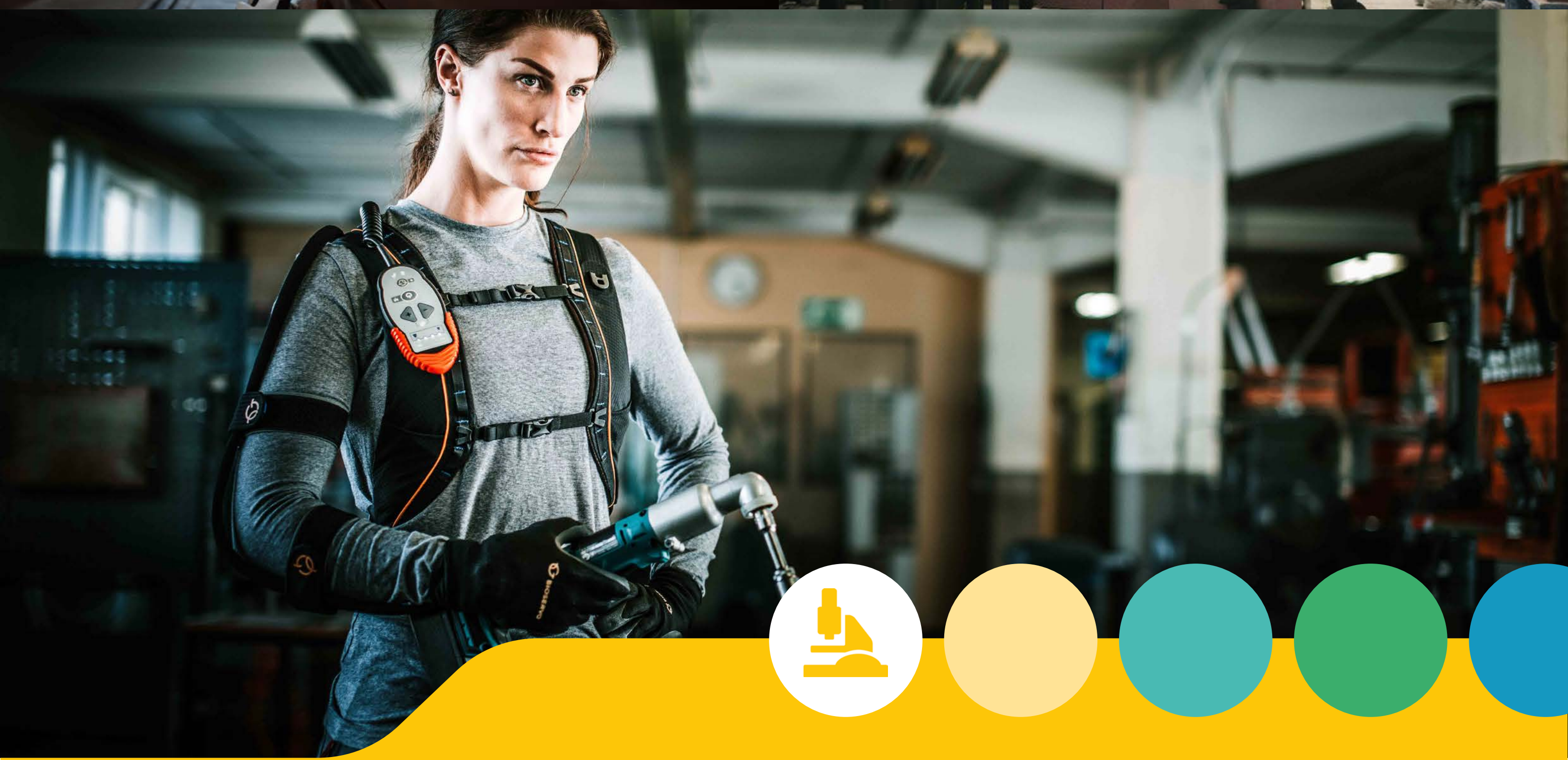
Interreg
North Sea Region
EXSKALLERATE
European Regional Development Fund

EUROPEAN UNION

EXOSKELETONS

Future exoskeleton technology application by 2030



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Introduction

For over a century, technologists and scientists have actively sought the development of exoskeletons designed to support or assist workers in heavy work. While many challenges associated with exoskeleton designs still exist, the advancements in the field over the course of the past decades have been impressive. Over the past 4 years the North-Sea region Interreg program 'EXSKALLERATE' has raised awareness with SME's regarding the benefits of passive occupational exoskeletons (OEs) through a series of workshops, and tested the use of exoskeletons extensively through field labs and pilot sites. EXSKALLERATE focused on promoting the adoption of passive OEs in the manufacturing and construction industry, and brought together stakeholders from different countries interested in the benefits of exoskeleton implementation in these sectors. The program's work has provided useful insights in applicability and required improvements to spur the adoption of occupational exoskeletons. With EXSKALLERATE coming to a close, this study looks ahead, envisioning the future for occupational exoskeletons.

In order to define the future of exoskeletons in the North-Sea Region and the rest of Europe, this report zooms in on the strategic thrusts that help to ensure a wider adoption of exoskeletons, delivering societal benefits, economic growth and increased competitiveness. The research will consider the facilitators, barriers and challenges that must be overcome to spur the adoption of exoskeletons. This scenario study aims to explore a future vision for exoskeletons in which two trajectories are mapped in a business-as-usual scenario and an intervention scenario. In doing so, this study equips readers with guidance for exoskeleton innovation and development.

Background

Problems and Trends

Over a decade ago, demographic trends indicated the number of older workers (aged 55 to 64) in the European Union would increase by 15% between 2010-2030, and the elderly population (aged 65-79) would increase by 37.4%. Meanwhile, the total working-age population (aged 15-64) was predicted to fall by 20.8 million (-6.8%) between 2005 and 2030. The main reasons for this demographic change are attributed to the ageing baby-boomer generation, an increase in life expectancy, and a significant fall in fertility. In 2022, the average birth rate in the European Union (EU) was estimated at 1.49 births per woman, compared to 2.7 births per woman in 1950. A fertility rate of around 2.1 births per woman is generally considered as the replacement level in developed countries to keep the size constant in absence of migration. Simultaneously, the life expectancy at birth in the EU has increased from just over 60 to about 80 years old.

The impacts of these demographic trends are expected to manifest increasingly over the coming decades. The share of working-age population (aged 15 to 64) in the EU-27 in 2021 was estimated at 64% of the total population (447 million). The total labour force in the EU-27 that year totalled just over 217 million, with an average unemployment rate of 6.4%. The share of working-age population is expected to fall while the proportion of elderly (aged 65 and over) is projected to increase over the coming decades.

Governments in Europe are trying to reduce the impact of the ageing effect on the labor force via pension reforms. In Germany the retirement age is gradually increasing, projected to reach 69 by 2029, while in Belgium the retirement age is forecasted to increase to 67 by 2030. In the Netherlands, the retirement age is set at 68 with a possible additional increase linked to an increase in life expectancy. Similar gradual upshifts of the retirement age can be observed in other countries throughout Europe, such as Spain (67 by 2027) Sweden (67 by 2026), UK (67 by 2028), Ireland (68 by 2028) and Czech Republic (67- 70 for people born after 1977). The upshift of the retirement age creates a new population group within the working class that can be referred to as the 'young elderly' (65 – retirement).

Functionality and Potential of Exoskeletons

An ageing workforce will become increasingly prone to musculoskeletal disorders (MSDs). Occupational exoskeletons have emerged as a supportive mechanism to augment human capabilities, making future work more age-appropriate. Occupational exoskeletons promise to create low-fatigue work environments, improving the health and quality of work of employees over longer periods of time. As a result, exoskeletons could reduce employee absenteeism caused by MSD related incapacitation.

Exoskeletons support workers in stressful body postures and movements and are dressed externally. The concept was first mentioned around 1968 by Ralph Mosher. Exoskeleton research and development first started in the military domain, focused on enhancing soldiers' strengths and endurance. Augmented performance in walking, running, and load carriage has been a common goal in this context. Exoskeleton development focused on reducing human energy costs to perform these activities and over time, the first exoskeletons for medical applications were developed to improve the conditions of physically impaired people or support injured patients during their rehabilitation process. More recently, the potential benefits of exoskeletons have attracted interest from industry.

While robotics and automation have reduced the need to expose people to heavy physical labour, workers are still needed for various reasons such as human flexibility, high motor skills or craftmanship. These workers continue to be exposed to phyisical workloads. Work-related musculoskeletal disorders (MSDs) remain the most common cause work-related incapacitation, resulting in significant costs for enterprises and healthcare systems. Exoskeletons could preserve human dexterity, agility, and adaptability, while reducing the burden physical labor exerts on the human body. Something the robotics field has been unable to achieve with industrial robots in specific situations and environments where the more common type of robotic automation is not possible. Furthermore, only limited modifications to the workplace are needed to integrate exoskeletons.

