Exoskeletons

Comprehensive, comparative and critical analyses of their potential to improve manufacturing performance

Stephen Fox
Teknologian Tutkimuskeskus VTT Oy, Espoo, Finland
Olli Aranko
Terveystalo, Helsinki, Finland, and
Juhani Heilala and Päivi Vahala
Teknologian Tutkimuskeskus VTT Oy, Espoo, Finland

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Abstract

Purpose – Exoskeletons are mechanical structures that humans can wear to increase their strength and endurance. The purpose of this paper is to explain how exoskeletons can be used to improve performance across five phases of manufacturing.

Design/methodology/approach – Multivocal literature review, encompassing scientific literature and the grey literature of online reports, etc., to inform comprehensive, comparative and critical analyses of the potential of exoskeletons to improve manufacturing performance.

Findings – There are at least eight different types of exoskeletons that can be used to improve human strength and endurance in manual work during different phases of production. However, exoskeletons can have the unintended negative consequence of reducing human flexibility leading to new sources of musculoskeletal disorders (MSD) and accidents.

Research limitations/implications – Findings are relevant to function allocation research concerned with manual production work. In particular, exoskeletons could exacerbate the traditional trade-off between human flexibility and robot consistency by making human workers less flexible.

Practical implications – The introduction of exoskeletons requires careful health and safety planning if exoskeletons are to improve human strength and endurance without introducing new sources of MSD and accidents.

Originality/value – The originality of this paper is that it provides detailed information about a new manufacturing technology: exoskeletons. The value of this paper is that it provides information that is comprehensive, comparative and critical about exoskeletons as a potential alternative to robotics across five phases of manufacturing.

Keywords Manufacturing management, Manufacturing technology, Production improvement, Skilled workers

Paper type General review

1. Introduction

It has been claimed that there will be a "rise of the robots" throughout workplaces (Brynjolfsson and McAfee, 2014; Ford, 2015). Yet despite such claims, there are reports of increased robotics leading to reduced manufacturing performance, which necessitates the removal of robots and reemployment of human workers (Gibbs, 2018; Harbour and Scemama, 2017). One reason for poor outcomes from expensive investments in robotics is the limited ability of robots to deal with frequent production variations arising from demand uncertainty in assembly-to-order and engineer-to-order (ETO) production. This is a challenge that cannot be overcome easily through

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artificial intelligence (AI) when frequent production variations lead to there being sparse rewards for robot learning. Hence, humans continue to perform better than robots where production work involves frequent variations (Fox and Kotelba, 2018; Gibbs, 2016). Importantly, the frequency of production variations will increase as demand uncertainty increases due to expansion of customization and personalization (Liu *et al.*, 2018; WMF, 2018).

Given the profound challenges of improving the ability of robots to deal with more frequent production variations, an alternative for improving production performance can be to use industrial exoskeletons. Exoskeletons are mechanical structures that humans can wear to increase their strength and endurance, and so reduce workplace causes of musculoskeletal disorders (MSD). When exoskeletons incorporate sensors, actuators, motors, etc., they can be referred to as wearable robotics (Bosch *et al.*, 2016; de Looze *et al.*, 2016). The purpose of this paper is to explain how exoskeletons can be used to improve manufacturing performance by combining the capabilities of humans with some of the capabilities of robots. In particular, to combine human ability to work competently amidst frequent production variations with some of the strength and endurance of robotics. Accordingly, three manufacturing technology management research questions were addressed:

RQ1. What are the attributes of different types of industrial exoskeletons?

RQ2. How can exoskeletons be deployed in different manufacturing phases?

RQ3. What are the effects of wearing exoskeletons?

In addressing these questions, the contributions of this paper address three research gaps in the extant literature. The first contribution is that the paper provides comprehensive analysis by encompassing eight different types of exoskeletons. The second contribution is that the paper provides comparative analysis in comparing exoskeletons to robots as an option for improving performance across phases of manufacturing from materials extraction to product assembly and installation. The third contribution is that the paper provides critical analysis in encompassing multiple factors that determine whether or not exoskeleton implementations can be successful. Also, the paper provides critical analysis by encompassing potential negative, as well as potential positive, outcomes from exoskeletons. Together, the comprehensive, comparative and critical contributions of this paper relate its contents to challenges of manufacturing technology management where managers are faced with different options for the same technology, which may or may not have positive effects in different manufacturing phases depending upon multiple factors.

Furthermore, the paper's contributions are relevant to function allocation research concerned with manual production work. When robotics were first being introduced, function allocation between humans and machines was based on the view that humans are "flexible but cannot be depended upon to perform in a consistent manner whereas machines can be depended upon to perform consistently but they have no flexibility whatsoever" (Jordan, 1963). This sharp summary was consistent with more detailed analyses of that time, which noted that humans surpass machines in ability to improvise and machines surpass humans in ability to perform repetitive tasks (Fitts, 1951, 1962). Since then, human consistency has been improved through methods that reduce boredom and fatigue such as job enlargement and job enrichment. Concurrently, the flexibility of robotics has been improved through multiple innovations in mechatronics and AI. For both humans and robots, potential for error has been reduced through methods such as design for manufacture, task analysis, job design, failure modes and effects analysis, statistical process control, etc. Nonetheless, the natural limitations of human performance continued to be a major focus in function allocation research (Johannsmeier and Haddadin, 2017).

The remainder of the paper comprises the following six sections. Next, in Section 2, the research methodology is described. Then, in Section 3, a review of extant literature is presented. Subsequently, in Sections 4–6, comprehensive, comparative and critical analyses are provided. In the concluding Section, 7, principal findings are stated, implications are discussed for research and for practice, and broader relevance to challenges in manufacturing technology management is described.

