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Wu, N. and Xie, S.Q. orcid.org/0000-0002-8082-9112 (2024) Adaptation of hand exoskeletons for occupational augmentation: A literature review. Robotics and Autonomous Systems, 174. 104618. ISSN 0921-8890

https://doi.org/10.1016/j.robot.2024.104618

Adaptation of Hand Exoskeletons for Occupational Augmentation: A Literature Review

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***Abstract*-- Limited research has been conducted on hand exoskeletons for an augmentative role. Hand and wrist exoskeletons for therapeutic purposes, however, are widely researched featuring existing technologies which can be adapted for occupational augmentation. This paper presents a literature review of upper-body exoskeleton systems researched within the past five years with a focus on the systematic comparison of augmentative or occupational design compared to other roles. Several important aspects of exoskeleton development for augmentation are identified and evaluated within this review. This includes actuation methods, which determine workspace and scalability, human-robot-interaction, thus ensuring affinity with the wearer, and use of modelling, design optimisation or generative design methods to arrive at effective solutions. This paper systematically reviews 108 upper limb exoskeleton systems and compares their design in three main aspects: The optimisation of their design, their physical features, and the data published to evaluate their effectiveness. Design optimisation in the exoskeleton field faces challenges in parameter choice, lack of integrated personalisation, complex models, computation time, and limited access to effective optimisation techniques. Although there are no perfect combinations of design features, observable trends suggest certain choices are more viable and efficient. The wide range contemporary hand exoskeleton systems indicates both potential for diverse form factors and a need for further development to converge on a concise solution like that of shoulder exoskeletons.**

1. INTRODUCTION

General labour is irreplaceable in modern society, and while there is increasing adoption of exoskeleton systems in specific industrial settings, the lack of integration and augmentation of human hands is a roadblock to proliferation. Existing industrial exoskeleton devices are found to beneficial to throughput [1] and efficiency [2], as well as to reduce the frequency of Work-Related Musculoskeletal Disorders (WMSDs) [3] [4]. These devices most often do not extend their support past the upper arm. While exoskeleton systems for the extremities (i.e., hands and wrists) also exist, their development is overwhelmingly for patient assistance and rehabilitation.

Within this review, exoskeleton systems with applicability for conversion into augmentation systems are categorised based on a list of qualities, and the findings from their development were summarised. The key features and design processes of occupational exoskeleton system design are extracted to conclude on the necessary advancements in hand exoskeleton design for general application to be viable., and the contemporary practices for an occupational exoskeleton that may be applicable.

1.1 Objectives of this review

- Determine the limitations for existing hand/wrist exoskeletons for assisting in an industrial setting.
- Define the contemporary design and implementation of related exoskeleton devices.
- Discover assistive exoskeleton features suitable for adoption for occupational application.
- Define the challenges that must be overcome for the proliferation of such a device.

The goal of this review is to explore the feasibility of a general-purpose occupational hand exoskeleton system by examining upper-body occupational designs and comparing the state-of-the-art technologies employed by upper-extremity exoskeleton. This review is distinct in terms of focus from currently available reviews which critique and categorise existing exoskeleton systems in terms of device specificity, purpose, and the aspect of the exoskeleton design reviewed. For example, a significant amount of accessible literature which reviews exoskeleton design is centred around rehabilitation [5] [6] [7] [8] [9] [10], or a general review of exoskeleton designs [11] [12] [13] [14] without a focus on comparing elements of design useful for occupational use.

2. METHOD

A systematic review method approach was taken using several online databases.

2.1 Inclusion and Exclusion Criteria

2.1.1 Inclusion Criteria:

- Focus on one or more exoskeleton devices encompassing the upper limb.
- The device must be capable of providing assistive force to the user.
- The device or the user must be able to grasp objects while it is worn.
- The device must have DoF corresponding to the biomechanical system.
- The text must be published in English.

2.1.2 Exclusion Criteria:

- The device is not wearable by someone without an impairment.
- The design is purely theoretical and has no construction or simulation.
- The paper does not contain details of the design needed for review.
- The paper is not accessible to the author.

2.2 Information Sources

Results from the last five years are used, sourced from a number of online databases, i.e. IEEExplore, ScienceDirect, PubMed, Frontiers, Wiley's Online Library, Proquest, DOAJ. Two distinct searches are done to construct the two categories of exoskeleton systems. Entries such as “hand exoskeletons” and “wrist exoskeletons” were used to search the databases for the first set of results, and “assistive” “power amplification” and “augmentation” were used to filter them. The second set of results were found using entries such as “upper limb”, then filtering for items that included the terms “occupational”, “power amplification”, “industrial” or “augmentation”, and by removing results with “rehabilitation” or “patient” in their titles and keywords. The results are tabulated as table 1.1 and table 1.2 below.

2.3 Search

Database	Search terms	Results (n)
IEEExplore	("power amplification" OR "augmentation" OR "assistive") ("hand exoskeleton" OR "wrist exoskeleton")	27
ScienceDirect	("amplification" OR "augmentation") and ("hand exoskeleton" OR "wrist exoskeleton")	48
PubMed	("power amplification" OR "augmentation" OR “assistive”) ("hand exoskeleton" OR "wrist exoskeleton")	47
Wiley’s Online Library	"hand exoskeleton" OR "wrist exoskeleton"	13
Proquest	("amplification" OR "augmentation") ("hand exoskeleton" OR "wrist exoskeleton")	86
DOAJ	"hand exoskeleton" OR "wrist exoskeleton"	58
Google Scholar	allintitle: amplification OR augmentation OR assistive "hand exoskeleton" OR "wrist exoskeleton"	19
		298
Duplicates removed		40
No full text / not published in English		1/1
Publications filtered with inclusion criteria		80
Further publications with included designs		11
Individual designs within included literature		73

Table 1.1 Search terms and number of results for hand/wrist exoskeleton systems.

Database	Search terms	Results (n)
IEEExplore	exoskeleton AND ("upper limb" OR "upper body") AND (occupational OR augmentation OR industrial) NOT ("Author Keywords":rehabilitation OR patient% OR rehabilitative)	23
ScienceDirect	((augmentation OR occupational OR industrial) ("upper limb" OR "upper body") "exoskeleton" "active") NOT (rehabilitation OR rehabilitative OR patient%)	50
PubMed	((augmentation OR occupational OR industrial) ("upper limb" OR "upper body") "exoskeleton" "active") NOT (rehabilitation[Title] OR rehabilitative[Title] OR patient*[Title])	5
Wiley’s Online Library	"((augmentation OR occupational OR industrial) AND ("upper limb" OR "upper body") AND "exoskeleton" AND "active")" anywhere and "NOT (rehabilitation OR rehabilitative OR patient%)" in Keywords and "NOT (rehabilitation OR rehabilitative OR patient%)" in Title	57
Proquest	((augmentation OR occupational OR industrial) AND ("upper limb" OR "upper body") "exoskeleton" "active") AND Subject(design) NOT (subject(rehabilitation OR rehabilitative OR patient*))	77
DOAJ	((augmentation OR occupational OR industrial) AND ("upper limb" OR "upper body") "exoskeleton" "active")	0
Google Scholar	allintitle: ((augmentation OR occupational OR industrial) AND ("upper limb" OR "upper body") "exoskeleton" "active")	2
		214
Duplicates removed		212
Publications filtered with inclusion criteria		36
Further publications with included designs		2
Individual designs within included literature		35

Table 1.2 Search terms and number of results for occupational/augmentative exoskeleton systems.