The exoskeleton market is comprised of different market segments; product type (soft / rigid), power type (active / passive) body type (e.g., arm support /back support / leg support), application (e.g., industrial / medical) or purpose (e.g., rehabilitation / assistance to worker). An occupational exoskeleton is meant to augment, amplify, or reinforce an individual's physical performance. Arm support exoskeletons are focused on supporting the shoulders, elbows, and wrists. Leg support exoskeletons provide support for the ankle, knee, or hip, while back exoskeletons provide support primarily for the lower back.

Active exoskeletons have an electric motor or hydraulic actuators, while passive exoskeletons make use of components such as springs to provide assistive power. Semi-active exoskeletons make use of low-power sources to provide increased adaptability to otherwise passive exo-skeletons. Currently, the exoskeleton market is largely dominated by passive exoskeleton technology, which is considered more practical, is not power restricted, and is much cheaper than active (powered) counterparts.

Occupational exoskeletons and exosuits are designed to play an important role in various sectors:

Medical: In healthcare, the growing population of elderly and disabled is generating growing demand for medical rehabilitation. Lightweight and flexible exosuits can replace traditional methods for daily assistance and muscle training purposes.

Military: Exosuits can be applied for military purposes, improving maneuvering speed, load capacity, and the endurance limit of soldiers. The exosuit can also become a mounting platform for equipment and weapons, enhancing the abilities of combat and survivability.

Manufacturing: Workers can perform manual labor such as lifting, carrying, overhead work and assembly using exosuits, reducing the physical workload. Additionally, exosuits can reduce work injuries from overstraining activities.

Agriculture: As in the case of the manufacturing sector, exoskeletons can assist the tasks of heavy work in the agriculture sector, decreasing the workload and fatigue of the workers.

Healthcare & Home care: Significant numbers of nursing personnel deal with back problems as a result of their duties related to manipulation of patients. The need for assistive tools and protective equipment increases in light of the current demographic trends of aging populations and the prevalence of chronic diseases in the EU population.

Public services: Workers in the public domain perform a range of services such as infrastructure maintenance, gardening or waste management, where exoskeletons can aid individuals in their tasks and ensure better safety and working conditions.

Construction: Due to the specificity of the changing environments in the construction sector, it is challenging to create adequate working conditions. Exoskeletons can be of significant help for workers at construction sites, ensuring safety and decreasing fatigue.

Logistics: In the logistics sector, heavy lifting and manipulation of heavy objects is a daily occurrence. Exoskeletons can aid the workers in some of the repetitive tasks they perform.

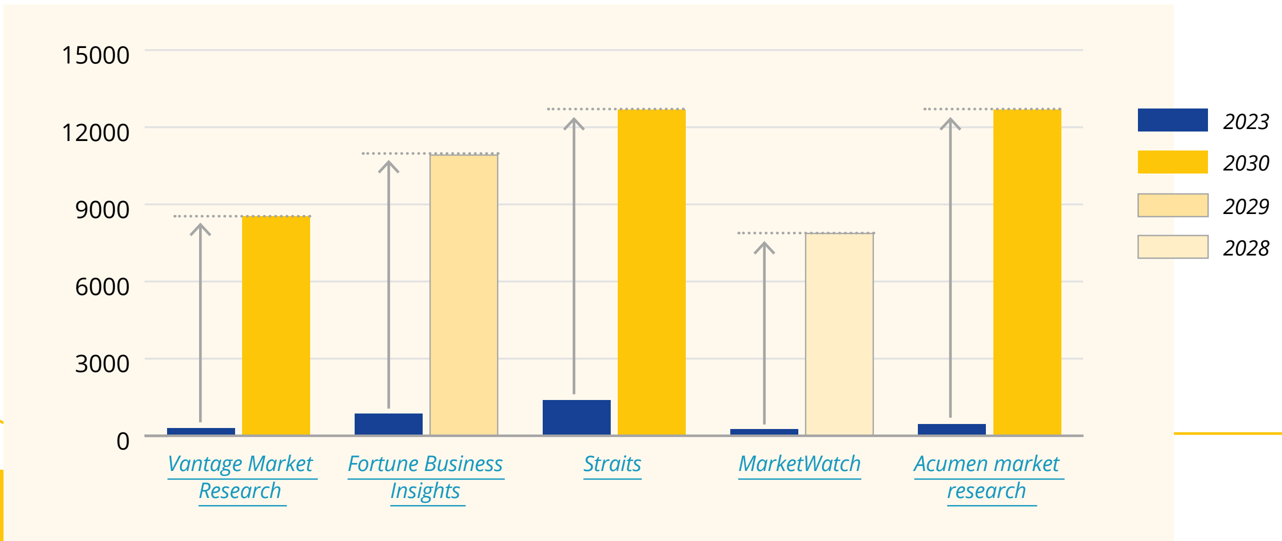
Personal: Exosuits may become part of our daily life as a smart wearable device used for power assistance when conducting physical activities.

State-of-the-Art
Exoskeleton technology with active components still resides in an early phase. Passive exoskeletons are specific in terms of the conditions where they provide support, resulting in a narrow field of application. In some professions, successful adoptions have been reported, but in many others design improvements are required to give meaningful assistance and truly gain acceptance.

Due to the relatively low product maturity, much of the development has until recently focused on the mechanical structure of the device and not human or organisational challenges. The mechanical structure of the exoskeleton concerns the design principles of the wearable (textile) architecture of the device. Technical definitions, standardisations and declarations of conformity are still under development. These issues all represent objective and subjective reasons for the low deployment of exoskeletons across industrial sectors. Indeed, few industrial exoskeletons are available to purchase as a final and certified product on the European market. In 2019, 62 industrial exoskeletons were under development, although not all are available on the market at present.

Nonetheless, the exoskeleton market is growing at a rapid pace. On average, market reports estimate the global market size for wearable robotics at about €1 billion in 2022. The European exoskeleton market alone is expected to grow from €500 Million in 2021 to over €4 Billion by 2030. Exoskeletons thus exhibit significant economic potential for both countries and companies. The total global market for wearable robotics is estimated to range from €8 billion to €14 billion by 2030. The graph below shows the expected growth of the global exoskeleton market between 2021 and 2030, as forecasted by various market research firms. The trends generally show a steep upward trajectory. Below some of the forecasts of market studies found online are visualised, showing the market will boom in the coming years, with a CAGR of 30% to 40% between 2022 and 2030.

Forecasted Trends of the Global Wearable Robotics Market



Methodology

This foresight study aims to provide a 2030 horizon for exoskeleton innovation and development. The study takes a mixed method approach, combining qualitative and quantitative data sources to describe four strategic thrusts for the adoption of occupational exoskeletons. Several methods were used to collect data including desk research, data collection from workshops, and interviews with stakeholders and experts. The study adopted a consensus development method known as Delphi method to gather insights from stakeholders and subject experts via brainstorming and discussion sessions. Over the course of the study two workshops were facilitated with partners from the EXSKALLERATE project. Additionally, 15 semi-structured interviews were conducted including experts from industry, academia, and public bodies. More information about the interviewees can be found in the *"Expert Interviews"* table in the Annexes.

Step 1 of the process involved the definition of the size and nature of problems stemming from an ageing and increasingly stringent labor force in the European Union, and the problem-solving capacity of exoskeletons in preventing fallout of workers through prevention of musculoskeletal disorders.

Step 2 of the process involved gathering insights related to the facilitators, barriers, and challenges for the adoption of occupational exoskeletons. A questionnaire for expert interviews was prepared on the basis of results from two brainstorming and discussion sessions conducted early in the study and additional desk research. The brainstorming and discussion sessions, expert interviews and desk research were used to gain insights into the state-of-play of exoskeleton technology.

Step 3 of the process involved the filtration and formulation of a list of main insights from the outcomes of the workshops, interviews and conducted desk-research. In addition, a shared aspiration for 2030 was synthesized on the basis of the outcomes.

Step 4 of the process involved the bundling of insights into 'vectors of transformation', a set of four driving forces that describe the strategic thrusts of occupational exoskeleton innovation and development to reach future-oriented objectives.

Step 5 is the last step, in which the strategic thrusts are used to inform a conservative and ambitious scenario for exoskeleton innovation and development. The scenarios present the strategic realities of stagnant or accelerated exoskeleton innovation by 2030 in light of the vectors of transformation.