2. Methodology

Multivocal literature review was carried out to inform comprehensive, comparative and critical analyses. Multivocal literature reviews include grey literature as well as formal scientific literature (Bogdanski and Chang, 2005; Patton, 1991). Grey literature includes publicly available online information that may be produced by academia, business, communities, industry or government, which is not necessarily peer reviewed and controlled by commercial publishers. An example of grey literature is the 2018 Report of the World Manufacturing Forum. This is cited in Section 1 of this paper as the Report highlights the trend towards hyper-personalized manufacturing (WMF, 2018), which increases production variations. Grey literature is relevant to this study because of two reasons. First, the development of industrial exoskeletons has become a fast moving trend, which is being reported contemporaneously in online media. By contrast, the formal scientific literature can be less up to date. Second, the fabrication of exoskeletons is also being carried within do-it-yourself manufacturing for use or sale (Fox, 2013), and this is reported online in blog reports, etc. Formal scientific literature was searched via Scopus Search Engine. The following search terms were used: factory exoskeleton, industrial exoskeleton, manufacturing exoskeleton, factory wearable robot, industrial wearable robot and manufacturing wearable robot. No type of exoskeleton was excluded. Compared to other topics relevant to manufacturing technology management, such as lean or sustainability, there are relatively few papers concerned with exoskeletons. Hence, the most up-to-date papers were selected, which together provide coverage of exoskeleton scientific research, irrespective of geographical origin or journal publisher. Formal scientific papers were found to provide detailed information focussed on individual issues in exoskeleton functioning. By contrast, grey literature articles were found to provide less detailed information but broader scope. Hence, multivocal literature review can reveal scope and detail. During the research, accumulative iterations were made of reference to grey literature and scientific literature to build up step by step a broad and detailed review of the state of the art and research gaps from the point of view of manufacturing technology management.

3. Literature review – industrial exoskeletons state of the art

3.1 Background

The concept of mechanical exoskeletons has existed since at least the end of the eighteenth century. However, the first examples of functioning exoskeletons did not appear until the 1930s. By the 1950s, there was research focussed on developing mechatronics for exoskeletons. Then, in the 1960s, the USA's Department of Defense began to develop an exoskeleton system and General Electric Co. developed a wearable robot. Subsequently, there was little notable progress until the 1990s when advances in materials technologies enabled lighter stronger exoskeletons to be developed. Then, in the 2000s, advances in micro-electronics and computer power enabled development in wearable robotics. Throughout, there have been exchanges between research for healthcare applications and research for military applications (Battye *et al.*, 1955; Gopura *et al.*, 2016; Pons, 2008).

3.2 State of the art

Since the new millennium, there have been efforts to transfer developments from healthcare applications and military applications into industrial exoskeletons (Bogue, 2018; de Looze *et al.*, 2016). Studies concerned with implementation have focussed on a range of issues, including individual aspects of the design of exoskeletons (Ebrahimi, 2017; Sposito *et al.*, 2018), health and safety standards (Bostelman *et al.*, 2017; Masood *et al.*, 2017; O'Sullivan *et al.*, 2015) and simulating exoskeleton use (Constantinescu *et al.*, 2016; Karvouniari *et al.*, 2018). In particular, the automotive industry has been a focus of several studies and is a focus of commercial development of exoskeletons (Gonzalez, 2017; Spada *et al.*, 2017b; Sylla *et al.*, 2014). Typically, studies concerned with industrial implementations have paid little attention to the complexity of humans wearing exoskeletons. By contrast, studies focussed on the ergonomics of wearing industrial exoskeletons have revealed that there are many issues that need to be taken into account.

For example, recent studies concerned with the ergonomics of exoskeletons have revealed that wearing an industrial exoskeleton can reduce loading one part of the human body, but in doing so increase loading on another part (Picchiotti *et al.*, 2019; Weston *et al.*, 2018). For example, there can be reduced muscle activity in the shoulder and back of the arm during overhead working, but increased muscle activity in the lower back, abdomen and legs (Rashedi *et al.*, 2014; Theurel *et al.*, 2018). Also, an exoskeleton can be comfortable to wear against some parts of the human body but cause uncomfortable contact pressure onto other parts of the body (Bosch *et al.*, 2016; Huysamen, de Looze, Bosch, Ortiz, Toxiri and O'Sullivan, 2018). Hence, the whole of the human body, both inside and outside, needs to be taken into account when considering implementing any exoskeleton: even if it is an exoskeleton for just part of the body (Huysamen, Power and O'Sullivan, 2018). Otherwise, intended effects, such as improved strength and endurance, will be accompanied with unintended effects, such as problems with balance (Kim, Nussbaum, Esfahani, Alemi, Alabdulkarim and Rashedi, 2018; Kim, Nussbaum, Esfahani, Alemi, Jia and Rashedi, 2018).

Also, it is important to note that positive effects from wearing an exoskeleton for one task can switch to negative effects for a related task. For example, wearing an exoskeleton can make lifting easier but make carrying more difficult (Baltrusch *et al.*, 2018). Conversely, wearing another exoskeleton can make lifting more difficult and walking easier (Theurel *et al.*, 2018). If perceptions of positive effects are outweighed by perceptions of negative effects, perceptions of usability can be low among potential users (Huysamen, Bosch, de Looze, Stadler, Graf and O'Sullivan, 2018). Hence, the design of exoskeletons needs to take into account related tasks, as well as principal task (Alabdulkarim and Nussbaum, 2019). Moreover, design of exoskeletons should take into account the whole physiology of those who will wear them, and where they will use them (de Looze *et al.*, 2017; Spada *et al.*, 2017a; Toxiri *et al.*, 2017). However, the design of exoskeletons is often focussed on one task, such as lifting (Masood *et al.*, 2016), or one characteristic of a task, such as increasing the weight of what can be carried (Choo and Park, 2017) or one part of the body, such as lower back (Zhang and Huang, 2018).

