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Exoskeletons: Productivity and Ergonomics in Logistics – A Systematic Review

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Exoskeletons: Productivity and Ergonomics in Logistics – A Systematic Review

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Purpose: *Exoskeletons are robotic wearables that have the potential to positively support employees during physical working operations. However, the technology is rather young, and long-term studies that could positively influence exoskeletons with respect to health, productivity, and ROI (and thereby support investment in it) are lacking. Accordingly, logistics companies are cautious about investing in exoskeletons. This paper identifies the research gaps that should be addressed in further research to change this situation.*

Methodology: *Based on an extensive literature review following the systematic approach of vom Brocke et al. (2009), this paper surveys current research regarding the impact of exoskeletons in intralogistics with respect to productivity and health.*

Findings: *Since exoskeletons in industrial contexts have been used mainly in pilot trials so far, few findings from long-term studies are available. Accordingly, the sustainable positive influence of exoskeletons on productivity and health cannot be empirically proved.*

Originality: *This paper identifies research gaps for a novel technology that could transform a sector which is characterized by a high proportion of manual labor, a high age average, a shortage of skilled workers, and beside increasing complexity.*

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1 Introduction

“Exoskeletons are wearable robotic systems that integrate human intelligence and robot power” (Chen 2016, p.1). Two goals are relevant to considering the implementation of industrial exoskeletons in operational logistics processes: Improvement of productivity and optimization of ergonomics (Dahmen et al. 2018a). Because logistics processes are still affected by a large amount of physical work, rising requirements, cost and performance pressure, and a lack of labor, strategies to reduce back-pain issues affected by repetitive lifting and moving of goods are needed to cover rising needs and requirements in this industrial sector. Exoskeletons have the potential to reduce back pain and support workers in lifting and moving processes (Constantinescu et al. 2016 I), especially in areas where layouts and working conditions cannot be easily changed (Ippolito et al. 2020). Exoskeletons can enhance strength, endurance and capacity and can thereby help to cover volatile peaks of demand, (reached especially during the Corona crisis). They can help to reduce repetitive strain occupational injuries, and their financial consequences (Bogue 2018, Burton 2020, Xie et al. 2014).

44 million Europeans suffer from musculoskeletal disorders (MSDs), 25% suffer from back injuries, and 23% of sick days in Germany are related to back injuries, caused by physical work. This leads to 10 billion euros of gross loss and 4% of gross national product annually (Bogue 2018, Burton 2020, Constantinescu et al. 2019, Koopman et al. 2020). Thus, exoskeletons exhibit huge economic potential both for countries and for companies.

Though exoskeletons have the image of being highly valuable for logistics and manufacturing optimization, statistical evidence and long-term studies that prove their effect on productivity and health and thereby support investment decisions are missing. So far, no reasons for this fact have been given, though the potential of exoskeletons to optimize productivity and ergonomics is stated in many articles.

By using a systematic literature review focused on empirical data and future research, this paper aims to discover why there is no holistic empirical evidence regarding the impact of exoskeletons in logistics.

2 Research Methodology and Literature Search Process

To determine why there is no holistic empirical evidence about the impact of exoskeletons in logistics despite many relevant articles in the literature, a systematic review of exoskeleton literature was conducted to follow out the thought that new knowledge is created by the combination of existing knowledge (Vom Brocke et al. 2019). The goal of this review was to compile scientific insights and empirical data based on structured testing and field research, thereby to identify further areas for investigation.

For the literature review for this paper, the theory of vom Brocke et al., based on Baker, and Durach et al. was chosen as an approved methodological framework, thereby facilitating a structured scientific overview of existing findings. While vom Brocke et al. follow a general approach, which fits rather well with exoskeleton technology, Durach et al. bring the industrial aspect of Supply Chain Management in (Baker 2000, Brocke et al. 2019, Durach et al. 2017). This combination provided a good fit for our research focus.

Based on the mentioned combined frameworks, the literature review used for this paper followed six process steps (Figure 1): 1) Definition of the research question; 2) definition of the research scope; 3) research conceptualization and definition of keywords; 4) literature search (database search based on keyword search); 5) literature analysis, evaluation and synthesis; and 6) research results and further agenda.

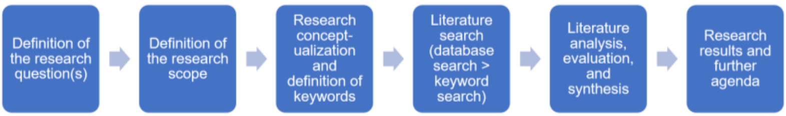

Figure 1: Literature-review process applied in this paper

In the following, the literature search process for this paper is described.