Overview of the step-based approach

Snapshot	Insights	Bundled into 4 'vectors of transition'	Business as usual scenario 2030	Intervention scenario 2030
Size and nature of the problem exoskeletons address	Insights around exosuits present and future from interviews, workshops and desk research	Design and manufacturing sophistication & efficiency	Improvements across the board at a low pace. Mainly big corporations benefit, not SMEs	Optimal price / performance achieved for large users, SMEs and freelancers
		Evidence of clinical and economic impacts for workers	More evidence but truly clinical trial level evidence is lacking and not catered to SMEs	Clinical trial grade evidence with specific applicability also for SMEs and public sector
		Regulation, standardisation, business models and health insurance contexts	More standardized, more regulation, but a les than optimal shaped landscape	Optimal regulatory / standard / business model landscape also for SMEs
		Ecosystem connectivity between stakeholders across the EU and beyond	More connectivity among stakeholders but mainly between a large producers and users	Connected pan EU ecosystem including all stakeholders, SMEs and public sector

Size of the problem that occupational exoskeletons can help alleviate

New approaches in human resources and occupational safety and health management are required to enable and motivate people to continue working. By 2030, about 30% of Europe's ageing workforce will consist of workers aged 55 to 64. Across the EU the official retirement age is increasing, but raising the retirement age does not mean all people work up to these higher ages. Many workers leave the labour market well before reaching the official pension age. On average, workers in the EU retire at an age of 52. Workers in labour intensive sectors such as construction, manufacturing, logistics, agriculture, or healthcare generally retire earlier than the official retirement age due to work-related physical health issues.

Correlated with the aging workforce, the percentage of worker drop-out due to MSD-related complaints has been steadily increasing over the past 15 to 20 years. Ergonomic hazards such as repetitive movements, manual handling, awkward, uncomfortable or static postures are risk factors that need specific attention in case of older workers and for a healthier workforce overall. To address the negative effects of an ageing workforce on absenteeism and mitigate the impacts of shrinking employee numbers on the availability of skilled labour in a timely manner, businesses need to improve working conditions.

MSD-related incapacitation in 12 EU states (65% of EU population)

Country	Population (x million)	Days lost to MSDs each year (x million)
Germany	83,2	217,00
Spain	47,4	26,00
Poland	37,6	21,70
France	67,8	13,40
Austria	9	7,70
Ireland	5	7,00
Finland	5,5	5,15
Romania	19	3,15
Slovenia	2,1	2,47
Greece	10,6	1,20
Estonia	1,3	1,02
Total	**288,5**	**306,00**
EU-27	**447**	**474,1**

Source: Fit for Europe

Roughly extrapolating the estimated number of MSD-related sick days taken by the workforces from 12 EU states, the EU-27 loses around 474 million days to MSDs each year. This corresponds to about 1.8 million annual full-time equivalents of work hours (FTEs) lost.

The total cost of MSDs for all EU countries in lost productivity, costs of treatment and early retirement is estimated at 300 billion EUR annually, roughly 2% of the EU GDP. With an ageing workforce, injury prevention becomes increasingly important as the risk of catching work-related MSDs caused by physically straining activities typically increases with age.

Construction, manufacturing, transportation and storage, agriculture, human health, and social work activities report the highest MSD complaints among workers, with backache as the most prevalent. Literature reviews and country-specific data do not change the overall picture that MSDs are more prevalent in physically demanding occupations.

Percentage of workers reporting MSD-complaints in the last 12-months for top sectors

	Back Pain	Upper Limbs	Lower Limbs
Agriculture	60%	56%	46%
Construction	52%	54%	41%
Human health (nurses, midwives & home care)	47%	46%	31%
Manufacturing	46%	43%	28%
Logistics	46%	37%	26%
Average	**50,20%**	**47,20%**	**34,40%**

Source: EU-OHSA

The clinical and economic impacts of an increasingly ageing workforce will therefore be most noticeable for companies in labour intensive sectors. Roughly 74 million people or 34% of the EU-27 workforce are employed in the five sectors reporting the highest number of MSD-complaints.

Share of the EU-27 labor force working in top sectors for MSD-related complaints

	EU Employment (x millions)
Agriculture	8,70
Construction	18,00
Human health	7,50
Manufacturing	29,00
Logistics	11,00
Total of sectors	**74,20**
Total labor force	**217,00**

Source: Europa.EU

Most workers in the EU are employed by small and medium sized enterprises (SMEs). SMEs represent 99% of all businesses in the EU. Eurostat data estimates 67% of the total EU workforce is employed by SMEs. More sector specific, in the manufacturing sector, 55.4 % of workers are employed with an SME, while in the logistics and construction sector, 54.2% and 88.5% of workers are employed by an SME respectively. The agriculture sector is dominated by SMEs, with small-farmers often organised in cooperatives. Finally, while healthcare professionals such as nurses are often working for larger organisations, 78% of home care providers employ fewer than 49 people. The homecare sector is thus dominated by small enterprises.

Occupational health and safety conditions are generally poorer in SMEs compared to large enterprises. Workers of SMEs are therefore more likely to sustain work-related MSDs. Fatal accidents are nearly eight times more likely to happen in SMEs and nonfatal injuries are as much as 50% more likely to happen. The lack of financial resources of SMEs pose a problem, as it is more difficult for SMEs to identify and implement preventative measures. Evidence suggests that the risk for injury including fatalities occurs at higher rates for SMEs compared to sectors dominated by large-sized organisations. Due to widespread availability of resources, large enterprises are able to provide better workplace conditions (e.g. high level ergonomics, proper functioning equipment). Nevertheless, it is crucial to increase the health and safety work conditions in both large corporations and SMEs.

A 2030 Horizon for Exoskeletons

Outcomes of the Literature Reviews, Workshops and Interviews

Occupational exoskeletons can provide significant added value in addressing MSD-related fallout of workers and improving the overall well-being and performance of the labour force. However, in order to spur adoption of occupational exoskeletons in the EU, experts recognise additional innovation and development is needed. Through consensus seeking expert online workshops, internal synthesis sessions and discussion rounds with relevant actors in addition to expert interviews, an image of the future for exoskeletons was created. From all these efforts, a shared aspiration for 2030 was derived. The vision statement reads:

By 2030, occupational exoskeletons are rapidly integrating into the work environment in all segments of society (including SMEs), to make workplaces more age-appropriate. Occupational exoskeletons make jobs more attractive, contribute to sustainable employment and prevent work-related MSDs by supporting workers with physically straining tasks, reducing the drop-out of workers with work-related MSDs in the process.

Furthermore, a number of key insights were gathered from the received feedback, further substantiated by literature research.

20 Insights on Exoskeleton Technology and Development

1. **Present day rigid passive exoskeletons are too bulky, limiting the locomotion of users, especially in cramped spaces.** The rigid exoskeleton adds on significant volume, protruded parts limit the mobility of users. This makes such rigid exoskeletons quite impractical to work with for longer periods of time and on a semi-continuous basis throughout a work day. Moreover, present day rigid exoskeletons are too heavy due to the materials used in their components. This provides problems in terms of user comfort and wearability when the weight of the system is exerted on the human. Weight is one of the main complaints of users of exoskeletons, together with discomfort caused by less than perfect fit.

2. **Application fields of passive exoskeletons may be more limited than originally hoped for.** This is because of their spring-based working mechanism that only provides support in back flexed and arms elevated postures.

3. **Present-day soft exoskeletons do not always provide the performance needed for optimal impact due to the limited assistive performance they can offer.** Soft exosuits are more suitable for applications that require lower levels of assistance, where the wearer does not have bone or joint conditions.

4 **Purchasing prices of particularly rigid exoskeletons are too high for many companies to invest in them.** Specifically, SMEs have limited capital. The price of exoskeletons is clearly affected by direct costs such as manufacturing, distribution & marketing, but also by the one-time investment in product development and certification shared over limited total production volumes through the lifetime of a specific product version. Despite the fact that some SMEs can afford to purchase exoskeletons, the return on investment is not yet clear, making it a barrier for the SMEs to consider the purchase.

5 **Present day designs reflect evolutions from original small series production concepts, and make use of traditional materials** such as high tech fabrics, polymers (including fibre reinforced plastics), aluminum alloy, titanium or titanium alloy. Soft exosuits are more suitable for applications that require small levels of assistance, where the wearer does not have bone or joint conditions. In general, cutting edge materials (e.g. memory foams, 3D printed carbon fibre reinforced custom-fitted parts, 3D textiles with extreme breathability, thermally adjustable polymer fitting parts such as those used in latest generation ski boots) are not commonplace in exosuits.

6 **Present day exoskeletons are often produced as one-size-fits-all models or produced in 3-4 sizes at best, to a large extent not capable of adjusting to non typical body types and often not envisioned for female body types.** In some cases, limited adaptability is achieved by means of basic technologies such as velcro. This negatively impacts the wearability of an exoskeleton, especially over longer periods of time.

7 **Very few exoskeletons on the market have personalised / customised parts to improve fitting.** Human-in-the-loop optimisation of occupational exoskeletons is crucial for their adoption. Experts have indicated this problem is even more apparent for female workers, as exoskeletons are developed based on a male physique. This will lead to the overall ease of use of the exoskeletons.

8 **Present day exoskeletons are produced in low to mid volumes (thousands rather than tens of thousands, let alone hundreds of thousands).** Exoskeleton technology is still in its infancy, and the stage of mass production has not yet been reached. The high costs of exoskeletons form an adoption barrier for many stakeholders, limiting the demand for exoskeletons.