3.3 Research gaps

Review of extant literature reveals three limitations from the perspective of manufacturing technology management. First, there is a lack of papers that consider the full range of exoskeletons. Rather, their focus is on one type of exoskeleton (e.g. Baltrusch *et al.*, 2018; Ebrahimi, 2017; Huysamen, Power and O'Sullivan, 2018; Masood *et al.*, 2017; Rashedi *et al.*, 2014), i.e. previous research does not provide comprehensive analysis. Second, there is a lack of literature that provides comparisons of exoskeletons to robots across the different manufacturing phases. Rather, studies have been predicated on the assumption that exoskeletons will be used in a particular phase (e.g. Constantinescu *et al.*, 2016; Djuric *et al.*, 2016; Karvouniari *et al.*, 2018; Spada *et al.*, 2017a; Sylla *et al.*, 2014), i.e. papers do not provide comparative analysis. Third, there is a lack of papers that encompass potential positive and potential negative outcomes, as well as the multiple factors required to bring about effects (e.g. Bogue, 2018; Choo and Park, 2017; de Looze *et al.*, 2017; Gonzalez, 2017;

Thompson, 2017), i.e. previous papers do not provide critical analysis. These shortcomings in previous research are addressed in the following three sections of this paper in order to address the three research questions:

RQ1. What are the attributes of different types of industrial exoskeletons?

RQ2. How can exoskeletons be deployed in different manufacturing phases?

RQ3. What are the effects of wearing exoskeletons?

4. Comprehensive analysis – different types of industrial exoskeletons

Comprehensive analysis encompassed identification and study of eight different types of industrial exoskeletons. Exoskeletons can be categorized in terms of sources of support and sources of power. Exoskeleton sources of support can be the human body, exoskeleton framework and/or external support such as a concrete floor. Exoskeleton sources of power can be human body, exoskeleton framework and/or motors, etc. Exoskeletons with motors can be described as active exoskeletons, while exoskeletons without motors can be described as passive. Exoskeletons can be worn for only a part of the body, worn for the whole body or can be worn to extend the body by providing extra limbs. It is important to note that exoskeletons can provide lift assistance of about 15 kilos (35 pounds). Thus, exoskeletons do not make humans as strong as robots. So, humans wearing exoskeletons still need to make use of mechanical equipment for heavy lifting such as Intelligent Assist Devices. On the other hand, it is important to note that cobots (collaborative robots) that work in close proximity to human workers typically cannot handle the same payloads as robots that work behind the safety fences of segregated work cells (Djuric *et al.*, 2016). Thus, a human worker wearing an exoskeleton can have more strength than a cobot.

As illustrated in Figure 1(a), exoskeletons for only part of the body include exoskeleton gloves. These can incorporate pressure sensors and actuators to mimic human nerves and muscles. By doing so, exoskeleton gloves can reduce by up to half the amount of force an assembly operator needs to hold a tool during a task (Davies, 2016). It is important to note that gloves, like the other types of exoskeletons described below, do not augment human capability to undertake work that requires very fine motor skills such as the most dexterous manual work involved in handling very delicate materials and/or small components.

Other exoskeletons for only part of the body also include exoskeletons for arms/shoulders, for back and for legs. Some exoskeletons can be designed to be used separately. As shown in Figure 1(b), these include “chairless chairs”, which are wearable chairs comprising two supports for the backs of the legs that reach the ground when wearers go into a sitting position by bending their knees.

As illustrated in Figure 1(c), exoskeletons for arms/shoulders, for back and for legs can be designed to be modular to enable them to be worn together as a whole body exoskeleton. Some such exoskeletons utilize human body support by transferring the weight of work from arms, shoulders, neck and upper back to the human body’s core musculature. This can reduce human musculoskeletal strain from highly repetitive lightweight overhead working. For example, musculoskeletal strain arising from human factory operatives using their own strength and powered hand tools to fix bolts to the underneath of cars (Gonzalez, 2017).

An alternative, which is illustrated in Figure 1(d), is that exoskeleton frameworks can provide support and power through the use of carbon fibre rods, which act as artificial tendons by bending when the wearer squats, and springing back when they stand up. The exoskeleton stores then release energy as the wearer bends and lifts, similar to a bow and arrow. Such exoskeletons can reduce human musculoskeletal strain from highly repetitive lightweight lifting (Thompson, 2017).