2.4 Results

Data extracted from literature is compiled into a table, followed by subsequent exploration of more novel concepts shown in the designs or the design processes. In order to organise the table, the routine features present in the systems are classified with the categories listed and explained below. The common trends within the designs are identified and those with comparatively novel features or methods are discussed in more detail. It is important to note that due to the format of these publications it is not feasible to consider features of a system omitted within the papers describing their design, either through text or clear imagery, which may influence the results.

3. DISCUSSION

In total, 108 distinct exoskeleton systems featuring technology applicable to human augmentation were selected by applying the inclusion/exclusion criteria outlined in 2.1. The designs were each classified in terms of a list of attributes: its purpose, form of actuation, transmission, sensing capabilities, degrees of freedom, personalisation features; and whether the papers published about them contain information: experimentation used to validate the device, range of motion data collected of it, and design optimisation used in its development. Within this section, it is important to note that due to the format of these publications, it is not feasible to consider features of a system omitted within the papers describing their design, method, or results, either through text or clear imagery, which may influence the content.

The purposes for which hand and wrist exoskeleton systems are developed are predominantly rehabilitation or to assist with Activities of Daily Living (ADL). Some designs are created for augmentation of individuals without a motor impairment, or for haptic feedback with interactive virtual reality. A small number of systems are developed purely for the research in the construction of hand exoskeletons or their application. To first divide the exoskeletons within the found literature, the first categorisation made was for their purpose: Assistive, Rehabilitative, Augmentative (henceforth interchangeable with occupational), Virtual Reality and Research. Of those with only one primary purpose stated, there were 30 augmentative designs, 22 rehabilitative, 21 assistive, 4 for research and 1 for interaction with virtual reality. Of the mixed-purpose devices, 24 were both described as assistive and for rehabilitation.

Within this classification, the designs are indexed within the references as: Augmentative - [15], [16], [17], [18], [19], [20], [21] [22], [23], [24] [25], [26], [27], [28], [29], [30], [31], [32], [33], [34] [35], [36], [37], [38], [39], [40]-a, [40]-b, [41], [42], [43], [44], [45], [25]. Rehabilitative - [46], [47], [48], [49], [50], [51], [52] [53], [54], [55], [56], [57], [58], [59], [60], [60], [60], [61], [62], [63], [64], [65], [66]. Assistive - [67], [68], [69] [70], [71] [72], [73], [74] [75], [76] [77], [78] [79], [80] [81], [82], [83], [84], [85], [86], [87], [88], [89], [90] [91], [92], [93], [94], [95]. Research - [96], [97], [98], [99]. VR Interactive – [100]. Multi-purpose - [101], [102], [103], [104], [105],

[106], [107] [108], [109] [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128] [129] [130], [131], [132], [133].

3.1 Design Optimisation

Design optimization is the process of using mathematical models and algorithms to identify the best design of a system or product that satisfies given performance requirements and constraints. In the context of occupational exoskeleton design, mathematical design optimization can be used to identify the best combination of exoskeleton design parameters (such as material selection, actuator placement, and joint stiffness) that will result in optimal performance, such as reducing the risk of musculoskeletal disorders and increasing the comfort and usability of the exoskeleton for the wearer.

Mathematical design optimization is important for occupational exoskeleton design for several reasons. First, occupational exoskeletons are designed to assist workers in performing physically demanding tasks, and therefore must be designed to provide optimal support and assistance while minimizing any potential negative effects on the worker's motion and exertion. It can be used to identify the optimal design parameters that will provide sufficient support and assistance while minimizing negative effects.

Second, mathematical design optimization can help designers to improve the overall efficiency and usability of occupational exoskeletons. By optimizing design parameters such as the weight and size of the exoskeleton, the power requirements for the actuation system, and the control algorithms used to operate the exoskeleton, designers can create exoskeletons that are more comfortable, easier to use, and less intrusive.

Finally, mathematical design optimization can also help to reduce the cost and time required for exoskeleton development. By identifying the optimal design parameters early in the design process, designers can reduce the need for costly and time-consuming physical prototyping and testing, which is an often employed alternative to optimisation techniques.

3.1.1 Design Optimisation of Hand Exoskeletons

In this paper [104], the elastic characteristics of the tendons of an arm exoskeleton (figure 3.1) were optimised to minimise human effort required to actuate the joint by ensuring efficient transmission and storage of energy. MATLAB was used to perform forward kinematics modelling on the human hand with dimensions taken from a 3D scan. This model was used to derive the end factor coordinates of the finger, which, in turn was used to design the exoskeleton.

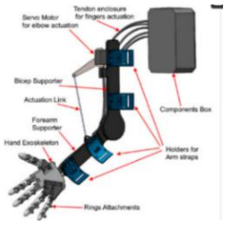

Fig 3.1 Arm and hand exoskeleton.

Fig 3.2 RELab Tenoexo.

Bützer et al. [71] presents an automatic tailoring algorithm for their hand exoskeleton system, the RELab Tenoexo (figure 3.2). It can generate new hand modules based on hand anthropometrics, kinematic relationships, and desired wrist angles. The tailoring algorithm considers the individual differences in hand geometry but must be provided with individually measured parameters. Another challenge to this method proposed is the custom-built nature of the tailored exoskeleton, resulting in a high part-count and reduced longevity due to the custom additively manufactured parts for the actuator at ~3200 grasp cycles. The work references the approach taken by Bianchi et al [134] which collects and utilises similar parameters but with 3D motion capture.

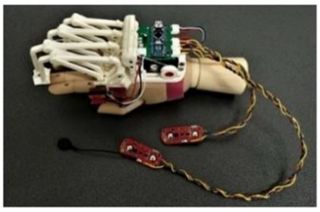

Fig 3.3 Prototype HES.

Fig 3.4 HES continued.

