Identification of Usage Scenarios for Robotic Exoskeletons in the Context of the Hong Kong Construction Industry

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Abstract –

Exoskeletons can be seen as an archetype of a truly sustainable manufacturing technology since they empower human beings rather than aiming at their substitution. Exoskeletons have been characterized by rapid technological advances in the last decade, as well as an increase of activities attempting to develop feasible usage scenarios for many industries. However, usage concepts for this technology in the construction industry are still rare. This contrasts with the fact that exoskeletons are theoretically ideal for labor intensive industries such as construction. Therefore, in the study presented in this paper, we made a first attempt to conceptually bridge the gap between exoskeleton typologies and construction tasks so as to provide guidance for future target oriented scenarios and technology development. We utilized the Hong Kong housing construction industry as a case study. Consequently, we developed a construction specific classification of exoskeletons and analyzed the suitability and applicability of the resulting exoskeleton types for Hong Kong's housing construction tasks. Our study identified, amongst others, hotspot task areas with high appropriateness for exoskeleton use, task areas with similar needs and usage patterns regarding exoskeletons. Furthermore, our study sheds light on the regimes and rationales behind the identified appropriateness levels. Based on our findings, a set of basic guidelines was developed to support and govern future research and development activities targeting the exoskeleton usage in construction.

Keywords –

Exoskeletons; Classification; Task Analysis; Housing Construction; Hong Kong; Sustainability

1 Introduction

In the study "The Future of Employment", Frey and Osborne [1] argued that in the next decades labor intensive and repetitive jobs such as those in the construction industry will be gradually substituted by automation and robots. On the contrary, recent technological advances indicate that we are able to develop sustainable technological solutions that can literally "bring back humans to work" [2]. According to the authors of this paper, exoskeletons can be seen as an archetype of such solutions, since they empower human beings rather than aiming at their substitution. The term "exoskeletons" (i.e., robotic exoskeletons) refers to a specific branch of wearable devices employing person-external mechanical structures to assist or enhance the physical, motor, and cognitive power of a person [3]. The last decade has witnessed its rapid technological advancement, alongside an increase of projects and activities attempting to develop realistic usage scenarios for many industries (e.g., manufacturing, shipbuilding, agriculture, care, etc.). However, concepts for the usage of this technology in the construction industry are still rare. Exoskeleton technology could provide a couple of performance features such as force augmentation for human beings, high flexibility, the combination of human intelligence with machine capability and improved workplace ergonomics; features ideal for labor intensive and on-product customization focused industries such as construction.

The fundamental motivation to adopt exoskeletons in the construction industry - besides the demands for productivity increase - is to improve the health and safety of workers by enhancing their muscle strength, mobility, and endurance. Construction is a highly physically demanding industry, while musculoskeletal disorders, often caused by overexertion of repetitive works or from heavy lifting or squatting jobs, is one of the leading type of injuries in construction industry [4]. Exoskeleton technologies, therefore, have the potential to dramatically reduce the risk of injuries and illnesses by amplifying the power of construction workers and providing back support. Also, faced by the challenges of an ageing workforce and labour shortages in cities like Hong Kong, exoskeletons and other wearable devices can help to solve the problem by enabling elderly or female workers to perform physically demanding construction tasks in a highly productive manner. Besides, exoskeletons may also be capable of autonomous decision making to achieve certain goals such as being an agent of humans in construction activities [5]. Notwithstanding the tempting potentials, the unstructured and dynamic site environment, combined with the diverse tasks and complicated processes, highly raise the requirements of exoskeleton technologies for construction than traditional military or medical use. To avoid additional risks by wearing exogenous devices, it is of great importance to warrant a high level of portability, flexibility, and coordination with the wearer.

