01 February, 2022

Design Improvement suggestions in “LegX” based on our Field Testing while performing workers tasks

Background:

As many as 44 million workers in the European Union (EU) are affected every year by workplace-related musculoskeletal disorders (MSDs), inflicting costs in excess of €240 billion to the European economy. The use of proper exoskeleton for a job can reduce fatigue and MSDs of workers. Therefore, as part of “EXSKALLERATE” research project, University of Gavle, Sweden, is reaching out to our local SMEs and construction companies to create awareness about the advantages of exoskeletons.

As part of “EXSKALLERATE” project, University of Gavle performed extensive testing, while doing different tasks of workers. We used LegX developed by your company, SuitX. Based on our experimental study and from the feedbacks of the users, we have found some main issues hindering the adoption of LegX on a wider scale among our industry. Kindly consider it and we hope you will ponder it while developing your next version of LegX. We are very enthusiastic to share with you any further information and our test results voluntarily as our aim is to accelerate and facilitate the adoption of exoskeletons by Swedish and European companies so that huge financial losses due to worker’s injuries and MSDs can be reduced.

Design Improvement Suggestions:

1. **Unable to balance their bodies** is found almost in all new users and they feel scary this issue when in their sitting position, this is a major issue which create fear of falling. Our suggestion is that by providing a redundant support or mechanism which ensures that the user will not fall backwards will greatly increase the trust of the user on LegX.

2. **The back sitting belt** do not assist properly while sitting at chair and knee position, maybe a relatively flexible belt can have better grip and less slipping.
3. **Reduction in the weight** of the Leg-X will reduce the overall inertia of the LegX and will assist the users in balancing their bodies without feeling any notable extra load; this will also facilitate the users to move freely through their tasks and premises.
4. **Leg-X cannot be properly knotted** around both thighs, which causes consumers to feel unpleasant in their working position. Improvements in interfaces is needed particularly in straps for better human-exo mating.
5. **Knee guards of Leg-X** are unable to adequately protect the user's knee. It needs a lot of practice and time to get any sort of assistance at knee. During all this activity, the users already got demotivated and pessimist about it.
6. **Wearing of Leg-X** on their own is quite difficult. Simplification in design can reduce this issue. It might be having lesser sub-assemblies so that the user can just use it straightaway without any external help.
7. **Upper height adjusting level** button create issues to sit properly to their working positions.
8. **Leg-X only offers two sitting positions** (Chair and Knee Position), however industrial employees want additional working sitting positions such as, kneeling and at other bending angles.
9. **Bending and adjusting the foot b**elt and altering the lower levels' height are quite difficult and cannot be done without the assistance of another person.
10. **The battery should** be put in a secure location where water cannot affect it, for outdoor working environments.

EXSKALLERATE Design improvement template

30th May 2022

Partner/Field lab: HAWK University
Exoskeleton tested: Paexo Back
Design improvement: New clip/pin in the hip area

Through feedback calls that have been held during the implementation process of exoskeletons in SMEs participating as pilot site, first subjective results were derived from the exoskeleton use. Feedback and design improvement requests have been sent back to the manufacturer (Otto Bock):

Feedback: Forklift driving is aggravated and uncomfortable with a passive back exoskeleton as the forklift cabin is too narrow;

- The passive back exoskeleton is not versatile enough, e.g. driving lifting truck, lifting overhead and sitting are tasks were exoskeleton interferes;
- The work place can't be too narrow as the exoskeleton wears on around the sides (hips) and collisions with surroundings happen;
- Leg braces and sometimes hip belt of passive back exoskeleton are uncomfortable;

Solutions mostly contained adapting the work processes so that the function of the exoskeleton was suited better, e.g.:
- palletising low layers/levels first when wearing the exoskeleton, then without exoskeleton higher levels can be palletised (levels were there is no forward bend necessary);
- a co-worker is driving the forklift, not the exoskeleton wearer.