9 **Exoskeleton development often does not involve cutting edge novel materials and manufacturing technologies.** Exoskeletons are first or second generation technologies that make use of traditional materials and efficient manufacturing technologies and processes.

10 **Today's health impact evidence has not followed the reference standard methodology of clinical trials.** Control groups are not commonly used , sample sizes are small or one sided, and a strict comparison in equal conditions between an intervention group and an non intervention group is thus lacking.

11 **Today's health impact evidence is often obtained by experiments carried out with large adopters / users of the technology.** However, SMEs represent 90+% of all the businesses in the EU. SMEs have less financial capital and often cannot invest as large corporations in testing out new solutions for keeping their workforce happy and healthy until retirement.

12 **Today's economic impact evidence fails to convince most prospective adopters.** In particular, SMEs require more evidence before committing already limited resources to acquiring exoskeleton technology. The positive impacts and return on investment need to be clear.

13 **Standardisation is emerging, but far from complete.** Mechanical structures and technologies are not following the same design principles or materials and manufacturing guidelines.

14 **Regulation for the use of exoskeletons is still in its infancy.** The lack of rules and compliance results in a less-than-perfect landscape for exoskeleton application as there is no standard for how exoskeletons should be used, protecting the worker and defining the added-value for the buyer.

15 **Insurance pays, pay-per-use and other non classical business models are not yet commonly used.** While some high-end exoskeletons are available via hardware-as-a-service models. most exoskeletons remain beyond the reach of interested parties with limited capital.

16 **The present European exoskeleton ecosystem mostly consists of researchers, some smaller manufacturers and a few larger manufacturers, fostering little transnational collaboration.** Few potential users and health authorities are involved. Many partial networks exist within national borders that do not coordinate much on an EU level. There is limited knowledge sharing between stakeholders, slowing the pace of development.

17 **EU level funding for exoskeleton R&D&I and for research into impacts is limited, which restricts the scale of investment.** Manufacturers have little capital to invest in innovation as there is limited offsetting of products. The lack of funding therefore hinders market innovation and accelerated upscaling. This is especially true for higher risk 'breakthrough' innovation that could truly deliver significant changes in product sophistication and ROI of exosuits.

18 **Widespread adoption of exoskeletons could reduce economic costs caused by MSDs by billions of euros per year.** Exoskeletons can reduce healthcare costs and losses in productivity by preventing MSDs and reducing the amount of workers choosing (or forced into) early retirement due to MSD-related complaints.

19 **There is a lack of awareness and acceptance of exoskeleton technology as an assistive tool (or as Personal Protective Equipment PPE) in the workplace among workers.** The lack of acceptance and awareness creates social resistance to the technology within the workplace, manifested via alienation or negative preconceptions.

20 **The market for exoskeletons is emerging at a rapid pace, with the wearable robotics market expected to grow by 30 - 40% CAGR between 2022 and 2032.** Market research widely believes in the potential of the wearable robotics market, which is expected to grow worldwide from €1 billion to €14 billion by 2030. In the EU the market is expected to grow from €500 million to €4 billion in the same period.

Vectors of Transformation

The previously mentioned insights are bundled and translated into four vectors of transformation. These vectors represent the overarching strategic thrusts that are key in spurring market growth and exoskeleton innovation. High-level initiatives stemming from these thrusts can help to guide action plans over the coming years.

TRANSFORMATION VECTOR 1

Design and Manufacturing Sophistication & Efficiency

Passive exoskeletons are significantly cheaper than their active counterparts. However, in order to achieve widespread adoption of exoskeletons in the working environment, the price of both passive and active exoskeleton technologies must decrease. Stakeholders unanimously agree the price of exoskeletons is currently too high for widespread adoption, especially amongst SMEs. The high unit costs in combination with the uncertainties that remain regarding the economic efficiency gains form a barrier for market adoption.

The high costs per unit can be attributed to the immaturity of the market, with structural issues such as high marginal costs per additional unit produced, the use of product specific and capital-intensive materials and a lack of standardisation.

*Present day prices of various exoskeletons (2022-2023)**

PASSIVE (RIGID)		PASSIVE (SOFT)		ACTIVE & SEMI-ACTIVE	
SuitX LegX (leg support)	€4.576	**Herowear** Apex 2 (Back)	€1.192	**German Bionic** Crayx (Back)	€16.000
Skelex 360 XFR (overhead)	€4.500	**Herowear** Apex 1 (Back)	€1.100	**German Bionic** Apogee (Back)	€9.000
Ottobock Backx / Shoulderx	€3.990	**Auxivo** Liftsuit (Back)	€908	**AWN** (Back Support)	€5.560
SuitX BackX (Back support)	€3.660			**Ottobock Legx** (Lower Limb)	€5.000
SuitX ShoulderX (arm fatigue)	€3.660				
Laevo V2.5 (Back)	€2.657				
Hilti EXO-O1 (Overhead)	€1.864				
Auxivo CarrySuit (upper body)	€1.706				
Average Price	**€3.327**	**Average Price**	**€1.268**	**Average Price**	**€8.890**

** While these prices reflect values found online, none are officially confirmed by manufacturers. Actual prices will vary per geography and purchase volumes. Therefore, these prices should only be seen as indicative price points.*

In an effort to reduce the costs of exoskeletons, manufacturers have adopted various strategies:

Design simplification: A strategy employed to reduce the cost of exoskeleton devices is to take existing designs and remove non-essential components. Exoskeletons focusing on reducing physical stress to the back do not have to be designed as a full-body exoskeleton. For repetitive tasks, exoskeleton devices can function without many active components or extensive adaptability functionalities, and lower weight lifting requirements can be met with cheaper, lower-performance materials. Design simplifications have led to lower production costs.

Single-purpose exoskeletons: Specialised exoskeletons are designed to perform a single task. These exoskeletons are generally smaller and lighter than their counterparts. Creating specialised devices reduces the costs of the exoskeletons.

Passive exoskeletons: Passive exoskeletons use the same logic as "design simplification," but active components are removed altogether. Non-powered exoskeletons have no sensors, motors or controllers and are purely mechanical devices. This lowers the cost of exoskeletons to the absolute minimum and makes the exoskeleton devices easier to refine and redesign. Furthermore, design for manufacturability, also known as value engineering, and mass production can drive down costs. However, there is a trade-off in terms of performance as compared to their active counterparts. Soft exoskeletons take design simplification to the extreme, removing most, if not all of the rigid components. However, the performance of soft exoskeletons when compared to rigid passive exoskeletons is significantly lower due to the limitations of fabrics as opposed to rigid materials. This makes soft exoskeletons more useful for low intensity tasks.

Based on feedback from experts, the average price for rigid passive occupational exoskeletons likely needs to drop another 60% to around €1.000 per unit by 2030 to drop below the price barrier currently preventing large-scale adoption by the market. For passive soft exoskeletons, the buy-in price barrier should be even lower. A quick scan shows prices of soft and rigid passive exoskeletons on the market currently roughly range from €900 to €4.600, depending on the quality, performance and use case of the exoskeleton. Assuming similar price developments for the various exoskeleton types, the average price of exoskeletons will therefore have to come down by roughly 60 % on average to reach the buy-in price barrier by 2030. Active occupation exoskeletons with similar design purposes (e.g., back, lower-limb) now range from €5.000 to €10.000 and could drop to as low as €3.000 if a 60% price reduction on average can be achieved.