The study presented in this paper attempted to conceptually bridge the gap between existing exoskeleton technologies and construction tasks-based usage scenarios. The Hong Kong construction industry was utilized as a study setting due to its vibrant nature of demands for productivity as well as enhanced health and safety standards. At the same time, some unique characteristics such as Hong Kong's topography and building culture bring forth narrow and cramped sites and floor plans that largely restrict the usage of large machines or robots and demand for small-scale, human-centered approaches. This initial qualitative and exploratory study was conducted in order to pave the ground for larger, qualitative follow up studies involving extensive bottom-up input by relevant stakeholders. This initial study not only identified the relevant domains of knowledge but also combined a comprehensive literature review with a worldwide perspective to the secondary data on exoskeleton technologies by using the Hong Kong housing construction as a case study. The data was collected and developed through the analysis of relevant literature, reports, construction laws and guidelines, construction task descriptions, as well as product leaflets and documents.

The remainder of this paper is structured as follows; first, the background of exoskeletons is introduced, the important development tendencies are characterized, and the diversified technologies are analyzed and categorized. Then, while considering the housing construction practice in Hong Kong, work and labor structures are analyzed and task areas are identified and outlined. Next, usage scenarios that build on the task areas and specific types of exoskeletons to identify the usage scenarios are developed. Finally, a set of basic guidelines derived from the analysis is presented to support and govern future research and development activities targeting exoskeleton usage in construction.

2 Background

2.1 History of Exoskeletons

The development of the exoskeleton can be traced back to the 1960s when the first systems for power augmentation in the context of military applications [6] and physical therapy in medical services were developed [7]. Hardiman, the first full-body powered robotic exoskeleton prototype developed under the U.S. Office of Naval Research, was a heavy (680kg), hydraulically actuated wearable device, with the aim to amplify the muscular capabilities of the wearer [6]. Although its purpose to power up the human was never achieved, critical issues for future development such as power supply and human-machine interfaces were identified [7]. In 1991, the first energetically autonomous exoskeleton, Berkeley Lower Extremity Exoskeleton (BLEEX), powered by bidirectional linear hydraulic actuators, was developed to augment the human strength for material handling [8]. Continuous studies and development have been carried out on BLEEX, triggering out the spin-off company called Berkeley Bionics (now Ekso Bionics) [9]. BLEEX was initially funded by the U.S. Defense Advanced Research Projects Agency (DARPA), which has been regarded as a major impetus to the later development of performance augmenting exoskeletons for soldiers during load-carrying [10]. Medical use cases also played a major role in the evolution of exoskeletons [11] in terms of catalysing the recovery of neurological or orthopaedic patients in physical therapies [12], adding power to help people with muscular weaknesses while walking or stair climbing [13], assisting paralyzed people to regain mobility in daily life [14], etc.

In the recent years, the research and development of exoskeleton technology has prosperously spread in the USA, Japan, Korean, and in Europe. Currently, its applications are broad and vary from military and medical usage to emerging commercial and industrial applications [7, 11]. Although industrial grade exoskeleton usage is still rare in most-non-construction based industries, an enormous amount of research and development activities is currently taking place to crack the code for commercialisation.

2.2 Technological Development Tendencies

Technologically speaking, using exoskeletons as an integration of humans and machines into one system provides new possibilities to create assistive technologies for biomedical, manufacturing and aerospace industries. Even though human muscles have a limitation in power, they naturally use highly specialised control systems to perform complicated tasks. As opposed to humans, robotic manipulators can carry out higher forces on certain tasks, however, their artificial control algorithms compared to humans has less flexibility performance in a wide range of fuzzy conditions. Therefore, combining robotic manipulators directly with humans offers the opportunity to benefit from both sides and use advantages from each branch.

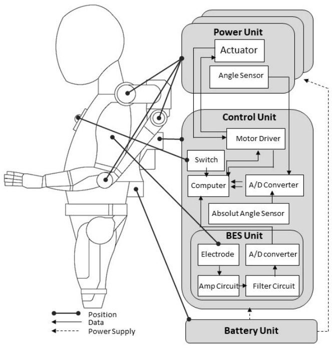


Figure 1. System configuration of the ULSS. All of the power units have the actuator and the angle sensor. The control unit contains the BES unit and the absolute angle sensor, and it controls the whole exoskelton [16].