Often, changes in settings of the exoskeletons size could be made that improved wearing comfort and pads for the thighs and hips could ease discomfort.

For example, when the hip part of the exoskeleton, where the setting is adjusted, bumped onto objects (due to bulkiness and narrow workplace), the setting on the exoskeleton changed accidentally. To counter this, **Otto Bock developed a clip/pin that keeps setting in place**.

In general, motivation and acceptance of wearing the exoskeleton was high, the better the workplace by itself suited the function of the exoskeleton the higher both reminded over time.

EXSKALLERATE Design improvement template

Date
13/07/2022

Partner/Field lab:

KU Leuven

Exoskeleton tested:

[custom] Quasi – passive hip exoskeleton prototype

Design improvement:

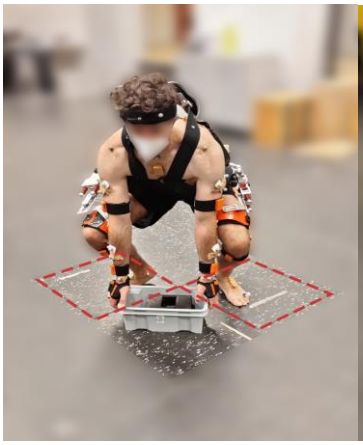
[hardware]: Additional padding to increase comfort
[hardware]: Increase flexibility to fit prototype to different users
[software]: Improved decision making under uncertainty of user intent
[software]: Different control actions based on identified user intent

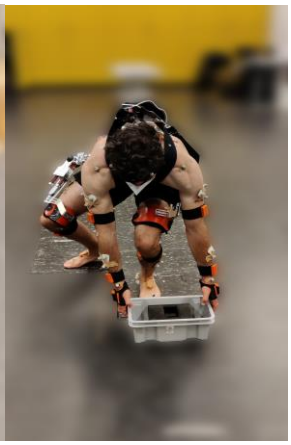
A custom hip exoskeleton prototype was evaluated on 5 subjects during a series of lifting tasks: asymmetric stoop (left/right) and squat lifting. The lifting tasks were performed with and without exoskeleton. Feedback was asked from participants about the performance of the exoskeleton.

The hardware of the exoskeleton was developed by the VUB (partner in the EXSKALLERATE project). The software was developed by KU Leuven.

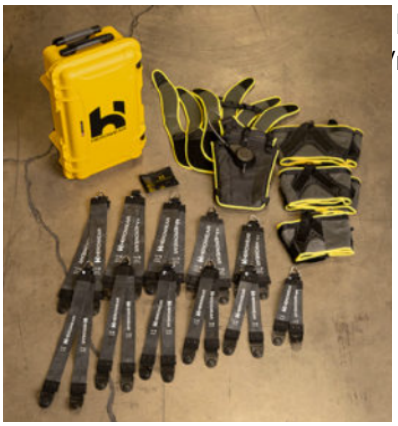
Discomfort during the tests was the main limiting factor of the exoskeleton. Limited adjustability of the exoskeleton to a user was increasing the discomfort as well.
The controller of the exoskeleton (determining when to provide support and when not to) made a wrong decision when it was unsure about the user intent. Moreover, the exoskeleton was able to recognize three different lifting motions, but was not yet able to provide differentiated support based on the recognized motion.

Since KU Leuven is responsible for software development, the software issues were already addressed. VUB is continuously updating hardware prototypes that increase usability and comfort for the users.





Partner/Field lab: BE-ST, NMIS, UoS
Field lab: Offsite & Roofing Field Lab
Exoskeleton tested: Herowear 'APEX', Auxivo Liftsuit
Design improvement: Customisable/modular to suit user's size

- 
lab that were conducted at BE-ST's Innovation factory the modularity of the exo-suits being used was highlighted when fitting the suits to the user.