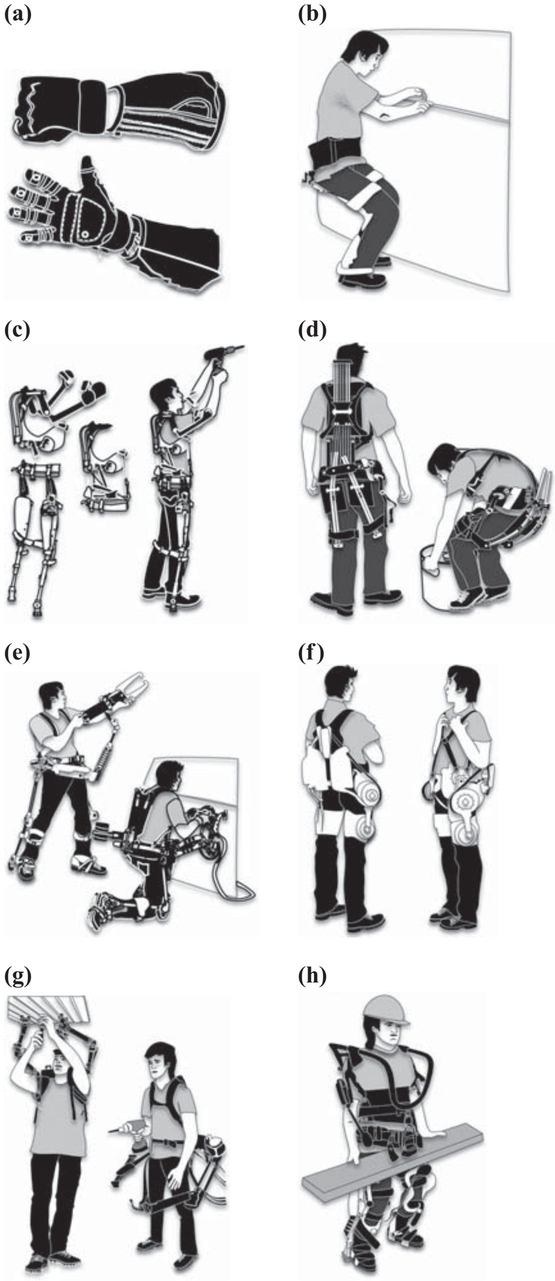

Figure 1.
Comprehensive analysis: eight different types of exoskeletons

Exoskeletons that can take support from adjacent infrastructure, such as concrete floors, can be useful for heavyweight work tasks. As shown in Figure 1(e), exoskeletons can provide direct support for heavy hand tools by transferring their load onto external support such as a floor, through a series of joints at hips, knees and ankles, and so bypass the wearer's body. Also as shown in Figure 1(e), exoskeletons can have gravity-balancing arms. An exoskeleton arm can be described as being gravity-balanced if its total potential energy remains invariant despite changes of its configuration during use. This can be achieved by inclusion of exoskeleton components that compensate for variations in the potential energy due to motion. For example, a gravity-balancing arm can be spring-loaded and counterweights can be included in the back section of the exoskeleton (Agrawal and Fattah, 2004; Liberatore, 2017).

As illustrated in Figure 1(f), powered exoskeletons can comprise bulkier framework sections. This can be because of the need to incorporate batteries, sensors, actuators and motors, as well as the need to withstand heavier workloads. For example, sensors can detect workers' motion and send signals to motors that rotate gears to provide back support (Burgess, 2016). As shown in Figure 1(g), powered exoskeletons can extend the human body by providing powered arms and/or powered legs. The human exoskeleton wearer can control these additional limbs to provide additional support for work pieces, etc. Such exoskeletons provide the examples of what can be described as wearable robotics (Parietti and Asada, 2016). As illustrated in Figure 1(h), the frameworks of exoskeletons can be made more elaborate and rigid in order to increase the loads that can be carried (Hodson, 2014).

Overall, Figure 1 shows that there are at least eight different types of exoskeletons that managers of manufacturing technology can consider as alternatives to robotics in different manufacturing phases.

5. Comparative analysis – exoskeletons for different manufacturing phases

Comparative analysis involved study of opportunities for application of exoskeletons, compared to opportunities for applications of robotics, in five phases of production from raw materials extraction/harvesting to installation of manufactured goods. Throughout this section, reference is made to four typical production categorizations: repetitive mass production, batch production of standardized products, configure to order production and concept/ETO production (Hill, 1995; Vonderembse and White, 2007). Based on prior research by others these are referred to, respectively, as Type 1, Type 2, Type 3 and Type 4, where Type 1 is characterized by low variety and high volume and Type 4 is characterized by high variety and low volume (Jonsson and Mattsson, 2003). It is important to note that exoskeletons can better enable human lifting and carrying in logistics operations throughout all the five phases. Also, exoskeletons can be useful in subsequent manual work related to recycling and remanufacturing operations.

5.1 Manufacturing materials extraction/harvesting

Much of raw materials extraction is heavily mechanized with large-scale capital equipment. Human work is involved in setting up large-scale equipment ranging from oilrig drill pipes to iron ore mine excavators (Type 4 production). Much of the human work involved is highly repetitive and hence well suited to robotics. Although the challenging locations of materials extraction sites can make robotics very costly, high costs are incurred in the context of what are already massive capital investments (Regan, 2017). The introduction of robotics brings big cuts to human workforces (Wethe, 2017). Some of the remaining human workers may be involved in remote operation of robotic materials extraction (Ghodrati *et al.*, 2015). For those still employed at mines, on oilrigs, etc., their work is likely to involve intermittent handling of heavy components, such as drill heads, for which heavy-duty exoskeletons are appropriate.

Much of harvesting work is also heavily mechanized with large-scale capital equipment. However, robotics in harvesting faces technical, practical and economic challenges. For example, varying light, dust, insects and other unavoidable image noises can confound accurate machine recognition, for example, of fruit ripeness, either by precision agriculture satellites or by agricultural robots on the ground (Pereira *et al.*, 2017). In addition to such technical challenges, there are practical challenges, such as irregular ground conditions that change due to weather conditions, etc. (Vidoni *et al.*, 2015). Typically, robotics is most viable at the huge flat fields of large-scale agricultural production. However, introduction of robotics is less viable for smallholdings where much of the world's agricultural production takes place amidst the technical and practical challenges arising from many different types of ground and weather conditions (Altieri *et al.*, 2012). Tealeaf harvesting provides an example of multiple challenges for robotics as follows: leaf maturity is difficult to recognize; leaves are fragile; and ground conditions can be irregular. Hence, human operated machines for tealeaf plucking have been introduced with different levels of automation depending on the tealeaf value, tealeaf fragility and ground conditions (Wijeratne, 2012). Some of these machines need to be held out over tea bushes for many hours during long working days (Han *et al.*, 2014). The musculoskeletal strain of doing so could be reduced by introduction of exoskeletons with gravity-balancing arms.