First generation of exoskeletons used position command from human body to control the exoskeleton. Usually it consists of two layers; a master internal layer providing the position command for the slave and external higher power layer. However, technical problems such as overweight, errors between master and slave layers and poor performance for leg control to achieve the balance for the body movement initially made the achievement of unsupported walking a challenge.

Second generation exoskeletons applied the interface in a dynamic manner; using direct contact force between human and the wearable robot. The measured force is the main signal sent to the exoskeleton. With both the first generation kinematic-position command type and the second generation dynamic-contact force command type, a slight delay to trigger the exoskeleton response by applied action of the wearer [15] represents the challenge with regards to control.

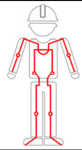
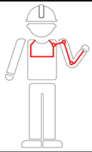
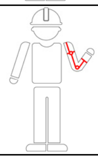
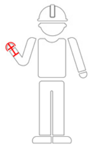
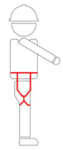
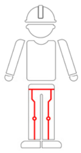
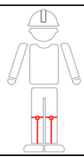
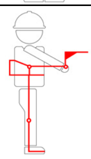
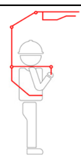
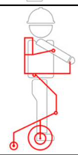
Third generation exoskeletons set the interface at a higher level, i.e., the human neurological system. Likewise, in the human body, a delay is presented between the neurological functions and muscle and body part movements. During this inherent delay, the system gathers information regarding the muscle's neural activation level based on a processed neuromuscular (EMG) signal or even maybe the brain signal, the joint position, and angular velocity, which allow it to estimate the force before the mechanical movement. Thus, the earlier developed dynamic and kinematic feedback types from older generation exoskeleton systems have been integrated and re-combined in the 3rd generation systems. Figure 1 shows exemplarily the system configuration used in upper limb support system (ULSS) [16]. It benefits from using the bioelectrical signal (BES) and automatic changes in the control algorithm. Based on neural network and fuzzy logic, the control algorithms can be developed and designed for specific operators and even specific tasks to fit different physical conditions of the wearers [15, 17] and the requirements of specific work settings and processes. In the development of the fourth generation exoskeletons currently taking place, the key lies in the improvement of technical features such as lower weight, high performance actuators, human–exoskeleton interface, safety, energy efficiency, and lower cost [17].

2.3 Important Definitions

Even though a diversity of definitions exists, the terms "wearable robots" and "exoskeletons" are widely used in the context of wearable robotic technologies. Pons [18] defined a wearable robot as "*a mechatronic system that is designed around the shape and function of the human body, with segments and joints corresponding to those of the person it is externally coupled with*". De Looze, Bosch [3] regarded an exoskeleton as "*an active mechanical device that is essentially anthropomorphic in nature, is worn by an operator and fits closely to his or her body, and works in concert with the operator's movements*". In compliance with definitions used by the International Association of Automation and Robotics in Construction (IAARC) [19], robotic construction technology for on-site construction can be sub-classified into several sub-categories such as; 1) robotised construction machines, 2) single-task construction robots, 3) on-site logistics solutions, 4) Building Information Modelling (BIM), and 5) data acquisition, monitoring, and sensing approaches. Bock and Linner [20] extended this classification by adding amongst others, 6) on-site factory approach, 7) humanoid robot technology, 8) aerial systems, and 9) wearable robot technology. Wearable robot technology can further be sub-classified in approaches such as; a) smart helmets [21], b) smart glasses and virtual reality [22], c) body sensor systems [23], and exoskeletons (which this paper focusses on).

In the study presented in this paper, we principally followed the definitions of Pons and De Loze, by considering "wearable robots" as an umbrella term to describe digital and robotic systems, while defining "exoskeletons" as more specific skeleton applied devices that are worn on the human body to improve or sustain the wearer's ability to perform specific required tasks. In light of our focus on analysing particularly the usage potentials of exoskeletons in Hong Kong's housing construction industry, exoskeletons were further regarded as physico-mechanical support devices that a construction worker can wear to augment or assist his physical abilities, strength, endurance, speed, precision, or general performance on the site.