An optimisation-based method was proposed to adapt the hand exoskeleton designed in [134] (figure 3.3) to different users by Bianchi et al. The method used is a numerical Nelder-Mead based algorithm which is used to solve non-convex, non-linear constrained problems. The data used as parameters for this algorithm was collected through motion capture and helps to provide customised geometry for each user that fits their kinematic profile. Motion capture was achieved with 4 infrared cameras recording the 3d trajectories of markers on the hand. The paper presents the protocol used to minimise artefacts. Once the mechanism was defined, SOLIDWORKS motion simulations were used to verify the validity of the structure. This was done with success in terms of trajectory agreement between hand and exoskeleton, the data shown within the paper supports this conclusion.

Pictured in figure 3.4, [79] is a continuation of the studies carried out by Bianchi et al referenced earlier [134], the Nelder-Mead based algorithm was implemented in MATLAB and used to minimise the nonlinear multi-variable function describing the kinematics of the mechanism. The parametric CAD model was developed to interface with MATLAB and directly receives the output of the optimisation routine without manual intervention. The algorithm modified the geometrical parameters of linkages to match the kinematics of the trajectories of the rigid joints of the exoskeleton and the hand at the distal and intermediate phalanges. Notably, the use of scanning was eschewed for a 2D method of finger-kinematic-capture. Additionally, only the index finger of the user was measured in this way, with the rest of the fingers were scaled from it. This represents a more streamlined approach taken to make the design procedure more robust and potentially more accessible.

In [106], the authors describe further Principally unchanged from previous versions [134] [79] of the HES but incorporates a degree or modularity to the system with regards to the actuation system. Modularity of the actuation system is conducive to the goal of the design as a generalised solution for hand exoskeleton systems for assistive purposes and reduced the lead time to production for the updated system.

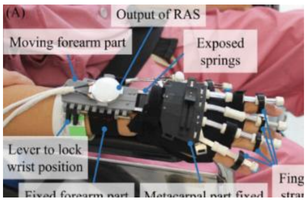

Fig 3.5 Modified PEXO exoskeleton.

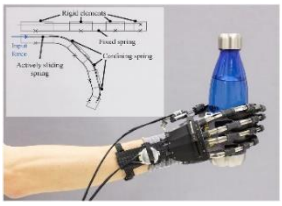

Fig 3.6 PEXO-inspired system with optimisation

The paper [73] publishes the results from an endeavour to improve the function of an exoskeleton design, the PEXO hand exoskeleton [75], by optimising properties of its actuation. The resulting exoskeleton is pictured in figure 3.5. Finite element analysis was used to solve for the optimal thickness and exposed length of the actuation spring between the metacarpal and the forearm. This was done using SOLIDWORKS Simulation and maximises the trade-off between flexibility and stiffness for force transmission. Specifically, this was done to prevent buckling of the actuation spring and limit axial force transmission. Simulations were done for all combinations of thicknesses and lengths to calculate the buckling force and the load factor, with the desired outcome being a load factor close to but greater than 1, as it indicates the spring can withstand the maximum force while minimising stiffness.

Another example of a system related to the PEXO system is shown in [89], included as figure 3.6. It is published by Dittli et al, with an alternative aspect of its design optimised compared to the example within [73], the resulting exoskeleton is shown in shown in figure 3.6. The sheathed-cable-based transmission system between the motors which create force, and the actuation system which generates bending torque for the exoskeleton fingers. Several design requirements for the system, efficiency, weight, range, size, and power, are defined quantitatively for the target of the transmission system. The optimisation was done via bench tests for each of the possible combinations of cable and sheath. The output behaviour of the remote-actuation-system was characterised to determine the control input that minimises force peaks while maintaining function.

Kinematic optimisation was used in [63] to optimise the meshing curve of an involute joint used to actuate an exoskeleton finger. The kinematic equation was derived for the finger and geometric differentiation was used to find the optimal positions for the shape of the rolling contact. The involute joint was fabricated, and motion capture was used to validate it, comparing the motion of the exoskeleton to that of the natural hand. While the output force and velocities were graphed and presented as part of the study, it is unclear whether they were considered as part of the optimisation process.

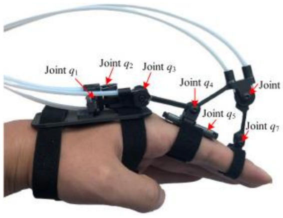

Fig 3.7 WIFRE exoskeleton

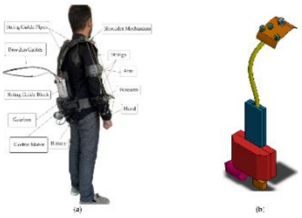

Fig 3.8 MOO Arm Exoskeleton

The WIFRE exoskeleton [88] (figure 3.7) utilised forward kinematics to optimise a 3 DoF finger exoskeleton in a manipulability framework. The objective functions are mapped to show the performance of various combination of variables. The solution was found within 10 hours using the toolbox method ‘‘gamultiobj’’ in MATLAB; "gamultiobj" is a function that implements the multi-objective genetic algorithm, which provides tools for solving optimization problems with multiple conflicting objectives.

The authors of the design described in [60] applied Genetic Algorithms for Multi-Objective Optimisation to an exposed cable arm exoskeleton, pictured in figure 3.8. The objectives chosen for the system are mass, force, and tension differential. The boundaries of the variables are stated, and a simple evolutionary algorithm is used to evolve parameters that generate minimised values. The exoskeleton is made simple and symmetrical to simplify the objective functions, only consisting of rigid links and the cable actuators.

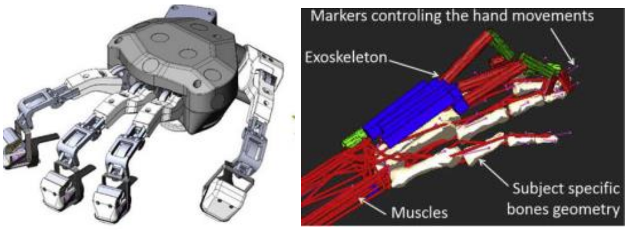

Fig 3.9 Haptic Exo with integrated musculoskeletal simulation

In [100], musculoskeletal modelling was used to validate the work of CAD software (SOLIDWORKS) based optimisation which had the goal of increasing maximum range of motion while minimising size, weight, and the space between the fingers and the exoskeleton. The optimisation was performed using a standard hand model that fits the median human adult hand as shown on the right of figure 3.9. Musculoskeletal modelling using an MRI image consisting of soft and hard tissue was also modelled and combined with motion capture to create a simulated environment in which to test the exoskeleton.

3.1.2 Design Optimisation of Upper-body Occupational Exoskeletons

Fig 3.10 Medical worker exoskeleton optimised through musculoskeletal simulation.