HeroWear Fit Kit - https://herowearexo.com/product-category/fit-kits/

- The Herowear suit which was purchased by BE-ST was purchased with the "fit kit". This provided alternately sized thigh and shoulder straps as well as alternate strength tension straps. Minor adjustment could also be achieved through adjustment to straps on the suit.
- The Auxivo lift suit 1.x that was purchased is a one size fits all suit that only offers adjustment through straps and buckles on the suit.
- During the plasterboard field lab the participant was heavier than the other field lab participants and as such was unable to comfortably wear the Auxivo suit during the field lab. The level of **customization and adjustment** of the Herowear suit meant that it was possible to use during the field lab.
- These suggestions have not been communicated to the Auxivo suit supplier however it should be noted that the Auxivo lift suit 2.x comes in two sizes (S/M & L/XL) suggesting this issue was identified and that they are trying to broaden the range that the product is suitable for. The 2.x suit was not assessed as part of this field lab.
- Naturally if the suit is uncomfortable due to poor fit then it is unlikely that users will continue to wear it and as such adoption will stagnate.

Partner/Field lab: BE-ST, NMIS, UoS
Field lab: Offsite & Roofing Field Lab
Exoskeleton tested: Herowear 'APEX', Auxivo Liftsuit
Design improvement: Suit Toughness & Cleanliness

W at BE-ST's Innovation factory the cutting operations conducted generated saw dust into the surrounding environment. The operator also spent a lot of time crawling along on dusty surfaces. During the plasterboard and offsite work operators also exhibited sweating at times. Finally, during the roofing activity elements of the suit were exposed to rough edges or high loads.

Auxivo & Herowear Suit Back Covering

- Despite the plasterboard and offsite field lab work being conducted in a clean indoor environment there were signs of debris from operation and wearing of the suit gathering on the thigh straps of the Herowear suit and the suit being exposed to underarm and back sweat during use.
- The Auxivo suit had to a lesser extent signs of debris gathering on the suit however when the suit did become dirty this was typically from the suit being left lying on a work surface when removed for breaks or at the end of the day.
- The Auxivo suit has a significant portion of the back open with mesh which helps keep workers cool during operation and should reduce the exposure of the suit to sweat

Herowear Suit, Roofing Field Lab

- The Auxivo suit allows for machine washing up to 30 °C. The Herowear suit can only be partially machine washed, the back and clutch cannot be washed and need to be wiped clean.
- During the Roofing field lab as the worker is raising the tile stack onto their shoulder for carrying, the tile stack will rest on the clutch cable of the Herowear suit (this will depend on the handing of the individual) which could over time lead to damage. Also as the worker lowers the tile stack from their shoulder the stack is rested on the thigh straps of the suit (both Herowear and Auxivo) this could over repeated operation lead to ripping, damage, or aesthetic degradation of the suit.

- The continued cleanliness and condition of the suit is important to ensure the continued use of the suit. If operators stop wearing the suits due to accumulated wear and cleanliness, then the broader adoption of exo-suits could stagnate.
- These suggestions were not communicated to either suit manufacturer and to the best of our knowledge have not yet been implemented.

Partner/Field lab: BE-ST, NMIS, UoS
Field lab: Offsite & Roofing Field Lab
Exoskeleton tested: Herowear 'APEX', Auxivo Liftsuit
Design improvement: Suit Padding & Comfort

Within the Offsite Field Labs that were conducted at BE-ST's Innovation factory it was identified that both the Auxivo and Herowear exo-suits used throughout the field lab were creating significant discomfort for the user and causing bruising/irritation.

- Through discussion with the offsite participant it was identified that after the first full day of wearing the suit they were experiencing pain from the suit straps applying pressure onto their collar bone. This lead to chafing and bruising. This was experienced by both workers using both suits and conducting the same operation. This discomfort did not worsen after the first day.
- During the offsite field lab the operators spent a lot of time in a forward bending or squatting position. Often holding these positions for minutes at a time before returning to an upright position. This means that the tension from the strap was constantly applying pressure to the operators shoulder and collar bone while in these positions.
- A lot of the working done by the operators involves rotating their shoulder during nailing operations onto low vertical struts using a nail gun (a heavy piece of equipment). This rotation means that they are applying further pressure onto their collar bone from the shoulder straps.
- Any alterations to the design that relieve the

pressure on the shoulders or provide **substantial cushioning** in this area would be beneficial.