The research question defines the focus of the scientific work and the research scope (Phase 1): *Why is there no clear statement in the literature regarding the effect of exoskeletons on productivity and ergonomics in logistics?*

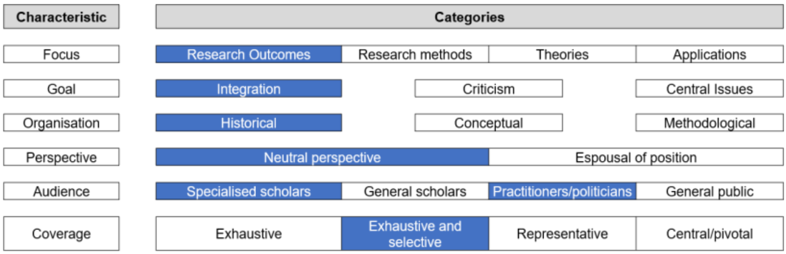

Figure 2: Taxonomy of literature reviews (following Cooper 1988, p. 109)

Based on the research question, a taxonomy matrix was created (Figure 2) to define the scope (Phase 2) of the literature analysis (Cooper 1988). Research outcomes were used, to understand why there is no clear statement in the literature regarding the effect of exoskeletons on productivity and ergonomics in logistics yet. An integrational approach was chosen to determine whether data exists already. This section summarizes the available data from a neutral perspective to shape future research investigation based on the current status quo. Focus groups for this paper include specialized scholars and practitioners from logistics, productions, and process disciplines. To initiate further research, an exhaustive and selective literature research procedure was chosen.

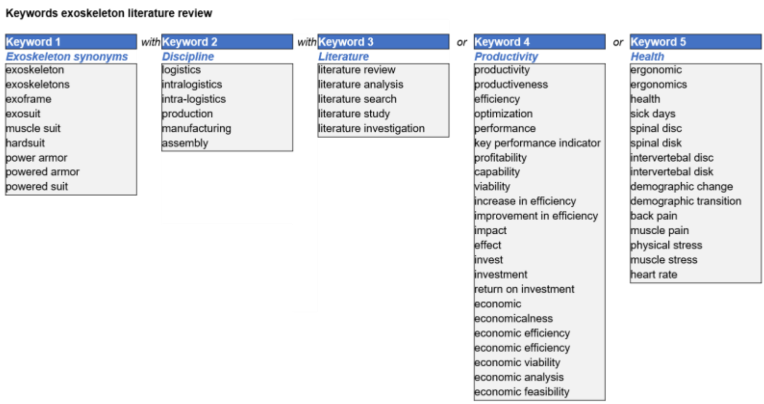

Figure 3: Keyword search concept

A catalogue of keywords was created and combined (Pateli and Giaglis 2004) to conceptualize the study (Phase 3, Figure 3). Synonyms were included, and the current state of research between the logistics and manufacturing literature was compared, as exoskeleton use was found to be mainly related to manufacturing. Further investigation was set to productivity and ergonomics content and empirical data. The first aim was to find out, if literature reviews already exist regarding exoskeletons, logistics, and impact on productivity and ergonomics by systematically screening reputable online data bases. The outcomes were documented in a concept matrix as a starting point for future research. Only English papers, preferably peer-reviewed ones, were considered; papers related to rehabilitation or the military were excluded.

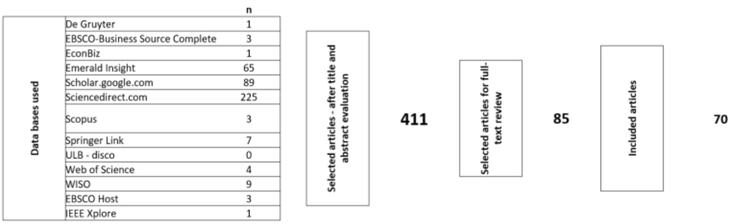

Figure 4: Paper extraction of the literature search

A total of 411 publications were identified in 13 databases (Phase 4). Title and abstract evaluations based on relevance, accuracy, and purpose were applied; whereby 85 articles were selected for a full paper analysis. After forward and backward analysis, 70 papers were included in this systematic literature review (Figure 5).

3 Literature Analysis and Synthesis

According to Cooper's taxonomy, the focus of this paper is set to identify missing research gaps (Phase 5). The findings were synthesized and documented in a concept matrix, thereby providing information regarding the content coverage, methodologies, and empirical data of the included articles to lay foundation for further scientific research into the application of exoskeletons in logistics and their influence on productivity and employee health.

Various synonyms for keywords were evaluated. *Exoskeleton* is the most common noun, found in the literature. *Powered suit*, *exosuit* and *muscle suit* created hits, while words like *exoframe*, *hard suit* or *power(ed) armor* did not yield much data. Therefore, the main keyword for the analysis became *exoskeleton*. More than 22,000 hits were found in all databases by searching only for *exoskeleton*. Many sources were found which are connected to the military and the rehabilitation of the elderly and invalids.