The healthcare worker assistive exoskeleton (figure 3.10) developed in Stuttgart by Tröster et al [23] is a thorough example of musculoskeletal-model-based development of an occupational exoskeleton optimised for a specific set of movements related to patient handling during surgical preparations. The objectives of the design were predicated upon subjective feedback provided by experienced healthcare personnel; the boundary conditions collected from the application environments, times and repetitions of the motion strategies required. The kinematics were physically simulated and captured in the laboratory through motion capture cameras. A subjective scale of perceived exertion (Borg-Scale) was also used to provide feedback through a questionnaire about the body-strain experienced by the subject. Model-based biomechanical analysis was performed on Anybody Modelling System (AMS), which analysed the rigid multi-body systems of the musculoskeletal structure and the exoskeleton. Concept exoskeletons were implemented and iteratively optimised within the modelling framework which outputs the biomechanical load values in each scenario to compare with recommended ergonomic limits and decern required modifications of design parameters. Two frameworks were used to test the exoskeleton mechanism, a static human model used to assess its range of motion and restrictions, and a dynamic multi-body simulation environment used to assess the ergonomic forces during anatomic movements, for which three surgical preparation tasks were chosen. The frameworks were used to analyse excessively strained body regions which can be targeted for exoskeleton assistance.

For the exoskeleton concept design discussed within the paper, the shoulder (GHJ) was chosen for augmentation. The optimisation process identified actuator attachment point as an important factor in the resultant forces within the targeted joint of the shoulder. The human body forces and maximum recommended hand reaction forces were used as boundary conditions to compute acceptable body loadings to keep them within acceptable levels from literature. After optimisation, the simulated results were used to determine the actuation forces required for the motions prescribed to fully realise the exoskeleton design. More considerations were made for other factors for the impact of the exoskeleton system, such as the global metabolic power of all the muscles of the user, which is significantly reduced by the device. Two other main factors observed and commented upon was pressure created between the body and the exoskeleton, and increased activity in some muscles when the exoskeleton is applied although this effect was not understood.

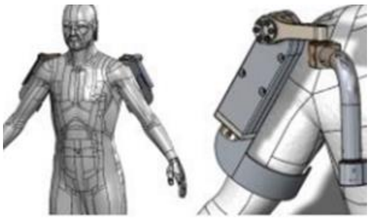

Fig 3.11 Upper-body exoskeleton optimised in Adams.

In Yin et al [29], an upper-body exoskeleton, pictured in figure 3.11, was designed and optimised for joint driving force effects using Adams, a multi-body dynamics simulation program. The two parameters optimised for within the method are spring stiffness and precompression, the objective is to minimize the work of the additional required force moment while considering constraints. One constraint discussed within the paper is the maximum precompression force that can be applied before undesired joint rotation against gravity becomes an issue. Through optimisation, the simulated energy consumption of the user was reduced by 90% while wearing the exoskeleton.

[39] The author performed design optimization for a 3-DoF prismatic-revolute-revolute (PRR) joint configuration industrial shoulder exoskeleton. The goal was to achieve a lightweight and compact design that can follow shoulder movements while limited to 2-D transverse plane motion, eliminating horizontal misalignments, and without any interferences. Several design constraints were considered. Interference with the human body was limited by defining boundary lines based on captured coordinate data. The objective functions for the optimization process included reducing misalignment by tracking the target position of the arm and minimizing frame protrusion, which corresponds to the bulkiness of the design. The objective functions were defined in terms of the root mean square error (RMSE) between the captured shoulder-motion data, and the possible joint configurations. Frame protrusion minimisation was achieved by defining a parameter which represented the maximal distance from the surface of the back plate to the protruded frame. The complete objective function combined these two objectives, with adjustable weights assigned to each function. A genetic algorithm was employed to determine the global optimal design variables due to the presence of multiple local optima. The optimisation required 36 hours of computation time with only 4 weight sets tested for the algorithm. The optimisation process was validated as part of the paper through experimentation of an unoptimized version of the exoskeleton compared to the optimised, where the motion capture showed improved agreement between the body and the exoskeleton joint orientations, and force data showing a reduction of undesired forces (those not conducive to assisting in lifts against gravity).

Two further examples of augmentation exoskeletons designed with an aspect of design optimisation were found with fewer included details. In [95], a 4 DoF active upper-limb orthosis was designed, and its geometric dimensions were optimised based on verifications conducted with a multibody model as well as a finite element model analysis. The objectives of the optimisation were minimisation of overall size, mass, and mechanical stress. For another exoskeleton published in [33], FEA was used to improve the design of this passive exoskeleton in iterations. The properties of the spring and frame were modified based on simulation results.

3.1.3 Design Optimisation of Other Upper-body Exoskeletons

The FC-WREI [135] is a wrist exoskeleton developed for use as an interface. Due to the number of iterations required to find a solution to the objective functions for multi-objective optimisation, the authors performed optimisation in two steps. A conditions index system which estimates kinematic performance of specific postures was applied to gauge the viability of the device by indexing the local proximity of configurations to singularities, named the Local Condition Index (LCI), which is averaged to calculate the Global Condition Index (GCI). The LCI can be maximised to derive critical design parameters. The other factor used for optimisation is the Interference Safety Margin (ISM), which describes the minimum distance between the links of the exoskeleton and the centre of the wrist. Non-dominated sorting genetic algorithm II was used to perform optimisation maximising GCI and ISM. The first optimisation stage consisted of 300 population and 200 iterations, with a preliminary workspace scope that covers ADL limits of the wrist. The second stage consisted of 100 population and 1000 iterations with a restricted scope to ensure minimum performance. The optimised design, as a result of the optimisation, is able to output relatively isotropic torque at any configuration, while maintaining a lower inertia by up to 5.35 times compared to similar devices cited in the text.

3.2 Human-Robot-Interaction

Human-robot-interaction (HRI) is an important consideration for occupational exoskeletons, as it plays a crucial role in determining the usability, effectiveness, and safety of the exoskeleton. HRI encompasses all aspects of how the exoskeleton system interacts with the human biomechanical system, how information, assistance, contact, and obstruction relate the two bodies. In this section the discussion is separated into sensing and feedback, reconfigurability, and actuation.

3.2.1 Sensing and feedback

Sensing enables the user to communicate to their exoskeleton, and for it to receive information about its surroundings. This is important for responsiveness to input, adapting to different situations, and contributes to the design's safety. The sensing features found within the literature are graphed to illustrate the distribution of different sensors between occupational designs and others in figure 3.12.