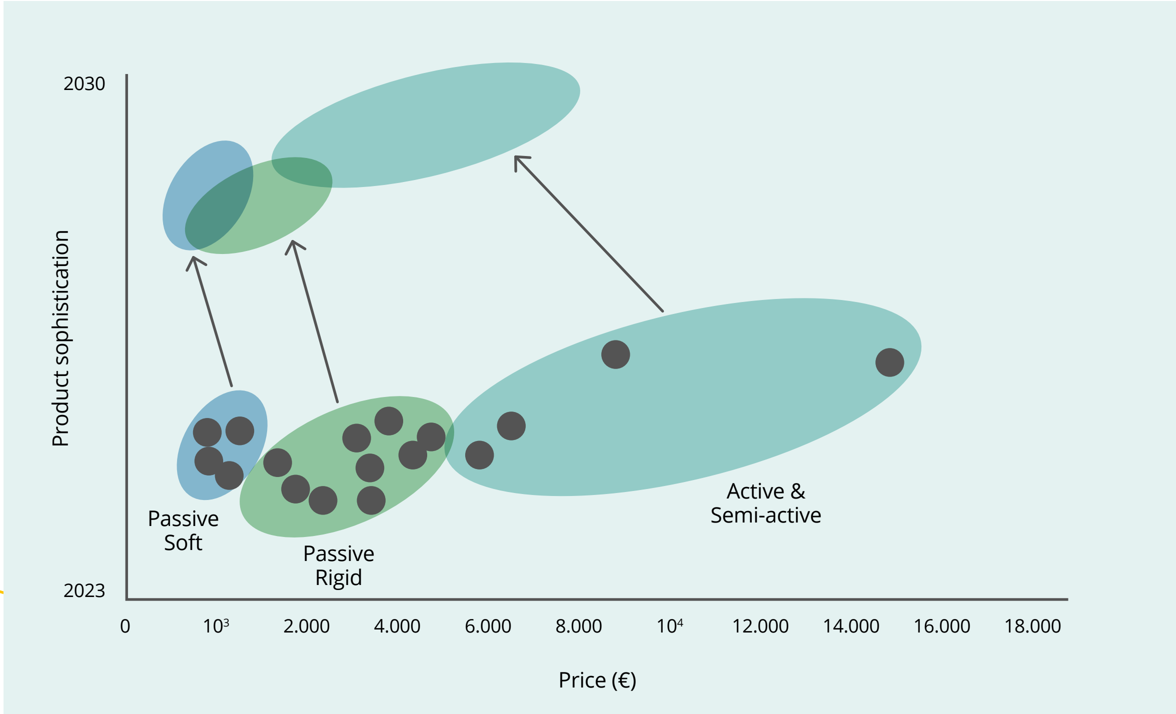
While a reduction in price can be a key factor for interested parties to acquire exoskeletons, the design of exoskeletons needs to become more sophisticated to attract the interest of a larger share of the market. Three key themes for design and manufacturing sophistication have been identified:

Weight: Heavy materials such as aluminum alloy, titanium or titanium alloy need to be replaced. For rigid occupational exoskeletons, when the weight is exerted on the user, lighter weight composite materials such as carbon fiber should be used. Soft exoskeletons stand out for their low weight, making the suits ideal for mobile applications. However, the reliance of fabrics reduces the performance of soft exoskeletons. While overall performance may decrease, lightweight devices improve the acceptability and usability of the device.

Fitting: Exosuits must be made adaptable to the unique human form of the user to improve comfort. For soft exoskeletons, fabric-stiffness should be customised for stressed parts of the wearable suit. If not, control errors can increase, and the effectiveness of power assistance is reduced. Efforts should be made to guarantee user comfort to avoid acceleration of the human body into a state of fatigue and avoid poor blood circulation. Additionally, friction between the binding or the rigid components of the exoskeleton and the body surface should be avoided in order to avoid skin damage or bruising. Exoskeletons that are customisable, adjustable and comfortable (e.g., adjustable padding, thermo shaping, breathable fabrics) need to be developed. Finally, ease-of-use should be improved. Feedback from users has indicated exoskeletons are too complicated in terms of fitting. It takes too long to put the vest on or take it off. The fitting procedures of exoskeletons thus need to be simplified.

Flexibility: Protruded parts of exoskeletons need to be removed as they reduce the locomotion of the exoskeleton user in tight spaces. Additionally, occupational exoskeletons need to be more versatile to be useful in a dynamic work environment and to enlarge their field of application. It is difficult for an exoskeleton to possess all performance features at a high level, such as portability, comfort, high efficiency, and be lightweight at the same time. For instance, passive exoskeleton designs have a limited capacity for versatility due to the limitations of passive materials. To overcome typical rigid exoskeleton problems and mitigate the loss of performance customary in exosuits, academics have suggested the use of modular soft-exosuit support systems. Hybrid mechanical architectures (rigid & soft) and hybrid assistive support (passive & active) are a relatively new phenomenon in the field of wearable robotics with limited coverage both in literature as well as development. The general idea behind hybrid systems is that when opportunely combined, tangible improvements can be made in terms of muscular efficiency.

Cost-reducing innovation for active, semi – and rigid passive, and soft exoskeletons by 2030



The figure above shows the relationship between product sophistication and price across a range of passive (soft and rigid) and active & semi-active exoskeletons. The spread of data points highlights the general price disparity of active and semi-active products currently on the market. There is more consistency in the price and sophistication of passive exoskeletons. By 2030, the majority of exoskeletons on the market should fall within the price range needed for widespread adoption, aided by increased innovation, research opportunities and market competition.

TRANSFORMATION VECTOR 2

Evidence of health and economic impact for workers

While it should be noted there is a lack of scientific evidence, a debated promise of exoskeletons is to prevent or reduce the risk of work-related musculoskeletal disorders (MSDs) by creating low fatigue work environments, assisting performance, improving strength, grip and physical stamina, to name a few. Prevention of MSDs will improve the overall health and wellbeing of the workforce. The percentage of sick days that can be reduced with the use of passive and active exoskeletons varies among different sources from 5 % to as much as 25 % according to German Bionic. Field experts consulted in this research study remain a little more conservative,estimating a potential reduction of MSD related sick days of up to 10 % in sectors where work-related MSDs are most prevalent. A 10% reduction in days lost to MSDs in the EU would equate to up to 182,300 additional FTEs available annually.

Additional workers available to work in the EU-27 in case of a 10 % reduction in MSD-related sick days.

Country	Days lost to MSDs each year (x million)	Number of sick days saved with a 10 % reduction (x million)	Additional number of workers (FTE) available to work with based on a 260 working days per year (x thousand)
Germany	217,00	21,70	83,46
Spain	26,00	2,60	10
Poland	21,70	2,20	8,46
France	13,40	1,30	5
Austria	7,70	0,80	3,07
Ireland	7,00	0,70	2,69
Finland	5,15	0,50	1,92
Romania	3,15	0,30	1,15
Slovenia	2,47	0,30	1,15
Greece	1,20	0,10	0,38
Estonia	1,02	0,10	0,38
Total	**306,00**	**31**	**119**
EU-27	**474,1**	**47,4**	**182,3**

Source: Fit for work Europe

When distributing MSD-related absences evenly over the labour force, a total of 162 million MSD-related sick days (34% of total MSD-related sick days) would be generated by the agriculture, construction, human health (homecare), manufacturing, and logistics sectors combined. However, this is a conservative estimate as these five sectors likely generate an above average number of work-related MSDs. The actual share of MSD-related sick days generated by these five sectors is estimated to be approaching 40% of the total number of annual MSD-related sick days (190 million MSD-related sick days or 731,000 FTE).

	EU Employment (x millions)	MSD-related sick days (x million) even distribution	MSD-related sick days (x million) 40% scenario
Agriculture	8,70	19,00	22,28
Construction	18,00	39,32	46,09
Human health (home care)	7,50	16,38	19,20
Manufacturing	29,00	63,35	74,26
Logistics	11,00	24,03	28,17
Total labor force five sectors	**74,20**	**162,08**	**190,00**

Source: Fit for Europe, Europa.EU

A reduction in worker drop-out caused by work-related MSDs would enable businesses to sustain their business activities with a smaller, but healthier, labour force. This is especially important for SMEs, for whom the impact of workers' fallout is relatively high when compared to large corporations. If exoskeletons help reduce the fallout of workers due to work-related injuries, health insurance costs can be reduced, higher operational productivity levels of human resources can be achieved, and desired operational performance levels can be maintained with a smaller workforce.

The number of workers suffering from MSD-complaints is significant, indicating the substantial liability businesses are exposed to in terms of MSD-related sickness absences and related treatment costs. The US Occupational Health and Safety Organization (US-OSHA) developed a tool to estimate costs of occupational injuries and illnesses, and the estimated profits required to cover those costs. The tool provides a variety of injury types, showing how costs vary between types. In the table below the tool is used to estimate the mean costs of an MSD case, based on the 'strain', 'sprain', and 'inflammation' injury types.

*Estimated costs of a work-related injury per case**

Injury Type	Instances	Direct Costs	Indirect Costs	Total Costs
Strain	1	€ 29.120	€ 32.032	€ 61.152
Sprain	1	€ 27.724	€ 30.495	€ 58.219
Inflammation	1	€ 35.576	€ 39.133	€ 74.709

source: US-OHSA

** While the tool only provides dollar figures, results were converted to Euro for the purpose of this paper. It should be noted there are differences in costs between the US and the EU due to various factors that are not accounted for here.*

Estimates of the costs of MSDs in relation to health care, lost productivity and injury or damage suggest that the incurred economic costs are considerable. MSD prevention or a reduced manifestation of MSDs can have a significant economic impact in physically demanding sectors saving billions of euros annually. In direct costs alone, with an exoskeleton MSD-prevention effectiveness of 5-15%, the use of an occupational exoskeleton by a worker at risk of MSD is likely to result in savings of between €1.400 - €5.300 per year. However, in order to effectively reap these potential benefits, it is critical to distinguish the types of work in which individuals are exposed to higher risks of suffering from a work-related MSD, from those in which the risk of suffering from a work-related MSD is low. The more optimally allocated exoskeletons are within the workforce in relation to MSD-prevention, the higher the cost savings on occupational injuries and illnesses will be. A poor allocation of exoskeletons may reduce the impact on MSD-prevention, with a poor return on investment as a result.

