeleton is considered as a potential device to reduce musculoskeletal risk due to prolonged standing.	[153]
	A leg support exoskeleton (LegX) was developed to assist industrial workers in performing welding, electrical panel work, grinding, sanding and concrete laying operations.	[94]
	Laevo – A back support exoskeleton was tested for manual materials handling in the automotive industry.	[71]
	Develop Chairless Chair to minimize body fatigue among industrial workers and farmers.	[154]
	A wearable lower-limb exoskeleton was developed to assist caregivers in hospitals and nursing homes for transferring the elderly between beds and wheelchairs or between wheelchairs and washrooms.	[155]
	A Personal Lift-Assist Device (PLAD) was applied by operators to perform automotive assembly tasks.	[156]
	A passive powered knee exoskeleton (PPKE) was developed to assist users in the squat lifting of objects.	[157]
	Lower limb exoskeleton for reducing forces in low back during manual materials handling activities.	[158]
	Lightweight passive lower limb exoskeleton for assisting industrial workers to carry heavy loads by supporting body posture and reducing stress in the knees.	[159]
	Several wearable exoskeleton chairs were developed to minimize stress on the leg muscles due to prolonged standing at the workplace. Examples of the exoskeleton are chairX, HUST-EC and SimpChair.	[160], [161], [162], [163], [164], [165], [166], [167], [168], [169], [170], [171]
Healthcare and rehabilitation	Portable Healthcare Chair to improve blood circulation in legs.	[172]
	Quasi-passive lower limb exoskeleton to improve motor recovery during early-stage rehabilitation.	[173]
	An exoskeleton called Human Body Posturizer was applied as rehabilitation device. It can improve accuracy, walking and posture among multiple sclerosis patients.	[174]
	Passive exoskeleton for voluntary sitting-standing posture. It allows toilet usage without transferring seating positions between the exoskeleton and toilet seat.	[175]
	Wearable exoskeleton for assisting patients in sit-to-stand exercises in rehabilitation.	[176]
	Skeleton Suit-H1 was designed to enable paralyzed people, especially hemiplegic individuals, to walk.	[177]
	Assistive lower limbs exoskeleton called MINDWALKER for assisting patients with spinal cord injury.	[178]
	Unpowered ankle exoskeleton for reducing the metabolic energy consumed in walking.	[179]
	A modular lower limb exoskeleton for assisting individuals to rehabilitate compromised lower limb movements resulting from stroke or incomplete spinal cord injury.	[180]
	Passive exoskeleton for low limbs to assist locomotion of paraplegic or quadriplegic individuals.	[181]
	Garment based exoskeleton for enhancing arm movement for children with movement impairments	[182]
	Hand exoskeleton for stroke and post-traumatic patients.	[183]
Military	Fully passive-type ankle exoskeleton was developed to assist ankle dorsiflexion/plantar flexion.	[184]
	Develop a quasi-passive exoskeleton called MIT Exoskeleton to enable soldiers to carry heavy loads.	[185]

	Lower limb exoskeleton to assist infantry soldiers in walking and carrying of loads.	[186]
	A passive lower-limb exoskeleton for reducing load carrying burden of dismounted soldiers.	[187]
Sports and recreation	A passive knee-extension exoskeleton (Breg X2K) was tested to reduce the energy cost of knee extension during cycling.	[188]
	Passive exoskeleton for easy running version IV (PEXER IV) for reducing physical load of runners.	[189]
	Elastic leg exoskeletons for hopping and running.	[190]

4. Discussion

The critical factors identified in the previous section is summarized in Fig. 4. The central notion is user experience, which is strongly influenced by nine critical factors namely engineering design, usability, flexibility, safety and ergonomics, aesthetics, accessibility, purchase cost, after-sales service and sustainability. Technically, these critical factors are a representation of voice of the users that need to be fulfilled by the exoskeleton designers to satisfy the users. To attract the users to use the passive exoskeleton, a designer needs to go and talk to the potential users of the device. There are many ways to do this such as, through questionnaire surveys or interview methods. In reality, the list of users' needs may have different priorities according to diverse group of users. It may also show a trade-off, meaning one requirement may contradict to the other requirement. This can be represented through the KANO model [191], shown in Fig. 5. Basically, the model is trying to differentiate among the attributes or features derived from the users' needs with regards to the exoskeleton design. Some attributes may give excitement to the users if they are incorporated in the exoskeleton, whereas others may make users feel indifferent. Based on Fig. 5, if the 'Basic Functional' is presented in the exoskeleton, then the users neither dissatisfied nor satisfied. On 'One Dimensional' characteristic, this attribute will cause the users to feel more satisfied as this feature is considered as value-added to the exoskeleton. The 'Exciting' characteristic will give the users feeling of enjoyment because this feature differentiates the exoskeleton and its competitors.