Taking the database of Emerald and combining *exoskeleton* with manufacturing terms such as *production*, *assembly* or *manufacturing* yielded 345 hits (10.05.2021), while the result for the combination with *logistics* or *intra-logistics* provided only 21 articles. This phenomenon suggests that a limited number of papers of exoskeletons in logistics exist compared to manufacturing. This finding can be retraced in other databases as well, as the results were familiar. Selected papers covered general information about exoskeletons (de Looze 2016), procedure models for implementing exoskeletons in logistics (Feldmann et al 2020) workplace designs to use exoskeletons (Dahmen et al. 2018a), and exoskeletons for age management (Grah 2020). In most papers, the potentials of exoskeletons are mentioned, but rather few papers provide specific data (Table 5).

Table 5: Concept Matrix

source	exoskeleton/exo - frame/exosuit/…	logistics	production/manu-facturing/assembly	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomics	empirical data	experimental results	measurement method	exoskeleton S) type	weights	tasks
Baltrusch et al. 2018	x						x	positive and negative results, decrease of performance in 7 out of 10 tasks (carrying, walking; improvement just in one. Difficulty increased in many of the tasks when wearing the ES; suitable for static tasks)	kg, time recording, distance. questionnaires	passive trunk ES	5-25 kg boxes	lower lifting, carrying, forward bending, one handed bank position, 6 minute walking test, sit to stand, stair climbing, ladder climbing, bending the trunk, wide stance, rotation of the trunk, squatting
Baltrusch et al. 2019	x						x	17 % decrease of metabolic costs during lifting 17 % increase during walking	energy expenditure, kinematics, muscle activity, metabolic costs	passive trunk ES		5 minutes of repetitive lifting, 5 minutes of walking w/wo ES
Bances et al. 2019	x	x	x		x	x		83 % reduction of injuries at assembly lines, liftable weight increased up to 50-70 %		passive ES at Ford		
Bogue, R. 2018	x	x	x									
Brown et al. 2003	x	x										
Burton 2020	x							analyzed fatigue reduction of shoulders and biceps, liftable weight increased about 50-70 %				

source	exoskeleton/exo-frame/exosuit/…	logistics	production/manu-facturing/assembly	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomics	empirical data	experimental results	measurement method	exoskeleton ES) type	weights	tasks
Butler 2016	x	x	x		x	x		improvement in productivity of 27-86 %; workers worked more efficient, more accurate and longer; muscle pain was reduced	muscle activity			welding and painting tasks
Chen 2016	x					x						
Chu et al. 2014	x				x							
Cimini 2020	x	x	x									
Cochran 2020	x		x			x						
Constantinescu et al. 2016 I	x		x									
Constantinescu et al. 2016 II	x		x									
Constantinescu et al. 2019	x	x	x			x						
Dahmen and Constantinescu 2020	x		x	(x) *no logistics, no productivity, no ergo.*	x	x						
Dahmen et al. 2018a	x		x		x	x						
Dahmen et al. 2018b	x		x									
Daub 2017	x											

source	exoskeleton/exo-frame/exosuit/…	logistics	production/manu-facturing/assembly	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomics	empirical data	experimental results	measurement method	exoskeleton ES) type	weights	tasks
De Looze et al. 2015	x		x	(x) *general ES review*			x	reduction of muscle activities in back, shoulder, arms, and legs (10–40 %); reduction in lumbar spine (23 - 29 %, static bending, dynamic lifting and lowering); Muscle activity reduction with active ES (20-35 % dynamic lifting, 40-65 % static holding, 70 % holding above head	26 ES from 40 papers, effect of physical loading for 13 ES; laboratory tests in small groups, statistical tests missing; muscle activity	passive and active; early stage ES	0.4-20 kg loads	holding, lifting, static bending, dynamic lifting and lowering
de Vries et al. 2019	x			(x) *arm ES*			x	reduction of muscle activity in the arms and shoulders (42 – 62 %), reduction of physical load w/wo ES, mixed findings and mixed results	muscle activity, realistic work activities	arm ES		over-head drilling, sanding, manual lifting, carrying weights, stacking and turning, gluing
Diefenbach et al. 2021	x	x										
Dimitropoulos et al. 2020	x		x									
Di Pascale et al. 2021	x		x		x	x						
Edirisinghe 2019	x											

source	exoskeleton/exo-frame/exosuit/…	logistics	production/manu-facturing/assembly	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomics	empirical data	experimental results	measurement method	exoskeleton ES) type	weights	tasks
Feldmann et al. 2020	x	x		(x) *focus procedure models*	x	x						
Fox et al. 2019	x		x	(x) *general ES review*	x	x						
Geregei et al. 2020	x	x			x	x	x	reduction of muscle activity (32 % bending, 40 % turning, 64 % squatting), no statistical difference between working w/wo ES, higher concentration in finding documents due to less fatigue with ES	muscle activity; logistician in a bank finds and handles documents, productivity comparison w/wo ES, laboratory simulation, labor productivity not accessed; speed in finding documents w/wo ES	ExoChair		moving documents, packed in standardized boxes; bending, turning, squatting
Gopura et al. 2009	x			(x) *S design*								
Grazi et al. 2019	x											Data based on primary literature
Hoffmann et al. 2020	x											
Hyun et al. 2019	x		x					reduction of muscle activity, enhancement of weight	muscle activity	H Vex		upper arm task above head in manufacturing