5.2 Conversion of raw materials into processed materials

Some of agrifood conversion of raw materials, such as milk, into processed materials, such as cheese, can be small scale in human artisanal "farm-to-table" (Type 2) production (Boyce, 2013; Hayes-Conroy, 2010). However, large-scale facilities are more typical in raw materials conversion (Type 1) production processes. For example, oil refineries convert crude oil into petroleum that can be shipped to chemical plants for processing into plastics; and pulp mills convert wood into fibreboard that can be shipped to paper mills for further processing. Such industrial processing is highly repetitive and well suited to robotics (Sharma, 2016). For example, it is reported that a steel mill, which once employed hundreds of workers, now needs only 14 employees to make 500,000 tonnes of steel wire per year. Of which, 3 of the employees monitor the steel mill's control systems, while the other 11 employees undertake maintenance work (Grossman, 2017). It has been reported that process industries have a long tradition of successful collaborative development between process firms and suppliers of new process-specific manufacturing technology (Lager and Frishalmmar, 2010). However, exoskeletons are not specific to particular processes in the conversion of raw materials. Rather, the full range of exoskeleton types could be needed from time to time for process plant maintenance work, which can be categorized as Type 4 ETO production work.

5.3 Manufacturing components

The higher the volume of components manufacturing, and the fewer tasks in component manufacturing, the greater is the potential for all work to be done with robotics (Schweder, 2017). Some high volume components can be standard, such as nuts and bolts (Type 1 production). Other high volume components can be product specific, such as car body panels (Type 2 production). Advances in robotics are extending the sophistication and the size of components that can be manufactured without human workers (Binder *et al.*, 2018; Gerngross and Nieberl, 2016). Such advances can reduce the work of humans to tooling changeovers. This can involve each human worker being assigned to one type of work task for a period of time, with only one type of exoskeleton being needed for that type of work task. By contrast, robotics is much less technically feasible and economically viable for manufacturing one-of-a-kind components manufactured in ETO (Type 4 production). This is because the forms and functions for one-of-a-kind components differ from one order to the next. Consequently, humans carry out work with general-purpose manufacturing equipment such as drills and lathes (Fox, 2014). Such craft-based Type 4 production parts manufacturing can involve one human worker carrying out a variety of lightweight tasks and heavyweight tasks. Accordingly, a range of exoskeletons could be needed for each skilled human operative. Hence, modular exoskeletons shown in Figure 1 can be most useful.

5.4 Assembling goods

Robotics has most potential for assembly of high volume goods involving minimal variation (Type 3 production). However, robotic assembly is not necessarily the most productive option for assembly of high volume goods. For example, one car maker invested EURO 10m in new technology that would install windshields on cars on the assembly line. Then, it turned out that maintaining the new production technology required twice as many workers as the company had previously employed installing the windshields (Harbour and Scemama, 2017). Such problems can extend to many production tasks. For example, one global car maker has replaced assembly robots with human workers. This is because the assembly robots could not handle increased uncertainty in the assembly tasks that they had been bought in to do (Gibbs, 2016). Such failings can even encompass all of production. For example, investments in robotics at Tesla slowed down production. So, its costly investment in automation was removed from its factory (Gibbs, 2018). Moreover, even when investments in robotics continue to be used, they can cause production defects that are more difficult to identify than conventional human errors, while having much more costly consequences than human errors (Charette, 2018). Such experiences are leading Toyota to invest in combining skilled human workers with robot assistants (Rothfeder, 2017). The modular exoskeletons shown in Figure 1 are well suited to car assembly work and are being developed with car makers (Gonzalez, 2017).

Other types of goods are assembled in fewer numbers with larger components that have more order-specific variation. Hence, the potential for robotic assembly is lower than in car assembly plants. For the largest engineered-to-order goods, such as one-of-a-kind ships, potential for robotic assembly is even lower (Type 4 production). This is because of uncertainty from one order to the next about the form and function of components and their interfaces in the assembly of the ship. The consequent need for continued employment of human workers has led shipbuilders to explore development of heavy-duty exoskeletons such as that shown in Figure 1(h) (Hodson, 2014).

5.5 Installing goods

The installation of goods can be associated with Type 4 concept/ETO production work, which is characterized by lack of repetition as it involves diverse work settings and goods that are at least to some extent location specific rather than wholly mass produced. Robotics has most potential for installing goods when there can be reliable robotic situation awareness at diverse locations. In particular, three-level situation awareness is needed, which involves robot perception (processing data inputs), comprehension (data evaluation) and projection (action selection based on data evaluation). Productive robot comprehension depends upon the robot having an accurate model of the work situation against which accurate sensory inputs can be evaluated. The robot's model can range from being preprogrammed to being learnt. However, neither will lead to accurate robot comprehension if the characteristics of the work situation are different for every installation job. Also, even if the robot's model is transferable between work settings, productive robot comprehension can be confounded by inaccurate sensory inputs (Endsley, 1995; Ghezala *et al.*, 2014).