- This suggestion was communicated to Herowear in a phone discussion. Herowear advised that they have developed and launching a new shoulder strap design that has greater padding to alleviate this discomfort.
- No discussion was had about this issue or design improvements with Auxivo.
- Continued/persistent pain will cause users to stop wearing the suit that will stagnate it's adoption.

Partner/Field lab: BE-ST, NMIS, UoS
Field lab: Offsite & Roofing Field Lab
Exoskeleton tested: Herowear 'APEX', Auxivo Liftsuit
Design improvement: Tool/Accessory and PPE Accommodation

Within the Roofing and Offsite Field Labs that were conducted at BE-ST's Innovation factory it was identified that neither of the passive back support exo-suits used throughout the field lab had suitable capacity to support tooling and PPE which the user would typically wear as part of their daily activities.

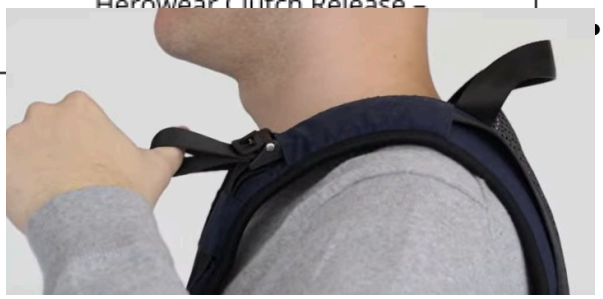
Offsite Workers –
Tool Belts Interfering with Exo-Suit

- Through discussion with the roofing participant it was identified that there would be times in their working day when they would be working at height. As part of their risk assessment they would be required to wear a safety harness. Naturally this would be problematic as certain safety harness designs would **prevent** the user from being able to wear the exo-suit continuously throughout the day. This did not impede the field lab as it was not required due to the nature of the lab.
- During the offsite field lab we noticed that both users wore tool belts (participants of all field labs wore a tool belt) and one user wore a tool vest during the offsite activity. These accessories were used to store fixings (nails, screws, etc.) and tools that they use frequently in their day. These belts and to a lesser extent the vest impeded the operation of the suit. With the belt and the pockets hanging from the belt, twisting and moving the position of the tension straps on the suit. This can cause the user discomfort or additional/imbalanced loading of the exosuit.
- Any changes in the design to accommodate PPE and tool accessories worn by users will encourage adoption of the exo-suits. This can be in the form of **recommended tool belts** which are known to not impede the operation of the suit or integration of the tool belt and other PPE features.
- These suggestions have not been communicated to either suit supplier or to the best of our knowledge adopted at this time.

Partner/Field lab: BE-ST, NMIS, UoS
Field lab: Offsite, Plasterboard & Roofing Field Lab
Exoskeleton tested: Herowear 'APEX', Auxivo Liftsuit
Design improvement: Allow Easy Disengagement of the Suit

Within the Roofing, Plasterboard and Offsite Field Labs that were conducted at BE-ST's Innovation factory two suits were trialed, Auxivo and Herowear. Each participant of the field lab got to spend time in each suit. Although both suits are passive back support exo-suits used throughout the field lab they each have different temporary release mechanisms, the Herowear has a one handed clutch release where as the Auxivo suit is a slightly more involved strap release.