source	exoskeleton/exo-frame/exosuit/…	logistics	production/manu-facturing/assembly	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomics	empirical data	experimental results	measurement method	exoskeleton ES) type	weights	tasks
Ippolito et al. 2020	x	x	x			x	x	58 % reduction of muscle activity, general reduction of muscle activities, wearing an ES; extension of movements of injured fingers	computer analysis, muscle activity	finger ES	15 kg	lifting stone quarters, unloading
Jo et al. 2019	x						x					
Kaasinen et al. 2020	x											
Karre et al. 2017	x											
Karvouniari et al. 2018	x		x			x						
Kawale and Sreekumar 2018	x		x									
Khakurel et al. 2018	x					x						
Koopman et al. 2020	x						x	21 % reduction of compression force (static bending), 14 % lumbar flexion reduction (lifting), 13-21 % reduction of compression force for static bending, 14 % in average for lifting, indicating a reduction of strain	muscle activity, compression forces, kinematics	passive back ES	10 kg	lifting a box with three techniques (free, squat, stoop) in six height positions, bending
Kuhlmann and Klumpp 2017	x	x										
Lanotte et al. 2020	x											

source	exoskeleton/exo frame/exosuit/	logistics	production/manu-facturing/assembl	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomic s	empirical data	experimental results	measurement method	exoskeleton S) type	weights	tasks
Lee and Cha 2021	x	x					x	reduced fatigue due to load carrying, increased walking lap times (productivity loss)	statistical analysis, 10 volunteers, 3 phases, lap time as measurement of effectiveness	higher limb ES	15 kg	10 meter walking without load and without ES, walking with load and without ES, walking with load and with ES
Li et al. 2021	x	x				x	x	reduction of reduction oxygen level by 9,45 %, thermal discomfort during lifting	motion capturing, sensors, dynamometer (movement of joints), oxygen levels, thermal response tests	passive ES	20 kg	lifting loads of 20 kg from the ground up to 1.5 meters lifting of a 10 kg box to a 74 cm height; courier company
Liu et al. 2021			x				x					data on thermal response to wearing an ES during lifting and resting
Maltseva 2020	x		x									
Miehe et al. 2020	x		x		x	x						
Moyon et al. 2018	x		x		x		x	lower heart rate	heart rate w/wo ES comparison			work above head
O'Sullivan et a. 2015	x		x		x							
Poliero et al. 2020	x				x	x	x	12 % reduction of lumbar muscle activity, no clear evidence; efficiency increase for lifting, efficiency decrease for walking	muscle activity w/wo ES	passive back ES	1,2–16,2 kg loads	non-lifting activities: lifting, carrying, re-placing, walking evaluation of switching features on and off
Rogge et al. 2017	x											

source	exoskeleton/exo - rame/exosuit/…	logistics	production/manu-facturing/assembly	literature review/ analysis/search/ study investigation	productivity/ effectiveness	health/ ergonomics	empirical data	experimental results	measurement method	exoskeleton S) type	weights	tasks
Romero et al. 2016	x		x									
Roveda et al. 2020	x											
Sahashi et al. 2018	x								motion sensors			
Schmidler et al. 2015	x											
Schnieders and Stone 2017	x			(x) *S design*								
Schröter et al. 2020	x				x		x	reduced fatigue, improved concentration, lowered concentration errors	influence on human cognitive functions, hypothesis: higher productivity due to higher concentration and less errors; items per time		crossbars of 3,5 kg	positioning of a crossbar of 3,5 kg two meters above standing level, above head; fixing the crossbar by using a hammer
Sgarbossa et al. 2020	x	x	x									
Spada et al. 2017	x						x	increased stamina in holding, time reduction in 2/3 of tasks, time extension in 1/3 of tasks, higher fulfillment rates by 1/3; 30 % performance increase by decreased fatigue	laboratory testing w/wo ES; semi-structured interviews		3,5 kg	static task (standing upright, holding a load of 3,5 kg), repeated manual material handling task (moving of a 3,4 kg load between two positions), precision task (following a line at a wall with a pen)

source	exoskeleton/exo-frame/exosuit/…	logistics	production/manufacturing/assembly	literature review/analysis/search/study investigation	productivity/effectiveness	health/ergonomics	empirical data	experimental results	measurement method	exoskeleton S) type	weights	tasks
Stadler and Scherly 2017	x		x									
Staub and Anderson 2019	x		x									
Sylla et al. 2014	x		x		x	x		16,72 % reduction of mechanical energy, decrease of the process cycle time, productivity increase	untrained volunteers; reflexing markers, floor scales, motion capture technologies	ABLE ES	1,335 - 1,935 kg tool	screwing task 2 meters above the ground
Theurel 2019	x			(x) *general ES review*								
Todorovic et al. 2018	x		x	x	x							
Toxiri et al. 2018	x											
Toxiri et al. 2019	x		x				x	muscle activity: w ES < wo ES, best results for active ES	muscle activity w/wo ES	active and passive ES, lower back ES	7,5-15 kg	movement of loads between 2 positions
Van der Vorm et al. 2015	x		x			x						
Winkelhaus and Grosse 2020	x	x										
Winter et al. 2019	x	x				x	x	moderate relief effects of 5-10 %, no difference in bio-mechanical efficiency while lifting; decrease of productivity for walking tasks; no difference in cycle times for lifting	warehouse; acceleration sensors, motion recording and electromyographic measurements (EMG)	passive ES	3-50 kg	lifting the load, carrying and placing, walking without load, carrying in pairs w/wo passive ES, 5 -15 m of walking
Xie et al. 2014	x											
Yong et al. 2019	x				x		x	reduction of muscle activity: 24–39 %	muscle activity		0, 5, 10, 15, 20, 25 kg	lifting of loads w/wo ES