Table 1 A construction specific sub-classification of exoskeletons.

Main category	Subcategory	Basic kinematic composition	Graphical illustration	Power (type*)	Examples
Full body	Full body	Full body is actuated or powered		Active (*a*) Passive (*b*)	• HULC by Lockheed Martin and Ekso Bionics • Ekso by Ekso Bionics • MAX by SuitX
Upper limb	Shoulder type for back support (without arm)	Provide support to the back		Active (*c*) Passive (*d*)	*upcoming development activity expected* • FLx ErgoSkeleton by StrongArm Technologies
	Shoulder type for arm support	Provide support to the arm		Active (*e*) Passive (*f*)	• Titan Arm by University of Pennsylvania • AIRFRAME by Levitate Technologies
	Elbow	Provide assistive power to elbow joint		Active (*g*) Passive (*h*)	• HAL Single Joint Type by CYBERDYNE • PEX by UC Berkeley
	Hand	Provide assistive power to the wrist or fingers		Active (*i*) Passive (*j*)	• SEM Glove by Bioservo Technologies • Pneumatic Power Assist Glove by Daiya Industries
Lower limb	Hip	Provide support to hip joint or lumber		Active (*k*) Passive (*l*)	• HAL Lumbar Type by CYBERDYNE • AWN-03 by Panasonic ActiveLink • Hip Auxiliary Muscle Suit by Innophys
	Hip-knee-ankle type for leg support	Provide support to the leg and reduce fatigue during squatting, standing or walking		Active (*m*) Passive (*n*)	• Walking Assist Device with Bodyweight Support System by Honda • Chairless Chair Wearable Ergonomic Device by Noonee • Archelis by Wearable Chair
	Knee or ankle	Provide extra force to the knee or ankle to improve walking performance		Active (*o*) Passive (*p*)	• HAL Single Joint Type by CYBERDYNE • Exo-Boot by Carnegie Mellon and North Carolina State
Body extension	Tool holding	With an additional arm to support the holding of a heavy tool, while the weight of the tool is transmitted into the ground		Active (*q*) Passive (*r*)	• Lower Extremity Exoskeleton Robot for Concrete Placing (HEXAR-PL) by Hanyang University • Ekso Works by Ekso Bionics • Fortis by Lockheed Martin
	Extensional / Supernumerary	With two or more extensional arms to perform material handling or other works		Active (*s*) Passive (*t*)	• Exoskeleton for handling heavy steel elements by DSME • Supernumerary Robotics Limbs (SRL) by MIT *upcoming development activity expected*
	Extensional / Wheeled	Extension with wheels or mobile platform which could be further integrated into body parts		Active (*u*) Passive (*v*)	• EXOwheel by Sogang University • iReal by Toyota *upcoming development activity expected*

*letters in brackets are referred to classified types of exoskeletons.

Exoskeletons can themselves be classified based on a variety of viewpoints such as active/passive, the body parts covered, functionality, the types of actuators used, or the types of control and feedback systems used, etc. When considering the power source, there exists mainly the active, or powered exoskeletons using electric, hydraulic or other connections to run sensors and actuators, and passive, or un-powered ones that require no external power but use springs, elastic cords, or other resilient elements to transfer loads to the ground. According to the supporting parts to muscle strength, they can be further categorized into: upper limb, lower limb, and full body [17]. By functionality, they can be considered as power assistance, power augmentation, and cognition and sensing augmentation [20]. Regarding the types of actuators, electric motors and pneumatic systems are mainly used in exoskeleton design. In terms of feedback systems, for example, we can distinguish between a control of the robot based on bio-signals from the wearer or from acceleration forces.