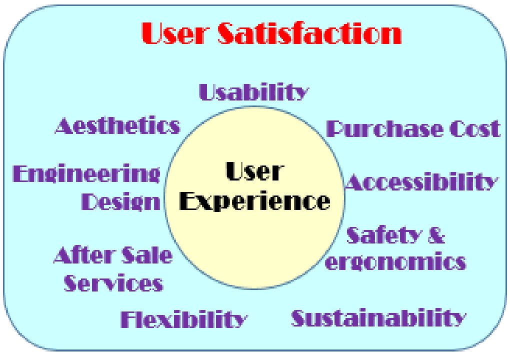

Fig. 4 - Critical factors influencing user experience of passive lower limbs exoskeleton

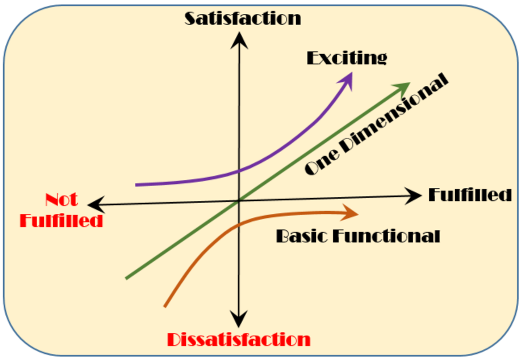

Fig. 5 - KANO model [191]

Referring to Table 9, technically the users' needs towards a passive exoskeleton can be classified as Basic Functional (B), One Dimensional (O) and Exciting (E). The basic requirements or Basic Functional (B) of the exoskeleton are lightweight, strength/ endurance, stability, safety and ergonomics, and accessibility. Meanwhile the One Dimensional (O) criteria are usability, flexibility, after-sale service and sustainability. The Exciting (E) requirements are aesthetics and purchase cost. These users' needs should be translated and incorporated in the technical or engineering design of the exoskeleton. The principal aim behind the application of exoskeletons in the industry is to minimize the risk of occupational injuries and cost for treating the injury [192]. Apparently, many studies paid attention and effort to develop wearable exoskeleton chairs for minimizing discomfort and fatigue in the lower back and leg muscles caused by prolonged standing at industrial workplaces. This is evidenced in Table 8. When workers are performing jobs in prolonged standing, static contraction occurred particularly in their back and legs, resulting in a diminished function of the muscle. Standing in a prolonged period has been identified as a vital contributor to poor occupational health such as musculoskeletal pain of the lower back and feet [193]. Many professions in the manufacturing industry such as metal stamping workers, electronics parts assembly operators, and automotive industry welders require standing in one area for an extended period. Application of a wearable exoskeleton chair (also known as sit-stand chair and chair-less chair) is one of the solutions to minimize the discomfort, muscle fatigue and stress associated with prolonged standing. The wearable exoskeleton chair allows the user to walk together with the sitting support without obstructing the workspace. Furthermore, it supports body weight and provides sitting and standing positions to the users. The pioneer commercially available wearable exoskeleton chair, called Nonee chair-less was deployed in the industry to reduce the pressure on muscles, knees and feet [194]. However, a field study conducted by Luger [153] highlighted an important concern, when and for how long workers should wear or utilize the wearable exoskeleton chair during their working hours as well as how the workers distribute the duration for standing and sitting to promote a good blood circulation? These concerns are closely related to the discomfort issue which significantly impedes the acceptance of industrial workers [153]. It was observed that the lower back is not firmly supported while using the exoskeleton in the sitting position which can lead to back discomfort. Furthermore, there is a concentrated pressure on the buttock area because the seat pan is not fully supporting the buttock and thigh. The straps which attaching the exoskeleton to the waist and thigh may cause contact pressure during prolong use. The contact pressure may cause a restricted blood circulation, specifically the blood flows from the lower leg muscles that are returning to the heart. An insufficient blood supply accelerates muscle fatigue and makes the workers feel tired and less productive. Hence the authors suggested to improve the lower back support and to minimize the contact pressure by padding the exoskeleton with soft materials to reduce stress on the buttock and thigh.