Within the reviewed exoskeleton systems, angular position sensing is the most popularly featured sensing capability and has been included within 33 designs, utilising potentiometers, rotary encoders, and other sensors. Force sensors are the second most often used with 30 inclusions of loadcells, force-sensitive-resistors, etc. Electromyography (EMG) on the surface of the skin follows closely with 25 inclusions. Inertial-measurement-units (IMUs) are found in 9 systems. Torque, pressure, electro-encephalogram, and linear position sensors are featured in 6, 2, 2 and 1 designs, respectively.

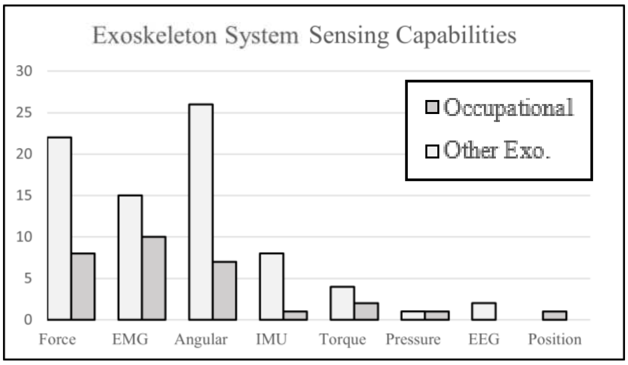

Figure 3.12 Sensing features used in exoskeleton systems of occupational and other types.

Some conclusions about the focus of exoskeleton control systems can be drawn from reviewing these trends. It is notable that EMG is frequently used for intention-detection as it correlates to muscle activation, a very intuitive form of control for exoskeletons of both occupational and assistive purposes. The predominance of angular and force sensors in the other category of exoskeleton can be attributed to a greater desire for precision for medical, research, and tactile-interaction-based exoskeletons, but is not easily ignored by occupational designs. The use of IMUs and EEG almost exclusively in the other category could be due to their data not being as robust.

While popular, EMG based control does create challenges for both the software and hardware technologies involved in signal detection and classification. Two requirements for EMG intention detection are clear, consistent skin contact and individual data training. The necessity of adhesives and evaporative gels was previously a problem for accurate EMG detection, more recently, developments in specialised electrodes are directed towards soft, dry, breathable devices, but such technologies are in active research and not yet prevalent [136]. The current dry electrodes are especially susceptible to EMG signals dampening with perspiration [137], and frequency changes caused by fatigue [138], which are two unavoidable factors that must be mitigated for occupational applications.

3.2.2 Reconfigurability

Reconfigurability in this context points to the degree to which a design can be adjusted to fit different users, which can be defined as a systematic way of fitting an exoskeleton to a user either through features to change the design's fit, or its parameters as it is manufactured. This feature is often lacklustre, or non-existent, which is the case for 25 (23.1%) of the 108 designs. This is common in the realm of exoskeleton research because experimental designs are often only manufactured once, and in many cases (9 of the literature containing user testing) only worn by one user during validation. The potential impact on wearability and effectiveness is undeniable. Reconfigurability is a concept applicable to many aspects of the design besides mechanical. Beside hardware-based solutions, some designs incorporate software personalisation, an example being [64] with its calibration procedure programmed into the exoskeleton system to control actuation depth.

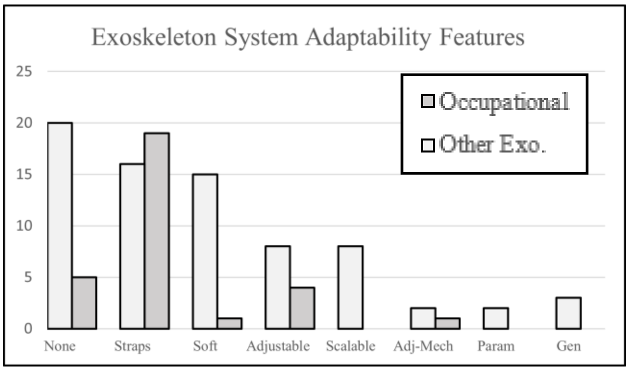

Figure 3.13 Reconfigurability features exhibited in exoskeleton systems of occupational and other types.

Abbre-viations	Meaning
Straps	The device is primarily secured using adjustable fabric fasteners
Soft	The device primarily utilises soft robotics to preclude the need for mechanical fasteners.

Adj	The device features components which can be adjusted to fit differently sized users.
Scalable	The device is designed to be scalable within CAD environment and can be manufactured to suit a range of users.
Adj-Mech	The device features components which not only adjusts for size, but the mechanics of its motion as well.
Gen	The device is created through generative design with fitment to different users in mind, it can be automatically fitted to new users without manual scaling.

Table 3.13 Abbreviations used for the table of reconfigurability features.

The primary reconfigurability features of the exoskeleton reviewed were classified and combined into a graph in the form of figure 3.13. Abbreviations used for this graph are listed in table 3.13. As shown in the graph, the primary methods of exoskeleton fitting are the use of straps and soft robotics, accounting for 35 (32.4%) and 16 (14.8%) of the designs, respectively. This is in contrast to the use of mechanisms that change the shape of the exoskeleton to match the user's body, or modifying the shape of the exoskeleton during manufacturing.. An example for a mechanism used to tighten itself onto the arm is shown in figure 3.14.

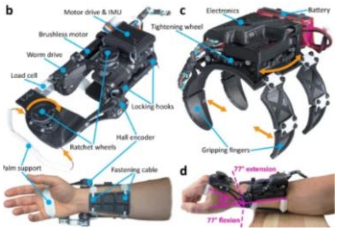

Figure 3.14 An example of a device featuring an adjusting mechanism for fitting purposes[99].

Additive manufacturing is a common feature in exoskeletons, particularly those designed for research purposes, for many reasons. Additive manufacturing is a cost-effective solution that is flexible, fast, and provides notable freedom in the geometries it can create and materials it can utilise. The implications of these advantages for exoskeleton development are the ability to rapidly prototype and iterate a design and for it to be customised to fit a user's body without increasing the difficulty of manufacturing the design, this is done at a basic level through scaling. Further, additive manufacturing is not only applicable for links, joints, and structures, but actuators as well. Additive manufacturing could either directly manufacture actuators [87], or aid in their creation through moulds [119]. Customised actuators provide the designer with a way to vary their power and shape to adapt to different users and functions.

Generative design utilises algorithms and computation to generate iterations of a design based on specified constraints and objectives. Generative design can be considered a form of design optimisation as it takes input parameters and creates solutions that fit within boundaries that satisfy certain conditions. In the context of HRI and reconfigurability, it can bridge the gap between an exoskeleton design, created for specific tasks, and the user, assigned to those tasks, by accounting for their human parameters. These can begin from their size and shape but should encompass other factors such as their strength and their ability to access its features.