4 Research Results

This chapter presents the results of the research analysis. Productivity and ergonomic impacts are considered separately. We begin with a general overview of the image exoskeletons have in most analyzed articles.

Image of exoskeletons in literature

In all the papers that were analyzed, exoskeletons are considered as a way to improve worker performance as measured in terms of productivity, quality, and efficiency in logistics at least in sub-processes, and depending on the device and user attributes (Constantinescu 2019, Butler 2016, Dahmen and Constantinescu 2020). Precision increase is valued as an aspect of performance and workplace increase (e.g. of air-freight forwarders or ship builders), though cycle times might increase (Dahmen and Constantinescu 2020, Constantinescu et al. 2019, Diefenbach et al. 2021, Feldmann et al. 2020, Kawale and Sreekumur 2018). Enhancement of strength and an increase of motion intension are supposed and therewith, an achievement of higher performance (e.g. to carry and lift heavy loads and reduce risks for injuries; Chen 2016, Cimini 2020, Kuhlmann and Klumpp 2017). Scientists even see the potential that exoskeletons could replace loading technologies like forklifts (Brown et al. 2003, Burton 2020).

It is expected that exoskeletons can reduce injuries and fatigue, especially for tasks related to extended standing, heavy lifting, moving, carrying, pushing, pulling, assembling, repetition, constant bending, and un-ergonomic body postures when the required level of vigilance needs to be high and constant (Braces et al. 2019, Bogue 2018, Burton 2020, Constantinescu 2019, de Vries et al. 2019, Edirisinghe 2019). Exoskeletons are seen as a technology that may be used to support the Logistics 4.0 operator in the future (Di Pascale et al. 2021, Kaasinen et al. 2020; Karre et. al. 2017, Romero et al. 2016, Schmidtler et al. 2015, Winkelhaus and Grosse 2020). Exoskeletons also show potential for use in the biological transformation of hybrid manufacturing (Dimitropoulos et al. 2020, Miehe et al. 2020).

However, there are also negative assumptions: Productivity decrease due to limitations of movements and motions are expected (Dahmen and Constantinescu 2020). Effectiveness may vary, while decision makers have to consider the benefits compared to the costs of exoskeletons (Toxiri et al. 2019).

The positive impact of exoskeletons regarding ergonomics and health is attested in literature (Constantinescu et al. 2016 I). Exoskeletons are thought to have the potential to reduce workload; to support the upper body and hips during heavy-load handling; to prevent muscle pain, stress, and injuries; and to reduce costs and sick days due to musculoskeletal disorders (MSD; Bogue 2018, Braces et al. 2019, Brown, et al. 2003, Cochran 2020, Chu et al. 2014, Constantinescu et al. 2016 I, Khakurel et al. 2018).

Also, the social component is relevant: Exoskeletons can support the reintegration of disabled workers and can enable elderly people to extend their longevity and retain the capability to fulfill their tasks. Employers benefit in terms of resilience and cost reduction, flexibility regarding shortages at the job market, and by avoiding investments in automation technology (Dahmen and Constantinescu 2020, Staub and Anderson 2019).

In the future, exoskeletons may collect data on heart rate, stress responses and fatigue and thereby keep workers healthy and productive (Khakurel et al. 2018, Maltseva 2020).

Thus, most of the literature expects exoskeletons to impact productivity and ergonomic optimization, but it does not prove that this will happen. Most papers do not provide empirical data (compare Figure 5) and build on each other by referring to a limited number of test scenarios which state that it “might be” that exoskeletons will influence ergonomics or that it is “foreseen” that researchers will measure the impact of exoskeletons with simulations (Karvouniari et al. 2018, p.3 & 6). However, the impact of ergonomics still “has to be critically proven for all situations”, as Dahmen et al. wrote in 2018 (a, p. 3).

Therefore, the authors analyzed and systemized existing empirical data in the literature regarding productivity and ergonomics in industrial processes.

Data-based findings regarding the productivity of exoskeletons in the literature

Compared to the number of papers reviewed, the number of papers that deliver data is small (19:70 = 27, 1%, Figure 5).