Table 9 - Categorization of users' needs using the Kano Model

Users' Needs	Kano
Lightweight	B
Strength/ endurance	B
Stability	B
Usability	O
Aesthetics	E
Flexibility	O
Safety and ergonomics	B
After sale service	O
Accessibility	B
Purchase cost	E
Sustainability	O

The selections of materials in the fabrication of passive exoskeletons are highly depending on their mechanical properties to meet engineering design requirements. Based on Table 3, most of the engineering design requires the materials to be lightweight, high strength and effective cost. However, detailed explanation on the materials in terms of their fabrication (e.g. weldability and machinability), component function, movement part and assembly are less explained. As tabulated in Table 3, materials for the main structure of exoskeletons include the mild steel, stainless steel, aluminum and its alloy, titanium, and carbon fiber reinforced plastic (CFRP). Consequently, Table 10 shows the comparison of the materials in terms of their mechanical properties. The CFRP can be suggested to have the best strength to weight ratio compare to other materials, however, the CFRP is relatively expensive and hard to fabricate in mass production compared to metallic materials. Furthermore, the CFRP usually uses fastener and adhesive joints for assembly which is susceptible to degradation, making it hard to maintain. The CFRP is also sensitive to moisture from humidity that reduces its mechanical properties [195]. The mild steel has sufficient mechanical properties, inexpensive and easy to weld and machine, hence having advantage for low maintenance cost. Nevertheless, the mild steel is weak against water especially near seashore, prone to atmospheric corrosion (approximately 6 µm/year at rural area and 43 µm/year) [196]. Hence, the mild steel requires protective coating to prevent atmospheric corrosion and mechanical loss due to corrosion. Furthermore, the density of mild steel is more than three times of aluminum and its alloy, makes it three heavier than the later. The stainless steel 304 and 316 grades are the most common stainless steel used widely from kitchenware to biomedical applications. Similar to mild steel, both stainless steels are considered three times heavier than aluminum and its alloy. It also has sufficient mechanical properties with high Young's modulus, shear modulus and excellent machinability. However, the price of both stainless steels is estimated at four to five times than mild steel [197]. The stainless steel has a good weldability; however, it is susceptible to chromium carbide precipitation at the heat affected zone (HAZ) which making it brittle [198]. In term of corrosion resistance, in rural areas with fresh water, both stainless steel 304 and 316 grades have very good corrosion resistance [199]. However, near seashore area where chloride exist, the stainless steel is prone to atmospheric pitting corrosion which can induce stress corrosion cracking. The titanium offers at least 50 % more mechanical strength compare to aluminum and its alloy with 50 % more weight. The price for titanium is at least five times higher than stainless steel, thus, the price for titanium exoskeleton is significantly expensive than the steel. The titanium has a very good corrosion resistance in both rural and near seashore area. Nevertheless, the titanium itself is hard to weld and machine, thus may increase the cost of maintenance significantly compared to steel and aluminum alloys. Having approximately a third of the steel density, the aluminum costs at least triple greater than mild steel, slightly lower than stainless steel price [200], [201]. Although the mechanical strength is approximately a third of the steel, it can be improved by using stronger design such as double walled pipe design, as applied in construction industry [202]. The welding of aluminum and its alloy, however, susceptible to hot cracking at weld [203], reduce the aluminum lifetime significantly. This can be overcome using bolts and nuts joint design instead of welding joint. The machinability of the aluminum and its alloy can be considered excellent since they have the lowest hardness compared to other materials in Table 10 [204], hence, the maintenance and the replacement of the exoskeletons are considered as low cost and easy. The 1000 series has an excellent corrosion resistance in all environment, followed by 5000 and 6000 series aluminum [204]. The 2000 and 7000 series aluminum alloys are weak against marine corrosion. Based on material's properties (Table 10) and corrosion resistance consideration, it is suggested that the aluminum 1000 series with anodized surface to be used in fabricating the main structure of exoskeletons.

Table 10 - Comparison of material's properties for exoskeletons structure

Materials	Density, ρ (g/cm^3)	Hardness (MPa)	Young's modulus, E (GPa)	Shear modulus τ, (GPa)	Weldability	Machinability
Mild steel AISI 1000 series [205]	7.80 – 7.87	863	180	72	Excellent	Excellent
Stainless steel 304 [206]	7.85 – 8.06	1700	190	74	Very good, susceptible to weak HAZ [207]	Excellent
Stainless steel 316 [208]	7.87 – 8.07	1700	190	74	Very good, susceptible to weak HAZ [207]	Excellent
Pure aluminum [203], [209]	2.70	147	68	25	Good, Susceptible to hot cracking [203]	Excellent
Aluminum alloy 1000 series [203], [210]	2.70 – 2.71	147	62 – 69	25	Good, Susceptible to hot cracking [203]	Excellent
Aluminum alloy 3000 series [203], [211]	2.71 – 2.72	284	68.9 – 71.0	25	Good, Susceptible to hot cracking [203]	Excellent
Aluminum alloy 6000 series [203], [212]	2.68 – 2.92	343	67 – 140	25.8	Good, Susceptible to hot cracking [203]	Excellent
Pure titanium [213]	4.50	588	116	43.0	Poor [214]	Poor [215]
CFRP [216]	1.15 – 2.25	1226 – 1275	2.62 – 520	1.93 – 5.60	Poor, ultrasonic welding [217]	Very poor, delamination, burrs and sub-surface failure [195]