Another important aspect of adaptability between individual users of an exoskeleton system, Range of Motion (RoM) data is not discussed in the literature of many designs but recorded in detailed for others. This depends significantly on whether the design includes sensors that can innately capture this data. Alternatively, RoM is measurable using optical motion capture, however, this is a costly and inefficient method, especially for soft exoskeletons, which lack a rigid system to constrict the relative positions of the markers used, causing problematic slip and occlusion [139]. This impedes effective diagnosis of alignment and motion issues. As such, design papers vary between providing no data at all regarding RoM to providing a long list of angles to report. In total, range of motion data is included within the published materials in 38 (35.2%) of the 108 reviewed devices.

RoM impacts both comfort and usability, although it is commonly stated that a functional RoM is not a full (anatomical) RoM [140], this is frequently used as a justification for a reduced biomechanical compatibility in exchange of robustness and convenience for the design process. A middle-ground solution for this challenge is the inclusion of passive degrees of freedom (DoF). While passive DoFs do not provide actuated support, they allow more natural movement, enabling more precise grip type control, and are capable of preventing hyper-extension through mechanical limits. Passive joints are much less mechanically complicated than actuated joints, although their inclusion could directly affect the placement and direction of actuators for active joints.

3.2.3 Actuation

An important aspect of mechanical design, actuation methodologies each have a set of positives and negatives which make them appealing for the specific purposes the exoskeletons are designed for. The relation of actuation strategies to exoskeleton type is graphed in figure 3.15 with its abbreviations explained below in table 3.15. The prevalence of cable sheath actuation can be attributed to its synergy with compliant exoskeletons more common in assistive applications.

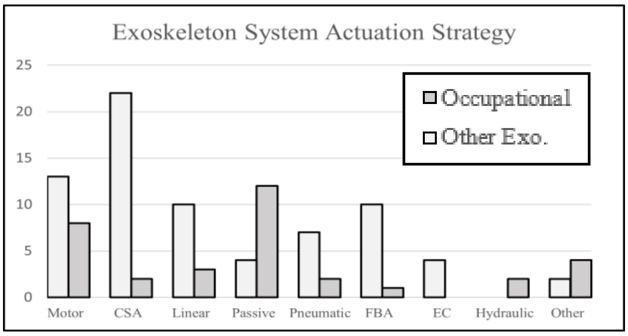

Fig 3.15 Exoskeleton actuation strategy distribution over purpose.

Abbreviations	Meaning
Motors	The device is directly actuated with any rotational motor.
CSA	Cable sheath actuation, the device utilises a system of flexible cables routed through low friction sheaths to achieve motion.
Linear	The device is actuated with electrical linear actuators.
Pneumatic	The device is actuated with pneumatic systems.

FBA	Flexible-bidirectional-actuation, the device uses the balance between stiffness and flexibility of a material to exert force.
EC	Exposed cables, the device is actuated through the tension of exposed cables.
Hydraulic	The device is actuated with hydraulic systems.
Other	The actuation strategy used by this device is unique.

Table 3.15 Abbreviations used for the table of exoskeleton actuation strategy.

The hand and wrist combined is a body part with a dense arrangement of many DoF, with each joint having a specific range of motion to the individual. Each finger is capable of flexion/extension in 3 locations, with two synergistic interphalangeal actuated in tandem, and 1 joint for adduction/abduction at the base relative to the palm. Therefore, to fully actuate just one finger requires 3 independent degrees of freedom, represented by 5 rotational joints. The thumb has one additional independent DoF, referred to as opposition, denoting the ability of the thumb to translate along the digits to contact them. Many DoFs are commonly ignored for the purposes of actuation. This is often cited as an acceptable compromise, only preserving a functional range of motion and fewer DoF than a natural hand as a measure to reduce complexity. There are three main aspects of hand motion not commonly addressed in the reviewed systems: the abduction-adduction of the fingers, the metacarpo-phalangeal (MCP) joint of the fingers independent of the interphalangeal (DIP and PIP) joints, and the nonplanar motions of the thumb.

The lack of abduction-adduction capability can be attributed to two factors that influence the exoskeleton designs of this review: it brings additional mechanical complexity for arguably diminished returns for performance of ADL and rehabilitative tasks; introducing another degree of freedom for each finger complicates EMG classification by multiplying the number of intentions that must be detected. The reduction of DoF by mechanically synching the rotation of related joints is a common form of under-actuation applied to finger exoskeletons.

Cable sheath designs actuate by loading the wearer's body parts and creating torque around their joints; within the realm of rehabilitation and assistance, the loads would be rehabilitative or natural for the body to bear, but in an industrial context for use with potentially intensive labour, the exoskeleton may cause an increased load on certain parts of the body [11] [12], this loading creates an unnatural force concentration which could lead to an injury. No published research has been found on the effects of increased pressure exertion on the joints using a soft augmentative exoskeleton, as studies so far have focused on muscle activation and strain, which are much easier to quantify. Another problem for compliant exoskeletons is the difficulty in accurately simulating their function in software, which limits their optimisation potential.

Back-drivability is a property of some actuation strategies that can be beneficial as it affects the exoskeleton's functionality. It allows bidirectional transfer of energy between the user and the device, reducing power consumption by enabling passive motion. Back-drivability also promotes natural movement and control, as users can modify and override the exoskeleton's movements through their own muscle forces. This enhances coordination and proprioception. Safety and compliance are improved as backdrivable joints can yield or give way in the presence of unexpected forces, reducing the risk of injury. Additionally, it improves versatility, as the exoskeleton can accommodate a range of tasks and variations in movement patterns with more robust control. Overall, back-drivability strengthens the relationship between the user and the exoskeleton, enhancing performance and user experience at the cost of some strength and protection.

Some actuation systems have benefits secondary to its role to provide motion. For example, Series Elastic Actuators (SEA) and some compliant, spring-based, actuation strategies` allow for output force estimation by measuring the displacement between the intended position and the physical position of the exoskeleton joint [97].

Most systems utilise a transmission mechanism to transfer force from the actuator to the location of actuation in the structure. This often, but not always, provides the advantage of translocating the heavy devices that create the actuating force away from the compact joints at the hand and fingers. It is essentially impossible to create actuated finger joints without a mechanism that serves this purpose. Plessis et al. [141] classifies the transmission systems in contemporary hand exoskeletons as rigid mechanical structures, cables mechanisms, and compliant mechanisms. An alternate classification is applied here, as more importance is placed on differentiating various rigid transmission mechanisms.

The transmissions of actuators without rigid elements are discussed in the section 3.4, and thus grouped together as compliant. Within this review, more importance is placed upon the transmission of mechanical force onto the human body rather than between mechanical parts, compliant mechanisms which interact with mechanical structures before exerting force on the human body are not considered a compliant system in this way. The main categories which the transmission systems are hence classified are compliant, linkage and parallel joints (with respect to the body). Four designs fell outside of these transmission categories, utilising instead gears, a belt drive, and a rack-and-pinion joint.