In terms of market potential, a significant demand for exoskeletons can be foreseen. With over 50% of workers in agriculture, construction, manufacturing, logistics and human health (homecare) reporting one or more MSD-related complaint, about 38 million workers would benefit from an exoskeleton to mitigate work-related MSD complaints. Most of these workers are employed with SMEs. If prices of exoskeletons come down sufficiently, a significant potential market will open up. With passive exoskeletons selling at €1.000 per unit this would represent a potential market for passive exoskeletons of about €40 billion for these sectors alone if all workers with MSD complaints were provided with a passive exoskeleton. The actual value of the market will likely be much higher, taking into account spin-off markets such as replacement and repair of exoskeletons. What is clear however, is that the pathway to adoption requires both a reduction in the price of an exoskeleton, and more sophisticated designs.

TRANSFORMATION VECTOR 3

Regulation, standardisation and business models

The adoption of exoskeleton by industry has really taken off in the last couple of years. Multiclient market studies indicate that in 2014, the global market was estimated at €68 million. In 2022, the EU market alone was estimated at €500 million, and in 2030 is expected to reach some €4 billion. These are 30+% Compound Annual Growth Rates (CAGR). Large multinationals like Toyota, Boeing and Volkswagen are making the use of exoskeletons part of the obligatory wearable equipment of factory workers. Nevertheless the potential impacts of exoskeletons across the European workforce exposed to MSD risk are not reaching all segments of that workforce equally. While large industry and logistics multinationals receive strong attention from researchers and exo manufacturers, many other sectors and especially SMEs (including freelancers and micro-SMEs) and public sector workers are adopting them at a much slower pace, despite the risks of work related injuries appearing higher in SMEs, as described in the previous section *"Size of the problem"*. To ensure that exoskeleton benefits reach all segments of the workforce, regulation, standardisation and business models are key.

Standardisation

Today, pre-standardisation preparatory work is ongoing in various standardisation bodies, ranging from national entities such as the Dutch NEN or German DIN to international initiatives with the US based ASTM and CEN-CENELEC in Europe. Fundamentally the pre-standardisation work considers industrial (non medical) exoskeletons as work related tools (in which case they can be compared with a drill, a screwdriver, or a tool belt) or as Personal Protective Equipment (PPE) which treats exoskeletons similarly to protective boots, a worker's helmet or a welder's eye protection. Each of these categories of use has its own specific standardisation pathway and regulatory framework. A key consideration in the establishment of a standard for exoskeleton technologies is ensuring their safety, efficiency, and optimal performance. A European standard is particularly needed to set minimum requirements for the design and use of these technologies. By proactively addressing these issues, it will be ensured that exoskeleton technology is effectively integrated into workplaces to improve workers' safety.

Manufacturers of exoskeletons have been focusing recently on the acceptance of their products as PPEs, which even though more demanding and more costly, offers the additional status of a protective device that workers should really use, even if it adds acceptable levels of discomfort or reduction of productivity (similarly to how helmets or protective gloves for meat industry workers were perceived 50 years ago). For exoskeletons to take off across Europe's workforce at risk of MSD, a strong regulatory framework and strong incentives to adopt approved exoskeletons that have demonstrated risk reduction effects will be crucial.

Regulation

The use of exoskeletons today is not enforced nor prescribed by regulatory bodies across Europe. Their adoption is voluntary to the employer, and in many cases also voluntary on the level of the individual worker. In each EU member state various bodies are in charge of regulating the use of PPE or workers tools; these include job safety inspection bodies, labour unions, public or private labour accident or labour related illness insurers and a wide range of sector specific platforms and coordination bodies in which such stakeholders focus on self-regulation or government imposed regulation.

As mentioned above, large multinationals are increasingly adopting their own self regulation around exo use. Their adoption is, in most cases, driven by extensive pilot testing in their own factories and warehouses, enabling detailed insights in how the exos lower the risks of MSD, and which trade-offs for this reduced risk occur (reduced comfort, reduced flexibility, sometimes reduced productivity per healthy worker). However, Europe's MSD sensitive workforce, like the overall workforce, is employed for 70-90% in SMEs or in public sector services. Here, self regulation takes a lot of time, due to a lack of funds to run proper pilots that closely resemble the reality in each SME, and lack of funds to invest in the equipment and in the proper training on how to use them. If adopting exoskeletons causes a reduced level of worker flexibility, then many SME directors will opt to wait until they become obligatory, which would take their adoption out of the competitive equation and create a level playing field where all SMEs (and large firms) invest in equipment for the sake of workers' health and wellbeing. From foresight interviews and workshops alike, the pathway to widespread adoption of exoskeletons throughout the European workforce involves a stronger level of regulation of their use, making sure that all workers have access to them.

Reimbursement and Certification
Reimbursement and certification are closely related to regulation and standardisation. A product which is new to the market, specifically an innovative technology that can have an impact on the health of its users, is always subject to close supervision of relevant regulatory bodies. Exoskeletons are no exception and are currently in the process of achieving product certification where at least a certain level of standardisation is a prerequisite in this process, as it provides the basis for the unified and validated approach to technology development.

The reimbursement of exoskeleton technology can be of significant help in terms of the widespread adoption of exoskeletons, but can only be so once the standardisation, certification and regulation is in place. In order for the technology to be reimbursed, there needs to be strong and extensive evidence coming from a large-scale trial. Thus, stakeholders need to focus on long-term large-scale studies to collect statistical evidence providing irrefutable proof of the positive effect of exoskeletons on health. To reach the necessary level of scientific evidence by conducting research experiments and large-scale trials, a substantial amount of funding needs to be accessed. This funding can come from various sources such as: the exoskeleton manufacturers or a union; private sector stakeholders from an industry where exoskeletons promise a large positive impact and return of the cost; or lastly it can come from a government which is acting in favor of prevention of injuries of its citizens. All experts reached a consensus that a large-scale controlled study is a precondition to achieve product certification and/or insurance by 2030.

In the words of experts from the labour unions, it is important to acknowledge that in terms of safety at the work, priority is given to securing the safety of the workplace itself in any way possible and only if there is no other way, the supportive technologies such as exoskeletons come in place. This comes from the general logic of the current regulation in place at EU level.

This expert insight suggests that there might be a reimbursement of the exoskeleton technology only for the specific types of tasks in which safety cannot be achieved differently than with an exoskeleton. An example could be the shoulder support for window cleaners.

Business models

Apart from a regulatory transition where the use of exoskeletons becomes the 'new normal', companies that are required to offer them to their workforce must be able to afford them. Again, SMEs and public sector employers often lack the financial muscle to invest up front, and perceive a larger risk of 'buying too early' due to their tendency to write off their investments over longer periods of time (while a multinational car manufacturer would typically write off protective equipment within 2 years, most SMEs would aim to use them for 3-5 years).

Innovative exoskeleton manufacturers are therefore introducing monthly use fee models (German Bionic offers its *Cray-X* and *Apogee* high end active exo at €450 ($499) and €225 ($250) per month). By offering such models, employers with limited ability to invest can harvest the benefits of exoskeletons without the need to pay up front. Alternative business models are being explored where the use of exoskeletons can result in lower premiums being paid for labour health risk insurance, or where insurers finance the use of exoskeletons for their smaller clients.

There is however a fundamental dilemma particularly relating to freelancers in certain sectors, such as construction. Specialist jobs like (wood) carpentry, roofing, or concrete steel reinforcement bar installation are, to substantial degrees, covered by freelancers employed by large or SME contractors. One can foresee a future in which such professionals acquire and maintain their own custom-tailored exoskeleton, as opposed to the contracting company investing in a range of exoskeletons with adaptable sizing (Small / Medium / Large etc). Related to this dilemma, the business model would differ. One can imagine a custom-tailored (and therefore less mass produced, ideally mass-customised produced) exoskeleton in which an individual professional invests, taking great care of it in order to enjoy a product lifetime of perhaps up to 10 years. Alternatively, one can imagine an 'off the rack' approach in which exoskeletons come in 3-5 different sizes, with adaptability incorporated into the design, allowing for the huge variety of body types of those that wear them. It is not unlikely that both models will co-exist for many years to come.

For the tailor-made exoskeleton, smart choices for mass-customisable manufacturing technologies and their related materials choices (transition vector 1) will be crucial, and will enable affordable business models to be applicable in this sub-segment of the overall exoskeleton market.

TRANSFORMATION VECTOR 4

Ecosystem connectivity between stakeholders across the EU and beyond

The lack of synergies between different stakeholders slows the innovation and development of exoskeleton technologies. Various stakeholders need to work together and engage in knowledge sharing activities, allowing for greater efficiency and effectiveness by coordinating action plans and initiatives for the innovation and development trajectory of exoskeletons. By developing synergies, stakeholders can combine resources and save costs.