2.4 A Construction Specific Sub-classification of Exoskeletons

In the study presented in this paper, exoskeletons were organized according to their applied body parts and active/passive features, considering that the analysis of the appropriateness of a certain type of exoskeleton for a certain type of construction task can best exploit these two factors. The body parts supported by an exoskeleton give a good hint about the task range and task type that an exoskeleton can cover, and the active/passive view indicates what payloads an exoskeleton can handle. Compared to many other manufacturing industries, building components cover a very wide range of loads and are key factors in deciding which construction processes and tools may be used.

Table 1 outlines the proposed construction tasks oriented classification of exoskeletons with key characteristics and example prototypes (or products) listed for each of the identified categories. The superordinate level of each category was formed by general body parts including full body, upper limb and lower limb, with body extension being considered as a fourth one to cover those with additional arms or support. Then, those four main types were further broken down into detailed body parts and kinematic features. Despite some overlaps, each second level category represents a distinguished body related feature, as manifested in the brief descriptions and graphical illustrations. In addition, the active/passive perspective was employed to determine the construction specific sub-classification of exoskeletons into 22 types, each backed with examples.

3 Housing Construction Tasks

To enable the assessment of the appropriateness of certain types of exoskeletons for specific housing construction tasks, we subdivided housing construction (Level 1) into basic task categories (Level 2) and then further into individual task areas (Level 3), as mapped in Figure 2 (mapping of housing construction tasks in Hong Kong). Relevant documents, like HK Cap. 123B Building (Construction) Regulations [24] and HK Cap. 583 Construction Workers Registration Ordinance [25], were analysed to define and develop the task areas map. On Level 2 the task categories identified are the following: 1) geotechnical and foundation work, 2) site operation, 3) main structure construction, 4) building services, 4) general interior finishing tasks, 5) general exterior finishing tasks, 6) landscaping, 7) ground investigation, site measuring, and monitoring, 8) civil works. Level 3 breaks down this task categories into specific task areas and is used as the basis for the analysis conducted in this paper. A further split down of this task areas as per the task specific execution or assembly process (i.e., sequence of sub-tasks and activities within an individual Level 3 task area; Level 4), would allow a very detailed assessment of the appropriateness of exoskeletons. However, this would require a very detailed decomposition which would go beyond the scope and resources of this initial study. In this study, we generally focussed on assessing the appropriateness of exoskeletons for Level 3 task areas. Our aim was to stimulate through this further research and development by Level 4 domain specific groups and consortia.

4 Analysis of Usage Scenarios

In this chapter, usage scenarios that were developed and built based on those identified in Level 3 task areas are presented. As outlined in Figure 3, we analyzed the previously developed classes of exoskeletons (Table 1) against the Level 3 task areas (outlined in Figure 2) and thus how specific categories and types of exoskeletons can be used within the context of specific task areas. We further identified technology appropriateness through pairwise analysis of task areas and types of exoskeletons (seen in Figure 3).

In general, our analysis revealed the following patterns in the usage of different exoskeletons in housing construction:

1. Active exoskeletons are appropriate in the context of tasks that involve the handling of rather large elements with high payloads (e.g., metal works, dry wall installation, etc.), whereas passive exoskeletons are suitable in the context of tasks that involve the handling of rather small and light components and fine motor skills (painting,

plastering, etc.).

2. Certain task areas show a similarity with regards to the type of exoskeletons used. So, for example, a relative task similarity can be identified within interior and exterior task categories. Also, tasks that involve similar tools and processes or have similar needs in terms of power augmentation, extra support or fatigue prevention (e.g., painting, plastering, etc.) result in similar requirements of exoskeleton use.

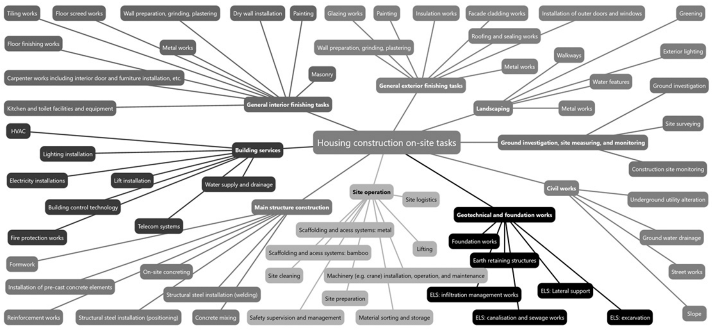


Figure 2. Mapping of housing construction tasks in Hong Kong. The map shows how housing construction (Level 1) can be subdivided into basic task categories (Level 2) and then further into individual task areas (Level 3) based on relevant building construction regulations in Hong Kong.