Compliant designs circumvent many issues which complicate exoskeleton design but creates its own challenges. Compliant designs have lower force output efficiency in general compared to rigid designs. Especially for sliding spring and bidirectional cable designs, there are elastic losses in the system that scale with their stiffness, which corresponds to their strength. Cable sheath designs also suffer from efficiency losses, some factors of their design can influence and mitigate this issue as detailed in the previously discussed optimisation discussed within Dittli et al [89].

Linkage and parallel joints are both kinematically defined by their rigid structures but differ in the complexity and proximity of the joint. Linkage structures are typically underactuated through multiple mechanical couplings to extend the reach of actuators to the user's body. Parallel joints are typically actuated directly and with rotational joints which are parallel and inline to the user's joints. Linkages and parallel joints share the issue of protrusion from the actuated body-part, as a result of scissoring mechanisms projecting outward and the location of the actuator, respectively

For hand exoskeletons, linkages and compliant devices are most popular for hand designs as the compactness required to be in place to actuate a finger in the context of providing mechanical assistance is difficult to achieve with conventional rigid actuators and limiting in terms of ROM. Parallel joints are, however, effectively applied to many other occupational designs due to its relatively robust structure, which is less likely to snag and doesn't have overlapping links which open and close which can be a hazard to its user.

Soft exoskeletons offer advantages such as comfort and flexibility. They provide a natural range of motion, are lightweight, and easy to don and doff. However, they may have limited torque and force capabilities, lack stability, and support, and have a shorter lifespan due to their softer materials. In contrast, rigid exoskeletons offer increased strength, stability, and support [105]. They are suitable for tasks requiring forceful movements and provide precise control. They are also more durable and have a longer lifespan. However, rigid exoskeletons are less comfortable, restrict natural motion, and can cause fatigue due to their weight. They are also more complex to design and maintain, resulting in higher costs [46] [96]. In summary, soft exoskeletons prioritize comfort and flexibility, while rigid exoskeletons excel in strength, stability, and durability. The choice between the two depends on the specific needs of the user and the tasks at hand, considering the trade-offs between comfort, mobility, and functionality.

3.3 Experimental Results

Experimental results are critical when evaluating an exoskeleton system for occupational use. This is because they provide objective data on the effectiveness and safety of the exoskeleton, which is essential for making informed decisions about whether the exoskeleton in a real-world occupational setting is suitable. Results presented in the papers are not systemised in any meaningful way. Due to the nature of experimental design, methods of validation and the data gathered are not often comparable. Echoing the previous comment regarding RoM documentation, how a design is characterised in its published document is often dependent on its construction and sensing capabilities, instead of adhering to any standard.

Common experimental results are questionnaires, interaction forces with the body, and the error of exoskeleton assisted motion compared to motion without the exoskeleton. Questionnaires are useful for qualitatively determining the wearability of an exoskeleton. In terms of multi-participant studies, this is more often done with assistive or rehabilitative systems ([67], [103], [71] [72], [82], [118], [119], [63]) because they are designed to interact with patients during physical therapy or to be worn for hour-long sessions of ADL. Between different body-parts the root-mean-squared actuation error can range from 1 to 5 degrees. The impact of this error on functional performance is not commented on for subjects who are not motion impaired, but the ability of some exoskeletons to maintain an acceptable level of error compared to the trajectory of an unrestricted body-part is an important criterion used for exoskeleton evaluation ([71] [72], [111], [142], [91]).

The difficulty of measuring grip force of a hand exoskeleton system illustrates the physical challenges surrounding the issue of consistency. There are two common ways grip forces are measured, through pull-force by gripping an object connected to a loadcell (also called a hand dynamometer) [118], or contact force by using a bendable pressure sensor [143]. Beyond that, actuation and transmission mechanisms have different kinematic characteristics, most combinations of those two variables do not output a constant torque with regards to joint angles, thus, the closing force of exoskeleton hands for different radii is a shifting variable. This means there is limited transferability of collected data and more independently conducted comparison studies should be done.

Novel approaches to systematise hand exoskeleton data acquisition has been tried, one example is an instrumented finger used for the SPAR glove [105] by Rose and O'Malley, which was used to compare the SPAR glove to 4 other exoskeletons. It was developed by Yousaf et al. [144] for their SEA-based rehabilitation HES [145] used in subsequent studies by its developers to characterise the performance of the SPAR glove. It can collect individual joint angle readings from 10 hinge joints, corresponding to the DIP, PIP and MCP angles of the index and middle finger, and MCP and IP, as well as the compound CMC joint angle of the thumb. However, it lacks the two ulnar digits, which should not be ignored as they are involved in all but one of the six grip types implemented during 70% of the activities of daily living [146] and have been shown to contribute significantly to grip strength [147].

Within the reviewed literature, there has been no practical hand exoskeleton system evaluations that focused directly on the augmentative hand exoskeleton system. Exceptions to this are single-digit actuating units ([15], [127], [128] [129] [130],) that only simulate a small fraction of the full application for such a device. Therefore, the true viability of occupational hand exoskeleton systems remains to be determined through experimentation. Most importantly, its ability to reduce fatigue, joint shear forces and exertion, as well as wearability implications for long term usage such as comfort and constraint. The contextual difference of such tests on able-bodied individuals, in contrast to current research, which focuses overwhelmingly on medical devices, warrants thorough exploration.

Lastly, it is important to note that data which does exist is at a high risk of bias as discussed in a review on the topic published by Bock et al in 2021 [148]. Authors of papers experimenting with their own exoskeleton systems have a vested interest in presenting their design as a superior option compared to others or to omit factors that reduce the marketability of novel mechanisms and devices. As a result, caution must be exercised when interpreting the existing research findings.

3.4 Summary of Discussion

The discussion section of the review delves into various aspects beyond design optimisation in the context of hand and wrist exoskeleton systems by reviewing the examples found within the literature. It explores the purposes for which these systems are developed, including rehabilitation, Activities of Daily Living (ADL) assistance, augmentation, haptic feedback, and research. The classification of designs based on attributes such as actuation, transmission, sensing capabilities, degrees of freedom, and personalisation features is also discussed.

Design optimisation in the context of upper extremity exoskeletons is not widely implemented, with a greater focus on rudimentary optimization techniques such as FEA and single-joint motion analysis rather than comprehensive system-level optimization. To advance the field, future research should explore unexplored areas of optimisation, including material selection, structural design, and their integration with control algorithms. Investigating the effects of optimisation on factors like weight reduction, energy consumption, and user comfort would provide a holistic understanding of the benefits of design optimisation. This knowledge could contribute to the establishment of design guidelines and best practices, fostering innovation and efficiency in exoskeleton development.