Currently, manufacturers, users, health and safety organisations and regulation bodies are not extensively organised in associations that can facilitate discussion amongst stakeholders and coordinate decision-making processes. To accelerate the innovation and development agenda of exoskeleton technologies, the organisation of stakeholders in a collaborative setting is vital. By connecting government-academia-industry stakeholders throughout the EU, connectivity of the exoskeleton ecosystem can be improved. This will enable the development of synergies facilitated by a shared innovation and development agenda.

One can imagine the development of an 'alliance' in which stakeholders from the quadruple helix join together to exchange knowledge and insights, and coordinate a follow-up agenda for exoskeleton innovation and implementation.

A Market in Transformation

The global wearable robotics market is expected to grow significantly from €1 billion in 2022 to over €10 billion in 2030. The EU wearable robotics market is estimated at €500 million in 2022 and is expected to grow to over €4 billion by 2030 with a 30% CAGR. The vectors of transformation discuss the key strategic thrusts that are fundamental in the market's trajectory towards 2030.

Prices of exoskeletons are currently too high, which limits market uptake. Assuming most exoskeletons sold are from the passive rigid type at a price of around €3.300, at present an estimated 150.000 exoskeletons are sold annually. By 2030 the market should have expanded significantly, and prices for exoskeletons should be reduced, with annual sales of over 4 billion units.

The adoption of exoskeletons can significantly improve the wellbeing of the labour force, attributed to the MSD-preventing capacity of exoskeleton technology. Active exoskeletons are said to reduce up to 25% of MSD-related sick days. For passive types, the effectiveness will likely be somewhat lower, estimated at 15% for rigid passive types and 5% for soft passive types. When allocated effectively to workers with a high risk of suffering work-related MSDs, exoskeletons can generate €1.400 - €5.300 in prospective cost savings per worker. The impact of exoskeletons on MSDs will be most noticeable for the construction, manufacturing, logistics, human health, and agricultural sectors due to the high prevalence of work-related MSDs and the high number of SMEs in these sectors. However, in order to reap these economic benefits, occupational exoskeletons should be provided only to those that need it. Exoskeletons allocated to individuals with a low risk of suffering work-related MSDs may not contribute sufficiently to cost savings in terms of occupational injuries and illnesses for a positive return on investment. There is insufficient knowledge available on how to allocate exoskeletons effectively, targeting the individuals or groups of people within the working population exposed to substantial risks of incurring work-related MSDs.

Standardisation and certification of exoskeletons is under development but resides in the early stages. A European standard for minimum requirements and design specifications needs to be developed. EU-wide approval of exoskeletons as personal protective equipment with proven risk reduction qualities will spur adoption rates. However, to achieve widespread adoption of exoskeletons amongst SMEs, strong regulation is needed, ensuring all workers have access to exoskeletons. Large corporations are generally able to apply self-regulation practices for exoskeletons in case-by-case tested environments. SMEs are less likely to adopt exoskeletons on their own due to limited funds to perform such tests and a lack of access to training or pilot testing to analyse the trade-offs of using an exoskeleton.

The outlook for 2030 seems positive for manufacturers, who will see their revenues increase as exoskeleton adoption within large corporations increases. However, the real impact of exoskeletons lies with SMEs, where the adoption of exoskeletons might not occur as rapidly without additional intervention. Reimbursement and certification can significantly help with the widespread uptake of exoskeletons, as financial incentives can reduce the capital barriers for SMEs. Alternatively, manufacturers or retailers should adopt alternative payment schemes, reducing the upfront investment costs.

While continued market growth is evident, accelerated development through a stronger commitment can bring significantly positive impacts, accelerating widespread adoption of exoskeletons and enabling SMEs to acquire exoskeletons at a faster rate. With SMEs making up 99% of businesses in Europe, a steep growth of potential impacts can be expected when reaching the point where SMEs begin to rapidly integrate exoskeletons in the workplace. However, to accelerate market developments, standardisation, certification and the formulation of regulatory frameworks, stakeholders must work together. An ecosystem as such does not currently exist.

This decade lends itself to address these issues adequately and maximise the potential benefits exoskeletons can bring to the labour force of the future. In doing so, workplaces can be made age-appropriate in a timely manner, mitigating the increased risk for work-related MSDs associated with ageing workforces.

Two Possible Future Visions of 2030

To reflect the potential for active intervention in this particular high impact market, both a 'Business-as-usual' scenario and an 'additional intervention' scenario have been developed. The business-as-usual scenario assumes the current development trajectory to stay the same, with no additional efforts to speed up exoskeleton innovation and development. In contrast, the additional intervention scenario assumes exoskeleton innovation and development is accelerated within Europe by implementing a well balanced package of interventions, and aims to visualise the additional impact accelerated development could bring by 2030.

Business-as-usual Scenario

TRANSFORMATION VECTOR 1

Exoskeleton manufacturers will continuously upgrade and optimise their products, conducting clinical trials, and expanding their sales and distribution network. Over time, orders will increase, in turn greatly decreasing manufacturing costs due to the economies of scale that will develop. In time, design refinements and agreements with insurers will also bring down the cost of ownership for exoskeletons. However, exoskeleton companies can't sell more units until they have more financial capital to refine their products, and so the cycle continues. Limited resources and the lack of cooperation amongst stakeholders reduce the rate at which upgraded and optimised products are developed and cost reductions are achieved. While exoskeleton technologies will have reached a reasonable level of sophistication; available in different sizes, improved practicality, final steps need to be made for widespread market adoption to occur. While revenues for manufacturers will increase, prices for exoskeletons remain too high for most SMEs and freelancers to start using exoskeletons.

TRANSFORMATION VECTOR 2

While revenues for manufacturers will increase, the overall health impact of exoskeletons in terms of MSD-prevention is limited, as exoskeletons will still be too expensive for wide uptake among SMEs and freelancers from which the largest fraction of work-related MSDs is generated. Additionally, exoskeletons are not optimally allocated, reducing the effectiveness of exoskeletons on MSD prevention. While limited, economic impacts are noticeable through higher sales for exoskeletons and reduced fallout of workers due to work-related MSDs at large corporations.

TRANSFORMATION VECTOR 3

While large corporations widely integrate occupational exoskeletons in the workplace, the uptake of exoskeletons amongst SMEs remains low. Standardisation for exoskeleton design and manufacturing is brought about but is not covering all bases. The experiences from self-regulatory practices of large corporations and clinical trials in the controlled environments on offer has resulted in the first regulatory standards for the use of exoskeletons in specific instances, but SMEs still suffer from an information gap. This leads to a large uptake of exoskeletons amongst large corporations, but SMEs remain hesitant as the trade-offs between health benefits and a loss of productivity remain too unclear to commit substantial shares of the limited resources available.

TRANSFORMATION VECTOR 4

While core relevant stakeholders have organised themselves in a true EU exoskeleton ecosystem, the development of the ecosystem has been slow, and it is still in its infancy. The full landscape of stakeholders including most SMEs are still outside of the organisation's ecosystem, and therefore do not participate extensively in knowledge sharing practices.

Additional Intervention Scenario

TRANSFORMATION VECTOR 1

More funding becomes available, notably private funding such as venture capital, greatly accelerating exoskeleton development. This allows manufacturers to upgrade, test, and optimise their products at a more rapid pace. The added value exoskeletons can bring to the workplace is therefore clearer, while the price per unit decreases as increasingly advanced and low-cost manufacturing methods and production processes are used, such as 3D-printing, and economies of scale are achieved. Manufacturers can bring down the costs of exoskeletons enough for the first SMEs to enter the market. Toppling the buy-in tipping point for the first SMEs will lead to a cascading effect of SMEs entering the market as prices will drop further. Exoskeleton devices will be available in various sizes with smart adjustability mechanisms allowing for improved individual comfort. Additionally, personalised exoskeletons will be available for professionals able to provide the higher investment required for such customized solutions.

TRANSFORMATION VECTOR 2

Health and economic impacts of exoskeletons are recognised by the extensive evidence stemming from clinical trials conducted in different work settings applicable to both large corporations and SMEs. Exoskeletons are allocated more efficiently to workers at risk of suffering work-related MSDs due to effectively matching exoskeletons to workers involved in working activities with a high prevalence of work-related MSDs. The effects of exoskeleton application on MSD-prevention are visible, with a reduction in the annual number of MSD-related absences and a reduction in annual costs incurred by companies for treatment and lost productivity.

TRANSFORMATION VECTOR 3

Exoskeleton manufacturing has become standardised, reducing the overall divergence between exoskeletons and ensuring product performance. Additionally, product certification and regulatory policies have defined in what instances exoskeletons should be offered and how they should be used, protecting the user and providing a directive for exoskeleton implementation to businesses. Insurance companies offer insurance schemes and/or reimbursements for exoskeletons guided by the certification and regulation directives. To further incentivise the uptake of exoskeletons, payment schemes such as hardware-as-a-service, pay-per-use or spreaded payment models are widely offered by manufacturers or third parties to reduce the financial risk for SMEs.