Baltrusch et al. tested a passive trunk exoskeleton in general tasks which are not directly related to logistics. The exoskeleton affected performance both positively and negatively. A decrease of performance occurred in seven out of 10 tasks. Still, the potential for use in static, repetitive bending tasks was described (Baltrusch et al. 2018). Efficiency was found to increase in lifting, but to decrease in walking (Baltrusch et al. 2019).

Butler executed a field test in a welding company. He expected that the welders would feel less fatigue and would increase productivity. In a test scenario, he demonstrated an improvement in productivity of 27-86% due to the better blood supply in the muscles of the workers. The workers worked more efficiently, more accurately and longer, and muscle pain was reduced (Butler 2016). He found that exoskeletons can prevent fatigue by slowing muscle activities, which can reduce the risk of injuries during work (Butler 2016).

Ford tested passive exoskeletons in 2015-2016 and reported an up to 83% reduction in injuries on assembly lines (Bances et al. 2019), Iowa State University analyzed fatigue reduction in shoulders and biceps (Bances et al. 2019, Burton 2020).

Range of motions (e.g. arm ranges) can be increased by exoskeletons and liftable weight can be increased up to 50-70% (Brown et al. 2003, Butler 2016).

De Looze et al. conducted a review of 40 papers and 26 industrial exoskeletons in 2015, analyzing potential impacts on wearers (De Looze et al. 2015). Thirteen exoskeletons were evaluated regarding the effect on physical loading, holding, lifting, and bending. Reductions in muscle activities between 10% and 70% were evaluated (De Looze et al. 2015). For active exoskeletons, muscle-activity reduction between 20% and 70% (dynamic lifting, holding above head) was documented (De Looze et al. 2015).

Studies with arm exoskeletons showed a reduction of muscle activity in arms and shoulders (42 to 62%) and an extension of working endurance in realistic work activities (de Vries et al. 2019). Overhead manufacturing tasks were also evaluated (de Vries et al.

2019). Reduction of physical load was measured to compare ability with and without exoskeletons. Mixed findings and mixed results were documented in the studies (de Vries et al. 2019).

In another example, muscle-activity reduction of between 32% and 64% were demonstrated for the bending, turning, and squatting tasks of logisticians in a bank (Geregei et al. 2020). Searching for documents with an exoskeleton was faster than without, thereby showing a connection between relaxed muscles and concentration due to less fatigue and less muscle activity (Geregei et al. 2020).

Reduction of muscle activity and the enhancement of weight handled during an upper-arm and upper-head task were registered in manufacturing. Muscle activities were reduced with the exoskeleton working with and without load (Hyun et al. 2019).

Koopman et al. evaluated a passive back exoskeleton. They measured a reduction of compression of 21% while bending and of 14% while lifting (Koopman et al. 2020).

Lee and Cha did a statistical analysis of walking tasks with and without loads and exoskeleton, taking lap time as measurement of effectiveness (Lee and Cha 2021). They demonstrated that the exoskeleton reduced fatigue of workers while carrying loads. At the same time, the lap times increased, using an exoskeleton compared to walking without one. This means a decrease in productivity (Lee and Cha 2021).

Li et al. analyzed a logistics operator who lifted 20 kg loads with motion-capture software, sensors, and a dynamometer treadmill. The oxygen level was reduced by 9.45% (Li et al. 2021).

Poliero at al. tested exoskeletons in lifting, carrying, re-placing, and walking with 1.2 to 16.2 kg loads, with and without exoskeletons. Lifting activities were supported well, but a negative impact for activities like carrying was found. Lumbar muscle-activity reduction up to 12% was measured, but no clear evidence for exoskeleton efficiency was found (Poliero et al. 2020).

Schröter et al. 2020 analyzed the influence of support systems on human cognitive function in construction. The exoskeleton reduced fatigue, improved concentration, and lowered concentration errors (Schröter et al. 2020).

Spada et al. tested exoskeletons in static and repeated manual tasks. A 30% performance increase due to decreased fatigue was observed. Stamina in holding was increased. Time reduction was reported in 2/3 of the cases and time extension in 1/3, but the task was fulfilled by three times more volunteers with an exoskeleton than without (Spada et al. 2017).

Toxiri et al. compared the effects of exoskeletons while moving weights between two positions. In all cases, muscle activity with an exoskeleton was less than muscle activity without one. The active one especially showed efficiency (Toxiri et al. 2018).

An analysis of lifting tasks based on muscle activity was conducted by Yong et al. They demonstrated a reduction of muscle activities by 24% to 39% (Yong et al. 2019).

Only one example for exoskeletons in logistics was found. Picking, lifting, and carrying of parcels from pallets in a warehouse was evaluated with acceleration sensors, motion recording and electromyographic measurements (EMG). Moderate relief effects of 5% to 10%, no difference in efficiency while lifting, and a decrease of productivity for walking were identified (Winter et al. 2019).

Data-based findings regarding the ergonomics of exoskeletons in the literature

Compared to studies focusing on productivity of exoskeletons, there are even fewer empirical studies available regarding the ergonomics of industrial exoskeletons.