Current applications of design optimisation in the field of exoskeleton research have specific focuses on design parameters difficult to home in using traditional design methods. As such, the use of design optimisation does not supersede the importance of manual input. Different approaches to design optimisation apply to different steps of the design process from ideation to detailed design, which bring different advantages and challenges which will be elaborated on in this section.

One limitation is in the number of variables that can be accounted for at once, as a result only those deemed most essential by the author is optimised for. Thus, an optimised design can be extremely efficient at its assigned tasks in a simulated environment but have aspects of their design that is less developed or practical. Most frequently these variables are ones that decide the broad mechanical structural of the exoskeleton and its kinematic properties. Some optimisation methods, such as that used by Tröster et al [23], require manual iterative numerical input, which can provide an accurate solution for a given objective, given time, but limits the variety of parameters that can be optimised, and their range. Simply due to the multiplicative nature of iterating through more than one parameter manually, in most cases only one variable will be modified in this way.

MOO methods do not solve the issue of oversight perfectly, while it does offer more a flexible selection of design parameters, it does so at the cost of computational time, and the multiple parameters considered with these methods are still manually selected by the user of the algorithm.

Considering the inconsistent documentation of exoskeleton systems, it is difficult to assign specific results to the application of design optimisation. However, it is evident that designs incorporating optimization exhibit greater maturity. This indicates the potential to significantly enhance the efficiency of exoskeleton designs using even simple optimization strategies. Additionally, the applicability of exoskeletons for occupational purposes relies on their versatility. This requirement can explain the observed properties discussed in this section. To meet the diverse needs of various occupational settings, exoskeletons should be reconfigurable to different body types, offer adjustable assistance levels, and be compatible with various work environments, ensuring seamless integration and unrestricted mobility. Emphasizing versatility in exoskeleton design enables manufacturers to develop solutions that maximize benefits and facilitate widespread adoption in occupational settings.

The aspects of HRI discussed within this review presented are subjects of ongoing research, and thus no completely optimal solutions are yet to exist for the challenges therein. One critical limiting factor of current occupational exoskeletons that must be outlined is their adaptability to different tasks and situations. It is a dominant factor in the applicability of an exoskeleton system to an industrial scenario. This can be used to explain the distribution of graphed properties discussed within section 3.2 as they favour robust solutions over specialised ones. A clinical exoskeleton can afford the specificity of providing specific motions and expect specific feedback, using personally customised hardware for an individual user, while an occupational system needs to be robust, apply to diverse situations, and be wearable by a wide range of users in order to be useful.

An exoskeleton with appropriate considerations for reconfigurability should be capable of accommodating different body shapes and sizes, allowing for personalised fits, and ensuring user comfort. There is a need for research into increasing the degrees of reconfigurability of exoskeleton designs, as there is a notable reliance on straps for interfacing with the body, which may have diminished effectiveness as the exoskeleton approach its user body size constraints. Lack of further adjustment, such as in terms of link lengths and mechanical parts responsible for motion, can subject the user to discomfort by creating misalignments and non-normal joint forces, which could eventually lead to injury.

Effective sensing and feedback enable an active occupational exoskeleton to respond to different work environments, enabling seamless integration between different tasks. To provide appropriate levels of assistance or resistance to cater for varying job demands, effective sensing technologies that are sensitive to external environmental information are required. For this reason, angular and force sensors remain excellent inclusions for any occupational exoskeleton, as they both observe the physical conditions of the exoskeleton, deviations between different operating and static conditions can be used to determine the effects weights and motions have on the exoskeleton and its user. In terms of interactions with the user, further development of EMG technology that addresses its current limitations for occupational applications can potentially enable it to increase the comprehensiveness of HRI through the incorporation of derived metabolic data, and to improve intention detection. The complexity for both the external environmental and user-centric aspects of sensing and feedback are both challenges that scale with the number of DoF of exoskeleton designs and may prove difficult to address.

The trend of occupational exoskeletons towards passive or motor-based actuation suggests that the more novel or complicated forms of actuation such as pneumatic, flexible bidirectional cables, or exposed cables, are not robust enough for the application. This is reflected by high part counts and low cycle life, which are not urgently researched issues within rehabilitative robotics, but are basic considerations for any industrial product. By comparing these two domains, valuable insights were gained that could encourage the development of more complex exoskeletons that are still suitable for occupational applications, thus expanding their potential impact and usability in real-world scenarios.

All other actuation technologies bring additional complications to the design process that have to be compensated for, with the exception of cable-sheath actuation. CSA is a strong contender for occupational exoskeleton actuation, being the most popular technology for non-occupational exoskeletons, there is massive potential in their adoption because it essentially functions as a transmission system for the exoskeleton as well as a method of generating motion which allows for remote actuation, reducing extremity weight of the exoskeleton system.

In summary, the discussion section offers an overview of the design optimisation of and the vital features for upper-limb exoskeleton systems for occupational use, with recommendations towards the research and application of relevant technologies. It emphasises the significance of mathematical modelling and optimisation methods and their role to enhance performance, efficiency, usability, and cost-effectiveness for cutting-edge designs, as well as the importance of versatility and robustness when making design decisions for the composition of an occupational exoskeleton. The pursuit of versatility and robustness in exoskeleton design may in turn be addressed using design optimisation, which will enable manufacturers to create solutions that meet the diverse needs of workers across various industries, maximizing the potential benefits and promoting widespread adoption in occupational settings.

4. CONCLUSION

An ideal design optimisation procedure is a wholistic, systematic approach that accounts for both the human and mechanical aspects of the exoskeleton system. Each part of this ideal is possible with current technology, but the integration into a functional system has not been done within the exoskeleton field. The currently challenges are optimising parameter choice, lack of integrated personalisation and “soft” HRI considerations within the parameters, (mechanical and biomechanical) model complexity and accuracy, computation time, and the use of proprietary algorithms and software that prevents proliferation of good optimisation techniques.

There are no perfect combinations of exoskeleton design features for occupational designs, there are, however, observable trends that have been exhibited in existing systems that shows that some choices are more viable or efficient than others, as well as areas requiring additional research to truly discern their ultimate applicability. Robustness and adaptability are two most vital components for the selection of effective design solutions to address the needs of an occupational exoskeleton.

The wide range of exoskeleton systems for the hand in current research and methods for their design indicate both a high level of potential in development for a variety of formfactors, and a low level of maturity in their development. Further exploration of the technology as a whole, and in its constituent parts, is necessary for their implementation into occupational applications.

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