TRANSFORMATION VECTOR 4

Stakeholders throughout the EU are organised as members of an interactive exoskeleton ecosystem, exchanging knowledge and coordinating innovation and development agendas extensively. As a result, synergies are developing between relevant parties on a continuous basis, pooling resources, aligning visions, keeping interested parties informed, and greatly accelerating development and decision-making processes.

Two 2030 Horizons

Indicator	2022	No Intervention Scenario 2030	Additional Intervention Scenario 2030
Market Growth EU	€ 500 Million	€ 4 Billion	€ 4.5 Billion - € 6.5 Billion
CAGR %	n/a	+/- 30%	+/- 32 - 38%
Price OEs Rigid Passive Soft Passive Active	 € 3.300 € 1.250 € 9.000	 € 1.250 € 750 € 4.000	 € 1.000 € 500 € 3.000
Design sophistication	Mostly first and second generation products with functional designs and inefficient manufacturing processes	Evolutionary improvement of products staying close to the materials and concepts used over the last 20+ years	3D printed, user specific fitted parts, user specific Thermo shaping, more advanced materials, smart modularity of designs etc. Smart adjuster mechanisms
Estimated number of exoskeletons sold in the EU	150.000	3.000.000 - 3.500.000	4.000.000 - 7.000.000
Cost savings per MSD-case assuming a 5-15% prevention effect on MSD-related sick days	-	€ 1400 - € 5300	€1400 - € 5300
Overall cost savings of exoskeletons assuming a low and a high allocation effectiveness to workers at risk of suffering from work-related MSDs.	-	Exoskeletons are not optimally allocated, reducing the effective-ness of the exoskeletons sold on MSD prevention in the workforce. The economic impact of cost savings on occupational injuries and illnesses are therefore limited	Exoskeletons are more optimally allocated and catered to individuals and groups working in jobs with a high prevalence of work-related MSDs. This results in a higher effectiveness of the exoskeletons sold on MSD prevention within the work-force, and higher cost savings generated by a reduction in MSD related occupational injuries

Indicator	2022	No Intervention Scenario 2030	Additional Intervention Scenario 2030
Standards	No uniform standardisation for exoskeletons in the EU	Design specifications have been standardised on a national level ensuring the safety of exoskeletons, but insufficiently address performance and use case scenarios	Design and performance of exoskeletons is standardised on both national and international level among EU member states, ensuring safety and performance of exoskeletons in different types of work environments
Reimbursement and Certification	Exoskeletons are not recognised as suitable devices for improving ergonomic conditions in the workplace by health and safety institutions, insurance providers only provide reimbursement on a case by case basis	Specific exoskeleton types have achieved partial certification and country-specific recognition, as PPE devices in situations where ergonomic conditions in the work-place do not provide sufficient protection to the worker. Insurance providers reimburse exoskeletons for use cases that are supported by some long-term studies providing scientific and clinical evidence	Long-term studies provide irrefutable proof of the positive effect of exo-skeletons on health. Exoskeletons are widely recognised and supported by the EU as PPE devices for the protection of workers and the improvement of ergonomic conditions. Insurance providers stimulate and reimburse exoskeletons for a wide variety of use cases in the working environment
Regulation	No publicly organised regulation, some large corporations adopt self-regulatory practices	Basic publicly organised regulatory standards are developed. However, SMEs continue to struggle with exoskeleton integration into the workplace due to the lack of funds for training, equipment and pilots focused on SME dominated sectors and specific work environments	Job safety inspection bodies, labour unions, public or private labour accident or labour related illness insurers fully support a common regulation for exoskeletons among EU. There are publicly organised regulatory standards with an extensive typology of safe exoskeleton use and implementation under varying working conditions both in large corporations as SME and sector specific working environments

Indicator	2022	No Intervention Scenario 2030	Additional Intervention Scenario 2030
Business models	Little to no payment schemes, no insurance compensation, high price barrier	Hardware-as-a-service and pay-per-use schemes for costly exoskeletons, insurance compensation offered for specific types and use-cases of exoskeletons, lower performance exoskeletons can be acquired for an affordable price. Exoskeletons are available for most large corporations but only some SMEs	Various payment and use schemes available including hardware-as-a-service, pay-per-use, insurance compensation for most exoskeleton types, low price barrier. Exoskeletons are available even for smaller enterprises and freelancers
Connectivity of the exoskeleton ecosystem	No solid network of exoskeleton players and representatives of the quadruple helix established	Core network of several key stakeholders across the quadruple helix but fragmented representation andlimited SME representation	Pan-EU actively engaged network of exoskeleton players across the quadruple helix and beyond

Numbers and ranges provided are roughly estimation based on available data, feedback from experts and internal discussions.

Recommendations for Intervention

As EXSKALLERATE is coming to a close, results have revealed consortia should continue to work together in gathering additional scientific and economic evidence from real-life test cases to define the added benefits exoskeletons can bring to the workplace.

From the work done in EXSKALLERATE and particularly from the Foresight work done in the framework of this study, some four lines of active intervention are concretely foreseen:

1. Stimulating disruptive product innovation in exoskeletons by means of specific cross-sectorial cross pollination and advanced design methods. Concretely the sector of exoskeletons should adopt into its products and manufacturing processes some elements that are used in mass produced yet person-customizable products such as walking boots, ski boots and 3D printed scaffolds for bone fracture fixations. By stimulating the composition of consortia in which experts in advanced product and production engineering for wearable products collaborate with exoskeleton developers, the advances of some of the leading industries in Europe (sports apparel) can be made to spillover to the exoskeleton sector.

2. Stimulating the design, execution and interpretation of medical-device grade clinical studies and workers' health economic studies in a broad variety of industrial settings (both larger corporations as well as SMEs and freelancers). Such studies must respect as much as possible the standards that are used in the validation of other health technologies, using proper control groups, strict inclusion and exclusion criteria. gender and age balance in study cohort selection, advanced statistics in the data interpretation, etc, etc. Only with a solid body of evidence that can withstand scrutiny by experts can we convince those that need to invest in (and perhaps regulate the use of) exoskeletons.

3. Actively stimulate EU level regulatory framework development around exoskeletons including EU coordinated certification / standardisation of such products. Moreover, involve all stake-holders in workers' health (regulatory bodies, trade unions, work risk insurers, workers health inspection bodies, etc, etc) in pro-actively designing policies that are conductive to the use of devices such as exoskeletons that can substantially reduce the risk of MSD.

4. Orchestrate the development and intense connection of the EU level exoskeleton innovation ecosystem and balancing this ecosystem to have more participation of the stakeholders that are to adopt exoskeletons into their work practice, covering all sizes of organisations and all categories of stakeholders involved.

Towards the EXSKALLARATE consortium, each of these 4 main lines of intervention has been detailed up to a level that permits concrete steps to be taken towards realizing them. Many funding opportunities have been identified on regional, national and European level. Over the next 6-12 months the consortium will actively pursue converting these 4 main action lines into specific proposals and plans that can deliver on the huge added value foreseen for an 'active intervention' scenario.

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Expert interviews

Stakeholder Type	Quadruple Helix	Country of Origin
Researcher	Academia	Netherlands
Researcher	Academia	Sweden
Researcher	Academia	USA
Entrepreneur and Researcher	Industry/Academia	Belgium
Safety expert (Researcher)	Government	Germany
Policy expert	Public Authority	Netherlands
Senior Ergonomist and Policy Expert	Public Authority	Netherlands
Entrepreneur and Researcher	Industry/Academia	Italy
Professor and Researcher	Academia	London
Researcher	Academia	UK
Doctor	(Health) Industry/Academia	Netherlands
Insurance expert	Insurer	Germany/ Iran
Labour inspector	Public Authority	Belgium
Supply chain expert	Industry	Spain
Exoskeleton manufacturer	Industry	Netherlands

Workshop stakeholders

Name	Position	Stakeholder type (1 of the 6)	Country of Origin
Frank Krause TNO	Researcher	Academia	Netherlands
Haibing Tian VUB	Researcher	Academia	Belgium
Sebastian Tischler RMNH	Project Manager	Government	Germany
Shaoping Bai Aalborg University	Professor	Academia	Belgium
Alan Johnston (BE-ST)	Impact Manager		UK
Astrid Heidemann Lassen (Aalborg University)	Professor	Academia	Denmark
Bert Vlaminck (POMWVL)	Cluster developer	Public Authority	Belgium
Holger Hoffman (HAWK)	Professor	Academia	Germany
Shaik Masud Rana (University of Gävle)	Researcher	Academia	Sweden
Xiu Yan (Strathclyde University)	Professor	Academia	UK
Andreas Hanssen (AAU)	Researcher	Academia	Denmark
Cameron Swanson (Strathclyde University)	Design engineer	Academia	UK

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