Many papers describe prototype testing of exoskeletons. Roveda et al. (2020) presented a design methodology for an active exoskeleton aiming to support the lower back by redistributing the spinal load and thereby relieving the operator (Roveda et al. 2020). Rogge et al. present the Stuttgart Exo-jacket and describe how functions could be designed and the impact of the exoskeleton can be analyzed. However, they mention that there are no standardized test procedures for exoskeletons (Rogge et al. 2017). Designing an exoskeleton is seen as difficult, as criteria include weight, performance, and comfort (Lanotte et al. 2020). Descriptions of the Robo-Mate project were summarized by O'Sullivan et al. (2015), and a qualitative study and interviews with farmers were conducted in 2020 (Omoniyi et al.2020). Schnieders and Stone (2017), and Stadler and Scherly (2017) summarized designs and exoskeleton types (Schnieders and Stone 2017).

Fox et al. (2019) describe the potential positive and negative effects of exoskeletons: e.g. reduction of forces, mechatronic support, reduction of strain, and transfer of loads. However, they do not provide concrete, quantified data (Fox et al. 2019). Furthermore, the impact of exoskeleton use depends both on the individual worker's health, body, and muscle conditions and on load characteristics like shape, weight, volume, and workplace (Fox et al. 2019).

Due to a lack of conversion methods to identify ergonomic impact, most available ergonomic investigation is based on virtual simulations (Constantinescu et al. 2019, Dahmen and Constantinescu 2020, Dahmen et al. 2018b). A computer analysis for lifting examined a reduction of muscle activity of 58% with an active exoskeleton. In addition, tests with finger exoskeletons proved the extension of movements of injured fingers (Ippolito et al. 2020).

Koopman et al. evaluated compression forces, muscle activity and kinematics, emphasizing that the exoskeleton might reduce the risk of low back pain during static bending and lifting activities (Koopman et al. 2020). The compression force was reduced by 13% to 21% for static bending and by an average of 14% for lifting, thus indicating a reduction of strain (Koopman et al. 2020).

Heart-rate measurements for ship-builder analysis demonstrated a much lower heart rate working above the head with an exoskeleton than without (Moyon et al. 2018).

Sylla et al. evaluated the ergonomics of an exoskeleton used to hit a target two meters above ground with a screw gun. They used reflection markers, floor scales, and motion-capture technologies. The exoskeleton reduced the mechanical energy up to 16.72% and decreased the process cycle time, which means a productivity increase.

5 Discussion

As demonstrated, only a limited amount of data is provided by the literature (Figure 5) to cover the influence of exoskeletons for operational logistics processes. Most articles that provide data regarding exoskeletons in an industrial context take pilot trials as a basis. Long-term studies are missing, and real-life data is rare, as most data is created in laboratories or by computer simulation. Accordingly, the sustainable positive influence of exoskeletons on productivity and health cannot yet be proved empirically. Therefore, two research questions are formulated for future investigation based on the findings of this systematic literature analysis:

RQ 1: Do exoskeletons increase productivity in logistics operations?

RQ 2: Do exoskeletons positively affect the health/ergonomics of workers in logistics?

To answer these questions, the following research gaps and potential further investigation must be considered:

No clear statements regarding the effects of exoskeletons

In the literature, you can find risk-management strategies, implementation procedures, decision guidelines, and other useful information regarding industrial exoskeletons; but no clear statement of the effects of exoskeletons exist at present. Most authors attribute to exoskeletons a high potential to support operational challenges like productivity, efficiency, ergonomics, safety, and integration of the elderly, but most papers do not provide appropriate data. It stands to reason that exoskeletons can improve productivity, but it is not clear to which extent.

Understanding the advantages of exoskeletons is partly given, disadvantages of exoskeletons or shifts of stain to other regions of the body are not analyzed yet.

Need of long-term studies

Most data provided by the literature covers trials and short-term test results. Long-term studies of the use of exoskeletons in industry have not yet been published (Dahmen et al. 2018a, Feldmann et al. 2020, Fox et al. 2019, Winter et al. 2019). Studies with appropriate numbers of participants, continuous screening, and long periods of use are needed to validate the effects of exoskeletons in practice and their potential to reduce work-related musculoskeletal diseases and sick days (Dahmen and Constantinescu 2020, Daub 2017, de Vries et al. 2019, Geregei et al. 2020).

Deeper investigation in logistics processes and tasks

In the current literature, only single-handling tasks, like static holding or dynamic lifting were evaluated. The trials were conducted mainly in laboratories, not in authentic environments that truly cover the challenges of logistics processes. Long term studies have not yet been conducted in factories or logistics facilities under real working conditions (Lee and Cha 2021, Poliero et al. 2020).

The complexity of logistics operations with experienced logisticians like changing packaging sizes and weights, picking, packing, forklift driving and changing tasks within one work shift have not been covered: The high diversity of tasks and features of exoskeletons makes it difficult to create a general estimate of whether and how exoskeletons support productivity increase (Dahmen et al. 2018a).