A passive exoskeleton which is designed by considering users' requirements, engineering design specifications, and enhancing users' experience before, during and after use of the device will directly fulfill the 'quality' attributes. Quality can be defined as features that are incorporated in a product that can fulfill the user's needs and contribute to the user's satisfaction [218]. Users will be satisfied if the exoskeleton can provide substantial benefits to them. Also, they would be happy if the exoskeleton is far from all problems in terms of maintenance hassle and defects that occur during usage which sacrifice the device's reliability. Numerous studies have been carried out to explore the end-users' feedbacks on the application of exoskeleton. This includes medical-use exoskeleton to improve safety [219] and health outcomes [220], increase user satisfaction [221] and ensure usability as well as functionality [222]. Moreover, some studies have highlighted that the exoskeletons could enhance the quality of life [223], [224], [225].

5. Summary

The passive exoskeleton has shown to be a promising wearable assistive device which can help to augment physical strength of industrial workers in manual materials handling activities, improve functional capability and life quality of individuals with neurological impairment, lessen the load-carrying burden of soldiers, and reduce the energy cost of runners. These different groups of users are not only considering basic functional features of the exoskeleton but also will be fascinated by perception values such as aesthetics and enjoyment. Satisfying these requirements resulted in a good user experience that can stimulate users' satisfaction. The major findings of this review revealed that engineering design, usability, flexibility, safety and ergonomics, aesthetics, accessibility, purchase cost, after-sales service and sustainability are critical factors influencing user experience before, during and after employing a passive exoskeleton.

The engineering aspect plays a significant role as its analysis is compulsory in the design and fabrication of a passive exoskeleton to ensure the device fulfills the basic purposes such as functional and safety requirements. Engineering design focusses on the technical specifications, including the selection of materials, structural design, weight, dimension and size, strength, equilibrium and stability, force or pressure distribution and spring stiffness.

Usability refers to functionality and 'ease of use' of the passive exoskeleton. It concentrates on the interaction between the user and the device. The exoskeleton should function as intended without scarifying the user's movement and comfort in order to fulfill the usability criteria. Additionally, good usability ensures the exoskeleton is easy to don and doff, and compatible with the footwear and clothing.

Flexibility factor means a passive exoskeleton is capable of providing the broadest range of functions. For instance, a sit-stand exoskeleton supports the body weight during sitting and standing positions, without limiting the user in walking, ascending and descending staircase.

Safety ensures the exoskeleton is not causing injury to the users. The exoskeleton should be easily and safely removable when the users are facing hazards such as entanglement and fire. Ergonomics concerns on the compatibility or matching of the exoskeleton to the physical, physiological and psychological of users. A basic requirement of ergonomics considers human anatomy, anthropometry and range of motion to fit the users as well as promote a feeling of safe while wearing the exoskeleton.

Aesthetics reflects the visual appearance of the passive exoskeleton with regards to shape, colour, materials and texture that are significantly influencing users' perception. An aesthetically designed exoskeleton makes it attractive and pleasant, stimulates users to feel more relax and happy to utilize the device.

Accessibility is the availability of exoskeletons and spare parts in the markets for enabling a user to acquire the device when needed. Application of e-commerce allows wider accessibility thereby a user can directly purchase the exoskeleton from the manufacturer or distributor via the internet. This platform is convenience to users who suffered from mobility impairment and spinal cord injury.

It is well known that the purchase cost of a passive exoskeleton is lower than the active exoskeleton. With an affordable purchase cost, the passive exoskeleton could offers a good user experience and wider usage among personal users and industrial workers.

After-sales service provides supports such as follow up contact, complaints handling, replacement parts and upgrades provided by the manufacturers or sellers after a user has purchased the exoskeleton. These supports play an important role for good user experience and directly contribute to user satisfaction and user retention towards the exoskeleton.

Sustainable design is referred to an exoskeleton that is manufactured with the least implication on the environment, a significant impact on the economy and substantial benefits to the personal users and industry practitioners. The manufacturers of exoskeletons must work towards producing exoskeletons that could be reused, recycled and disposed safely. The aforementioned critical factors will certainly be helping and guiding the designers and manufacturers of passive exoskeletons to satisfy users' expectations.

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