Herowear Clutch Release –



Auxivo Release -
https://www.auxivo.com/liftsuit

- Throughout discussion with participants of the field lab it became clear that they did not believe that the suits would be suitable for all activities. To address this, participants could either take off the suit or disengage it. Depending on the activity mix removal of the suit could become disruptive to completion of the activities. The participants did use the Herowear clutch release but did not use the Auxivo release. The Herowear suit clutch is a far more obvious design feature than the Auxivo and as such this may explain why participants used this feature more often.
- The Herowear clutch design, although more popular with participants (with some claiming that with the clutch disengaging the tension in the suit they felt no difference between wearing and not wearing the suit), did have a couple of issues. On the roofing field lab where the participant is applying an impact load onto the clutch cable when they raise the tiles up to their shoulder. In addition when participants were first using the clutch they often pulled off the clutch cover (this could be clicked back into place, so did not cause permanent damage).
- Measures to make the release of the tension straps of the suits a **more obvious feature** and make it simpler to release with one hand would encourage the user to keep wearing the suit as opposed to wearing it for a period and then giving up.
- These suggestions have not been communicated to either suit supplier or to the best of our knowledge adopted at this time.

EXSKALLERATE Design improvement template

Date
26/02/2023

Partner/Field lab: Aalborg University

Exoskeleton tested: Skelex 360
Design improvement: The lock system of the arm cuffs strap

Aalborg University within the ESXKALLERATE has tested the passive exoskeleton for shoulder support Skelex 360 with laboratory and field tests; more tests are ongoing/planned. During the execution of the tests, the following problem occurred, and therefore improvements are suggested.

The lock system of the arm cuffs strap (fig. 1) requires strength and resistance improvements to increase the device's safety. On several occasions, the lock disconnected, and the strap suddenly opened, creating risks for the user as the exoskeleton arm was no longer connected to the user's arm and tended to return to its initial position with rapid movement. There were different situations when this happened. With users with big arms, the arm cuff straps are in an elastic material and pull more when stretched. When users wore thick clothes. When the users had to assume a complex position for the device, for example, when they had to reach something placed on their side or behind them. Fig. 2 shows an example of a situation when this problem occurred; when the workers reached their nail gun, their upper arm was going behind their frontal plane, and sometimes the cuff opened. Finally, it also happened on a few occasions during not complex tasks, our opinion here is that there was a not perfect alignment between the user and the exoskeleton arm.

We suggest improving this system by increasing the strength of the magnet and/or the depth of the pin groove; If not possible, rethink the entire loch system with maybe a hook.

Figure 1. The lock system of the arm cuffs strap, with the strap open and closed.

Figure 2. Example of position requiring a complex arm position for the exoskeleton.

EXSKALLERATE Design improvement template

Date
26/02/2023

Partner/Field lab: Aalborg University
Exoskeleton tested: Skelex 360
Design improvement: Cuff-arm joint

Aalborg University within the ESXKALLERATE has tested the passive exoskeleton for shoulder support Skelex 360 with laboratory and field tests; more tests are ongoing/planned. During the execution of the tests, the following problem occurred, and therefore improvements are suggested.

On a few occasions, the exoskeleton cuff detached from this arm, creating a risk for the user as the arm moved backwards rapidly. We think that this problem happened because the joint between the exoskeleton's arm and cuff is not rigid. It has a rotation around the longitudinal axis of the pin. Furthermore, maybe due to the use, the cuff can achieve a small rotation around the vertical axis of the connection (Fig 1.A). If the alignment between the exoskeleton and the human arm is not perfect, these movements cause the arm-cuff joint to fail and the cuff to disconnect. Another possible reason is that the button to disconnect the cuff is very sensitive, as the internal spring is not too stiff.

We suggest improving the cuff joint by increasing the stiffness of the spring inside the arm part of the joint and/or the depth of the pin groove to improve joint strength.