Standardized productivity-measurement methods for exoskeletons

To analyze the positive or negative efficiency of exoskeletons in logistics, a concrete scientific assessment methodology based on data is needed (Dahmen and Constantinescu 2020). Suitable methodologies for calculating the operational impact of exoskeletons based on key performance indicators (KPI) are needed (Dahmen et al. 2018a, Dahmen et al. 2018b). Methods-time measurement (MTM; or an analysis according to *Verband für Arbeitsgestaltung, Betriebsorganisation und Unternehmensentwicklung* (REFA)) is an option for the evaluation of these KPIs (Lee and Cha 2021). Optimization of time, cost and quality can be used to evaluate the return on investment potential of exoskeletons (Dahmen et al. 2018a, Dahmen and Constantinescu 2020).

Standardized ergonomics-measurement methods for exoskeletons

Data regarding effects on ergonomics is rare. Loads that are reduced at one body part might be increased at another (Fox et al. 2019), and counter activating due to external forces is possible (De Looze et al. 2015). Lifting and carrying of loads, static working postures, and repetitive work require a uniform scheme to examine the impact of exoskeletons (Daub 2017).

Limited variety of measurement technologies – new technologies needed

The main analysis methods used to evaluate ergonomics are the measurement of muscle activity and heart rate. Alternatively, computer simulation is used. New technologies that evaluate the impact of exoskeletons are needed. Virtual simulation might be useful, but concrete data is still missing. One option to collect data could be the transformation of exoskeletons to smart wearables, connected to the Internet of Things (IOT). This could create feasible real-time data and the option to document productivity increase and cost savings by data analytics and machine learning (Constantinescu et al. 2016 II). Exoskeletons need sensors to analyze the impact on the human body depending on the individual attributes of the wearer (Braces et al. 2019, Lee and Cha 2021). A continuous improvement in performance, ergonomics, risk of disorders and stress levels might be possible in future (Braces et al. 2019, Hoffmann et al. 2020, Ippolito et al. 2020, Sahashi et al. 2018, Sgarbossa et al. 2020).

Economic evaluation of exoskeletons

Also, the economic impact of exoskeleton effects needs to be addressed. Monetary and non-monetary methodologies, like static (cost comparison, return on investment, pay-off method) and dynamic (net present value, internal rate of return, equivalent annual cost) methodologies can be applied to document the effects in productivity and ergonomics (Todorovic et al. 2018). Key performance indicators, like cycle time, throughput, overall equipment effectiveness, or reduced overtime, can provide a basis for the evaluation of product and process quality (Baszenski 2012, Bokranz and Landau 2012, REFA 1997, Todorovic et al. 2018). For ergonomics, the reduction of sick days and the motivation of the employees are mentioned most (Todorovic et al. 2018). Evaluation could be applied in three phases: as-is situation, optimized situation with exoskeleton use, and comparison of both situations over a certain time (Todorovic et al. 2018).

6 Conclusion

The objective of this paper is to identify research gaps that should be addressed in further research to demonstrate the influence of exoskeletons on productivity and ergonomics of workers in logistics operations. This academic examination and additional empirical evidence will support the investment in exoskeletons to counter operational peaks, labor shortage, and high rates of sick days in future. A systematic literature review was conducted to analyze the current *status quo* in the literature.

To this point, there had been no literature review which systematically covered exoskeleton impact on productivity and ergonomics in logistics. This paper closes this gap.

Based on the findings from the literature, detailed information regarding the investigation processes was created and summarized in a concept matrix, thus providing an overview of exoskeleton articles, involved industries, effects and empirical data.

Most papers emphasize an effect of exoskeletons on productivity and ergonomics which would economically support an investment, but most papers do not provide data. The data that is presented, is based mainly on temporary tests and trials with few selected tasks that do not cover the whole range of logistics processes. Long-term studies, particularly ones regarding the impact of ergonomics, are lacking. There is currently no clear procedure for tackling productivity and ergonomic benefits. Furthermore, the use of sensors and computer calculation has not yet seen development.

Based on these findings, two research questions were formulated to pursue the study of this processually and socially important topic: *RQ 1: Do exoskeletons increase productivity in logistics operations? RQ 2: Do exoskeletons positively affect the health/ergonomics of workers in logistics?* Further research is needed to create relevant data. Deeper investigation of logistics processes and mid- and long-term studies regarding productivity and ergonomics are needed to prove the positive influence of exoskeletons. Extension of applied technologies, such as sensors or simulations, could support further research. In particular, the development of smart exoskeletons as part of the Internet of

Things could transform a sector currently characterized by a high proportion of manual labor, high age average, a shortage of skilled workers, and increasing complexity.

Negative impacts have not yet been studied. Long-term evaluations and additional measurement technologies are needed to evaluate the influence of exoskeletons on the health of their wearers.

Limitations are given. Literature reviews cannot be complete and always represent a snapshot of time. More research results might become available or may be published soon.

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