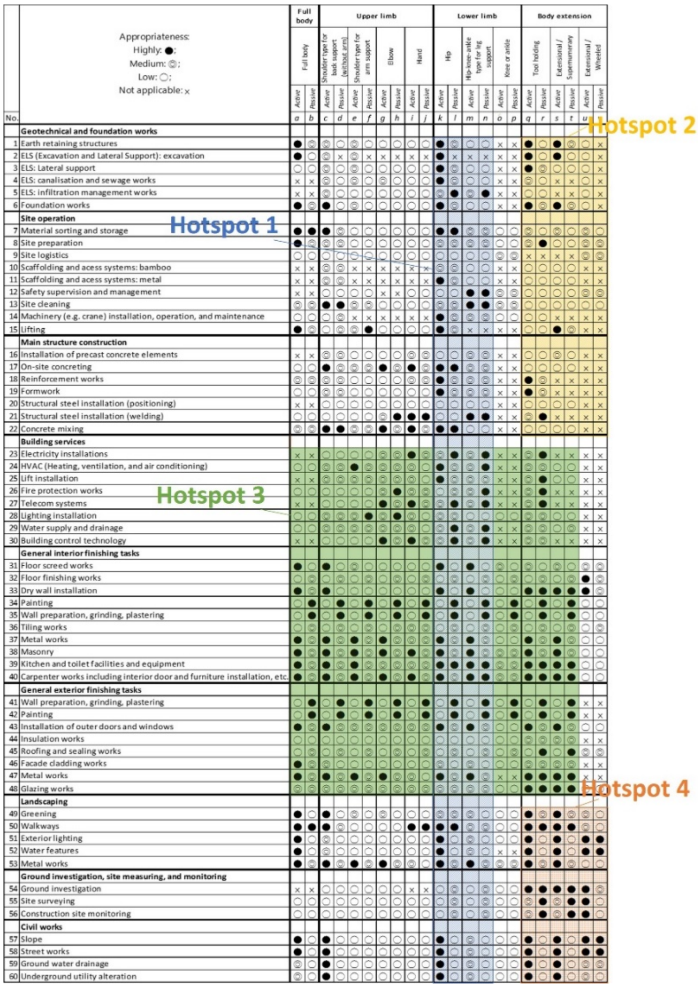


Figure 3. The pairwise analysis of task areas and types of exoskeletons. The previously developed classes of exoskeletons (Table 1) were analyzed against the Level 3 task areas (outlined in Figure 2).

3. Wheeled and full body exoskeletons face challenges in the rather unstructured environments related to geotechnical and foundation works and site operation works. Whilst after the superstructure construction, that the work environments are relatively controllable, the use of such types of exoskeletons is more suitable.
4. In Section 2.4, three exoskeleton types (types *c*, *t*, and *v*) were identified for which at present no developments or approaches are known. Our analysis revealed, in particular for type *c*, that a high appropriateness was identified for a number of tasks and that upcoming development activities for this type of exoskeleton would be justified.
5. Four hotspot areas were identified (see Figure 3):
   a) Hotspot 1: Preferred lower limb exoskeleton usage areas
   b) Hotspot 2: Preferred body extension exoskeleton usage areas
   c) Hotspot 3: Non-preferred body extension exoskeleton usage areas
   d) Hotspot 4: Preferred fully body-upper limb-lower limb usage areas