There are many differences in work settings, which can limit the transferability of robot models from one location to another. Consider, for example, the installation of elevator guide rails in lift shafts. Smooth operation of the elevator depends upon small tolerances between it and the guide rails. However, lift shafts are constructed to much larger tolerances. Hence, the positioning, alignment and fixing of elevator guide rails is high precision installation work, which is carried out in low precision settings. For example, the fixing of guide rails is affected by uncertainty about the varying positions of steel reinforcement bars inside reinforced concrete. This leads to holes for fixings being drilled partially into the reinforced concrete and then the position of the hole having to be moved when the drill hits reinforcement bar. Also, concrete pitting, spalling and other surface defects vary throughout each shaft and from shaft to shaft. In addition, there can be wide dimensional variations within construction tolerances, which differ from within and between lift shafts. At the same time, maintaining equally strong task lighting throughout lift shafts is difficult as many other types of construction work are carried out at the same time. Hence, many different sub-contractors are trying to access limited on-site resources for temporary lighting. Together these factors limit the potential for accurate robotic situation awareness of interrelationships between lift shaft conditions and guide rail positions. Moreover, the positioning of guide rails is a highly iterative process through which the final positions of guide rails evolve. Thus, the potential for using machine-readable positional markers to inform robot situation awareness is limited, compared to other installation work such as assembling external walls from prefabricated panels (Fox, 2018).

Exoskeletons are an alternative for improving installation performance where there are such challenging conditions for reliable robotic situation awareness. Different types of exoskeletons can be needed because of the variety of tasks that can be involved. For example, full body agility can be required in carrying long guide rails through crowded construction sites and into lift shafts. Accordingly, lightweight exoskeletons can be needed for getting materials to the work setting. Then, installation can involve static heavy work, such as holding heavy tools while drilling and fixing into reinforced concrete. For such work, heavy-duty exoskeletons with gravity-balancing arms are appropriate. Where working space is so limited that there is only space for one human worker wearing an exoskeleton, but several work pieces need to be positioned, it is most appropriate to deploy exoskeletons such as those shown in Figure 1(h). In particular, bespoke wearable robots can be developed with additional limbs that are designed specifically to hold particular types of work pieces into position while they being aligned and fixed (Parietti and Asada, 2016).

A summary of the potential uses for exoskeletons in different production phases is provided in Table I. In particular, there is limited need for exoskeletons in the first three production phases and most need for exoskeletons in the installation of goods, while need for exoskeletons in assembly work depends much upon the extent to which goods are one of a kind. Typically, exoskeletons are needed in Type 4 production work (T4) and to a lesser extent in Type 3 (T3).

6. Critical analysis – potential positive and negative effects from exoskeletons

Critical analysis encompassed study of both potential positive effects and potential negative effects, as well as multiple factors required in applications of exoskeletons in manufacturing. Potential positive effects are reported in exoskeleton vendors' literature. These tend to overlook potential negative effects arising from the restrictions to human psychomotor functioning caused by wearing exoskeletons. A summary of enhancement and restriction provided by different types of exoskeletons is provided in Table II. Different types of exoskeletons can bring different types of restrictions with different potential negative effects, including balance problems (Kim, Nussbaum, Esfahani, Alemi, Jia and Rashedi, 2018), friction at support points (Bosch *et al.*, 2016; Huysamen, de Looze, Bosch, Ortiz, Toxiri and O'Sullivan, 2018) and unpredictable loading (Picchiotti *et al.*, 2019; Weston *et al.*, 2018). Thus, the wearing of an exoskeleton can address an obvious problem, such as reduce the strain on shoulder muscles caused by overhead work, but bring new less obvious problems, such as increasing strain on lower back (Rashedi *et al.*, 2014; Theurel *et al.*, 2018).

Production phase	Extent of robotics	Appropriate contexts for use of exoskeletons
Extraction/ Harvesting	Increasing robotics, which is well suited to large-scale extraction and harvesting but harder to implement in small scale operations	T4 heavy-duty exoskeletons for changing drill heads, etc., for automated extraction Lightweight exoskeletons for manual harvesting at smallholdings and for specialist high value crops
Materials conversion	Increasing robotics except for in artisanal agrifood production	T4 little need for exoskeletons in production processes, but full range of exoskeletons can be needed for various types of process plant maintenance work
Manufacturing components	Increasing robotics in parts manufacturing, but the uncertainty in ETO component production leads to continued use of general-purpose manual tools and equipment	T4 different types of exoskeletons needed for tooling changeovers, etc. Different types of exoskeletons needed for variety of task involved in ETO component production
Assembling goods	Increasing robotics, but limited to assisting human workers where there is assembly uncertainty	T3 exoskeletons needed for lightweight for highly repetitive tasks involving light components, and for T4 heavy-duty intermittent handling of heavy tools and components
Installing goods	Increasing robotics limited by uncertainty arising from wide variations in work settings and the difficulties of obtaining accurate sensory inputs in diverse work setting conditions	T4 different types of exoskeletons needed for the wide variety of tasks involved in installation operations. Bespoke wearable robots with additional limbs suitable for constrained working spaces

Table I.
Comparative analysis: exoskeletons and robotics

Type of exoskeleton	Enhancement (potential positive effects)	Restriction (potential negative effects)
Power glove (Figure 1(a))	Reduces hand force needed by up to half	Generation of human hand force is generated by wider musculoskeletal systems, which can be strained by erratic loading to hand when glove is and is not worn
"Chairless chair" (Figure 1(b))	Support for intermittent sitting	Mismatches between the standard height of the chair and the varying height of work tasks leads to balance problems that introduce musculoskeletal tension
Lightweight modular (Figure 1(c))	Transfer work load to core musculature	Highly repetitive use causes friction at support points
Full body carbon fibre (Figure 1(d))	Reduce strain from lifting	Limits human three-dimensional rotational movements that are typically involved in lifting
Full body gravity-balancing (Figure 1(e))	Supports the weight of heavy tools	Gravity-balancing arm may provide only two-dimensional support, but work may require three-dimensional movement
Lightweight powered (Figure 1(f))	Provides mechatronic support for handling loads	Limits human rotational movements that are typically involved in work
Powered additional limbs (Figure 1(g))	Provides immediately available extra support at work locations with limited access	Introduces multiple new and unpredictable loads to the musculoskeletal systems
Heavy-duty powered (Figure 1(h))	Increases human strength for carrying heavy loads	Greatly reduces the range of human movement