5 Discussion

The research and development towards exoskeletons usage are manifold, whilst the applications in the construction industry are still limited. Our analysis, with the assignment of appropriate levels for the construction of specific exoskeleton types to the task areas in Hong Kong housing construction, made a first step towards defining and detailing the problem and requirements for exoskeleton use. All in all, the analysis conducted provides guidance for the following follow up activities:

- **Definition of problem**: Once the task areas in which the exoskeleton can be used are defined, the development teams can then focus on creating incremental or breakthrough innovations rather than on basic science. In that context a particular focus could be laid at the sixteen main types of workers highlighted by the Hong Kong Construction Industry Employees General Union [26].
- **Multi-use scenarios:** Using our matrix and the outcomes presented in it (Figure 3), developers can identify task areas with similar or same use patterns for exoskeletons and then attempt to develop one exoskeleton (maybe with slightly adaptable features for each task area) hat can finally be used in a multitude of task areas.
- **Exoskeleton-oriented task and component adaptation:** Existing or efficiently achievable technological systems or breakthroughs shall be exploited in a broader way, developers may also consider changing task and materials/components to make certain types of exoskeletons applicable and suitable.
- **Transform site to be more like a factory:** The unstructured environment of the construction site greatly inhibits the use of certain types of exoskeletons (e.g., fully powered body exoskeletons, wheeled ones, etc.). This circumstance may be equalized through a better structuring of the construction site.
- **Exoskeleton surrounding site infrastructure:** To successfully use the exoskeleton on site, not only must the core tasks be executable but the surrounding tasks and activities have also to be integrated as well. In the context of exoskeleton usage, a key aspect will be how the wearer puts on the exoskeleton. Will there be frames or cabinets available to help the user “slip” into the exoskeleton? Or will there be as in the rehabilitation use, service personnel on the site to support with dressing/un-dressing operations? How will tools or parts be provided to the wearer of the exoskeleton? All these should be considered in the future research.
- **Systematic improvement of exoskeleton key technologies:** As part of a detailed task and applicability analysis, key technologies that require systematic technological improvement such as battery technology and the control interface can be identified (sensors, feedback system, user interfaces, etc.).
- **Identification of new exoskeleton categories:** The analysis shows that all of the existing exoskeletons are not explicitly appropriate for certain tasks, e.g., scaffolding. Consequently, this may lead to the definition of new categories for exoskeletons such as suspended gondola type exoskeletons.
- **Develop exoskeleton complementary technologies:** Complementary technologies (possibly based on BIM, worker guidance systems, new types of Graphical User Interfaces such as smart glasses, etc.) and their usages shall be well-defined and systematically developed towards higher technology readiness levels.
- **Exoskeleton and site usability engineering:** Since the human being is the most important element in the efficient and sustainable use of exoskeletons on the construction site, studies on the short and long-term impact of the use of exoskeletons on human physical conditions, muscles, psychological conditions, and overall health must be conducted and fed back into systems development. Similarly, system features and requirements that enhance motivation to use the equipment and ease of use on the construction site must be identified through user studies.
- **Sustainability:** Exoskeletons can indeed be seen as an archetype of a truly sustainable manufacturing technology since they empower the human being (his capabilities as well as his health at the workplace) rather than aiming at complete substitution of human labor by machine technology and automation.

6 Conclusions

The study presented in this paper examined and explored the usage scenarios of exoskeletons in the construction industry, drawing on the case of the Hong Kong construction industry as an initial use case setting. A construction specific sub-classification of exoskeletons was proposed to support the fundamental understanding of potential usages of exoskeletons for construction. A comprehensive mapping of tasks in Hong Kong housing construction was provided. A pairwise analysis developed usage scenarios for exoskeletons in construction to facilitate future application oriented research and development efforts directed at exoskeleton technologies.

Future work will further split down the identified task areas into sub-tasks (Level 4) to analyze what activities can be carried out by exoskeletons, human beings only, or solely by robots or machines. Also, we plan to analyze in more details the impact of exoskeletons, while being used in specific tasks, on factors such as mental and muscle stress, work organization, and social and legal aspects.

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