Table II.
Critical analysis: potential positive effects and potential negative effects

A critical analysis diagram is shown in Figure 2. This is in the format of a critical realist diagram (Pawson and Tilley, 1998). Although the foundations of critical realism are rooted in deep philosophical debate about the nature of reality (Bhaskar, 1978), an important and very practical aspect of critical realism is its recognition that events are open to an enormous range of codetermining factors (Mingers, 2014). Hence, it shown in Figure 2 that improved work performance from use of exoskeletons depends upon multiple enabling factors. In particular, context for the use of exoskeletons includes the work and worker. Work context includes the unsuitability of the work for robotics; load characteristics, such as the shape, size, weight of what is to be handled; and workspace features including volume and access. Human context includes musculoskeletal condition, psychomotor skills and technological self-efficacy. All of these are person specific. For example, some people are suppler than other people; some people have more psychomotor skills; and some people have more confidence in their ability to perform tasks successfully with new technologies (McDonald and Siegall, 1992). A person who has poor musculoskeletal condition, poor psychomotor skills and poor technological self-efficacy is less able to undertake manual production work with more complicated exoskeletons such as those shown in Figure 1(g). It is important to note that while skills and confidence may be able to be improved quickly through task-specific job training, improving poor musculoskeletal functioning can take years of physical therapy and related exercising (Peacock, 2017).

7. Conclusions

7.1 Principal contributions

This paper provides three contributions, which address three gaps in extant literature. The first contribution is to provide comprehensive analysis encompassing eight different types of exoskeletons. This is important as extant papers typically focus upon one type of exoskeleton. The second contribution is to provide comparative analysis that compares exoskeletons to robots in different manufacturing phases. This is important because extant papers are predicated on the assumption that exoskeletons will be used in a particular phase. The third contribution is to provide critical analysis that addresses potential positive outcomes and potential negative outcomes, together with multiple factors upon which

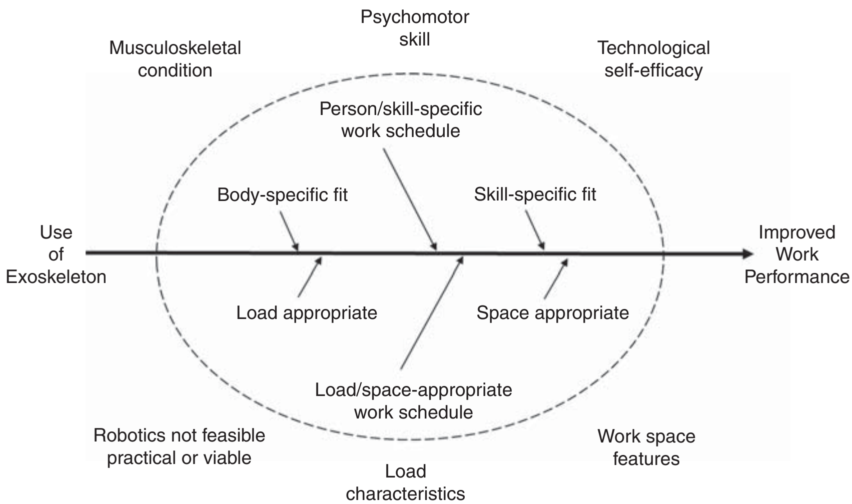

Figure 2.
Critical analysis: multiple factors required to enable successful implementation

outcomes depend. This is important because extant papers do not encompass consider positives, negatives and dependencies across a range of alternative exoskeletons.

7.2 Implications for research

Findings are relevant to function allocation research concerned with manual production work (Hancock and Scallen, 1996; Johannsmeier and Haddadin, 2017). Importantly, findings reveal that it is possible for the wearing of exoskeletons to have the unintended negative consequences of making human workers less flexible, because their movements are constrained by exoskeleton frameworks. Also, the wearing of exoskeletons could have the additional unintended negative consequence of making human workers less consistent as they suffer from unexpected loadings to different parts of the body (Picchiotti *et al.*, 2019; Rashedi *et al.*, 2014; Theurel *et al.*, 2018; Weston *et al.*, 2018). Thus, if their introduction is not managed carefully, exoskeletons could exacerbate the traditional trade-off between human flexibility and robot consistency (Fitts, 1951, 1962; Jordan, 1963) by making human workers less flexible and less consistent. Such outcomes are to be avoided in manufacturing organizations for at least two reasons. First, there can be negative health outcomes for human workers, such as new MSD and accidents. Second, robots are very far from being able to deal with increased production variations brought about by expansion of customization and personalization (Liu *et al.*, 2018; WMF, 2018). Hence, there is need for human workers who can deal with production variations, and who have improved strength and endurance that could be provided by careful introduction of exoskeletons.

Accordingly, an appropriate direction for future research is studies that can provide insights into how to avoid new MSD. Such research should encompass the role of the fasciae in transmitting loads around the human musculoskeletal system, and how physical exercise focussed on the fasciae can offset potential negative long-term effects (Schleip and Müller, 2013). The fasciae comprise bands and sheets of connective tissue beneath the skin that attaches, stabilizes, encloses and separates muscles. In doing so, fasciae provide an essential contribution to the human body's biotensegrity network. This involves unison of tensioned and compressed parts, with muscles and fasciae providing continuous pull and bones providing discontinuous compression. Hence, exoskeletons interfere with the wearers fine-tuned biotensegrity network. In particular, the rigidity of exoskeletons increases the standardization of human movements, which is contradictory to the human body's natural tendency to move with variation in every action in order to balance internal biotensegrity variations with external variations in load access, etc. (Levin, 2015; Swanson, 2013). However, physical exercises focussed on improving the fluidity of fasciae movement may be able to reduce negative effects (Schleip and Müller, 2013).

MSD are more likely to arise from repetitive motions whilst wearing exoskeletons for long durations than from occasional exoskeleton use. By contrast, accidents can be more likely during the occasional wearing of exoskeletons. This is because wearing an exoskeleton occasionally can increase cognitive load as the wearer engages in conscious thought about the exoskeleton as well as the work task itself. Importantly, increased cognitive load can negatively affect human postural control such as balance (Andersson *et al.*, 2002; Kim, Nussbaum, Esfahani, Alemi, Jia and Rashedi, 2018). Hence, another appropriate direction for future research is studies that can provide insights into increased cognitive loading caused by occasional wearing of exoskeletons. It can be anticipated that cognitive load will be highest for one-of-a-kind tasks in Type 4 production and installation work. This is because much conscious thought is required for the task itself, and for using exoskeleton in carrying out the task. By contrast, cognitive load is much lower in highly repetitive work, which is carried out with minimal conscious thought through the automaticity of muscle memory (Aarts and Dijksterhuis, 2000; Krakauer and Shadmehr, 2006). There are several well-established techniques for measuring cognitive load.

Some measures are sophisticated, such as measuring changes in eye pupil dilation caused by increasing task difficulty. Others are simpler, such as measuring the extent to which participants can undertake concurrent activities such as trying to count numbers aloud while undertaking a work task. Measurements of cognitive load are already being applied to some manufacturing work (Thorvald *et al.*, 2017), and can be extended in future research concerned with exoskeletons in manufacturing.

More generally, further research into exoskeletons in manufacturing should encompass efforts to integrate manual and automated operations (Cohen, 2015), especially, where manufacturing needs to be rapidly reconfigurable and the optimum allocation of work between humans and automation can change day by day (Andersen *et al.*, 2018). One issue to be researched is the relative applicability of different methods of time and motion study when the wearing of exoskeletons affects time and motion of interrelated actions positively and negatively (Baltrusch *et al.*, 2018; Theurel *et al.*, 2018). Another issue to be investigated is the effects of exoskeletons on workplace layouts. For example, exoskeletons can be quite bulky and take up extra space both when worn and when taken off. This could lead to need for larger workspaces where there is little extra space available (Jerbi *et al.*, 2010).

7.3 Implications for practice

The comprehensive analysis provides practitioners with guidance about what types of exoskeletons are available for different tasks. The comparative analysis provides practitioners with guidance about what types of exoskeletons to use in which manufacturing phases. The critical analysis draws attention to the potential for exoskeletons to replace established MSD with new MSD. Accordingly, the introduction of exoskeletons increases the need for workplace exercise programmes, which have hitherto been associated with Japanese factories and have been used to a limited extent in western workplaces (O'Gartley and Prosser, 2011; Vilela *et al.*, 2015). Also, it is important to note that wearing exoskeletons could lead to workplace accidents. For example, as well as increased cognitive load, there can be misalignment between the human anatomy and kinematics of the exoskeleton. Then, if the wearer needs to change posture quickly in order recover from poor balance due to anatomical misalignment and/or cognitive overload, wearing exoskeletons can reduce range of human lateral torsional motion and so increase stresses generated by balance-recovery manoeuvres. The more rigid the exoskeleton structure, the larger the reduction of human lateral torsional motion range and the greater the potential stresses generated by balance-recovery manoeuvres. While a large proportion of such injuries could be recorded in work injury statistics under body-stressing rather than in the fall-related categories, they should also be considered within the spectrum of hazards associated with gravity. Accordingly, the introduction of exoskeletons should involve thorough safety planning (HaSPA, 2012; Zanotto *et al.*, 2015). Overall, application of methods to improve production processes should take into account that the wearing of the same one exoskeleton can make some tasks easier but make other related tasks more difficult. Hence, it cannot be assumed that there will be overall improvement in process performance from wearing an exoskeleton. Rather, improvement in some tasks can be offset by worse performance in other tasks (Baltrusch *et al.*, 2018). Accordingly, application of methods such as failure modes and effects analysis should include thorough examination of interactions between exoskeletons' positive and negative effects.

7.4 Implications for manufacturing technology management in general

Together, the comprehensive, comparative and critical analyses are relevant to challenges of manufacturing technology management where managers are faced with different options for the same technology, which may or may not have positive effects in different manufacturing phases depending upon multiple factors. In particular, reference to comprehensive, comparative and critical analyses can support improved management decision making. For example, by presenting information in different formats such as pictures and tables (Huang *et al.*, 2006) that balance the sequencing of information presentation (Baird and Zelin, 2000) and draw attention to multiple factors upon which outcomes depend (Hodgkinson *et al.*, 1999). This can mediate bias in information from a single source such as a vendor (Klayman and Brown, 1993) and reduce overuse of one way of considering potential investments (Dearman and Shields, 2005). Accordingly, the comprehensive, comparative and critical analyses reported in this paper provide an example of how evaluation of new technologies can be improved in general.

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Corresponding author
Stephen Fox can be contacted at: stephen.fox@vtt.fi