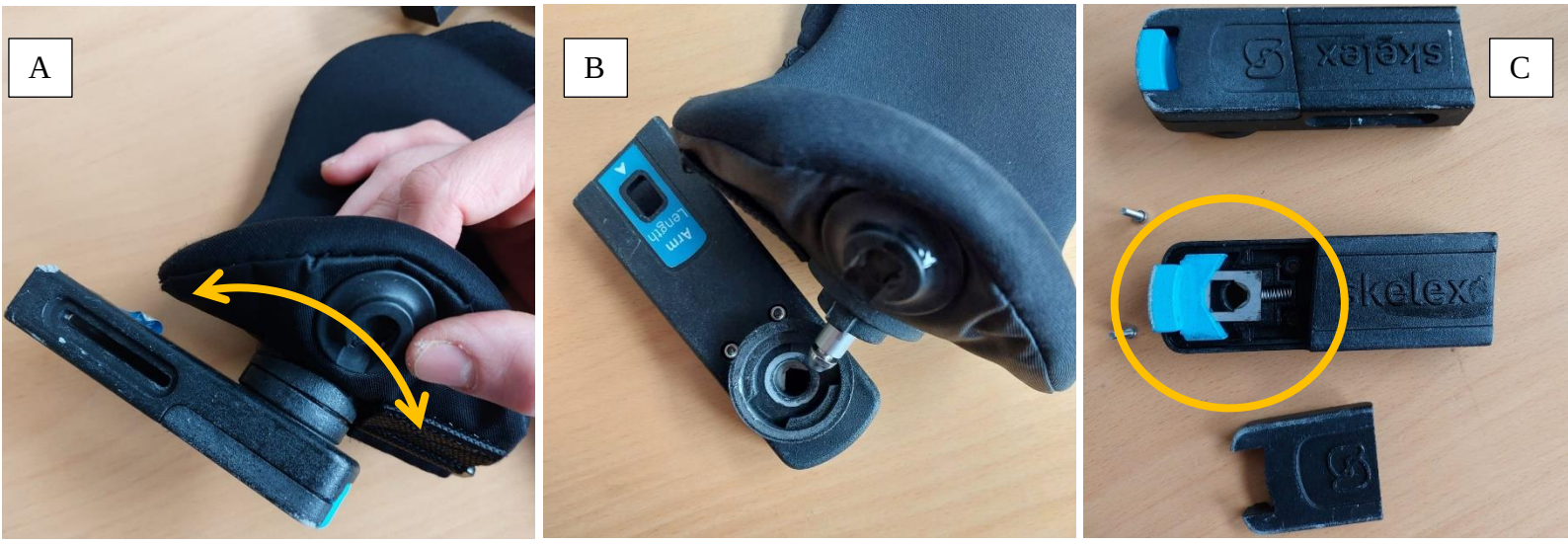


Figure 1. The lock system of the arm cuffs strap, with the strap open and closed.

EXSKALLERATE Design improvement template

Date
26/02/2023

Partner/Field lab: Aalborg University
Exoskeleton tested: Skelex 360
Design improvement: Add the possibility of setting the angle at which the exoskeleton provides the maximum support

Aalborg University within the ESXKALLERATE has tested the passive exoskeleton for shoulder support Skelex 360 with laboratory and field tests; more tests are ongoing/planned. During the execution of the tests, the following problem occurred, and therefore improvements are suggested.

During the tests, the exoskeleton received positive feedback from lab test participants and workers of the companies that agreed to participate in the EXSKALLERATE project.
One of the suggestions we received on different occasions was that allowing the possibility to change the angle at which the exoskeleton provides the maximum support would greatly improve the device. We received this feedback from, but not only, bricklayers and workers of the painting division of a truck trailers company. They both appreciated the device but had to work below shoulder level for most of the time (bricklayers) or in part of their work shift ("painters"). In particular, the bricklayers claimed that exoskeletons could be really helpful for their job, as they have to perform a very repetitive task; but right now, the exoskeleton is not well suited for it.

We understand that implementing this feature on your device will not be straightforward, but it can be really useful to allow its application in more jobs

Figure 1. Bricklayer [A] and worker of truck trailers company [B].

Partner/Field lab: University of Gävle, Sweden
Exoskeleton tested: Eksovest (by Eksobionics)
Design improvement: Removal of extra Protruded Parts.

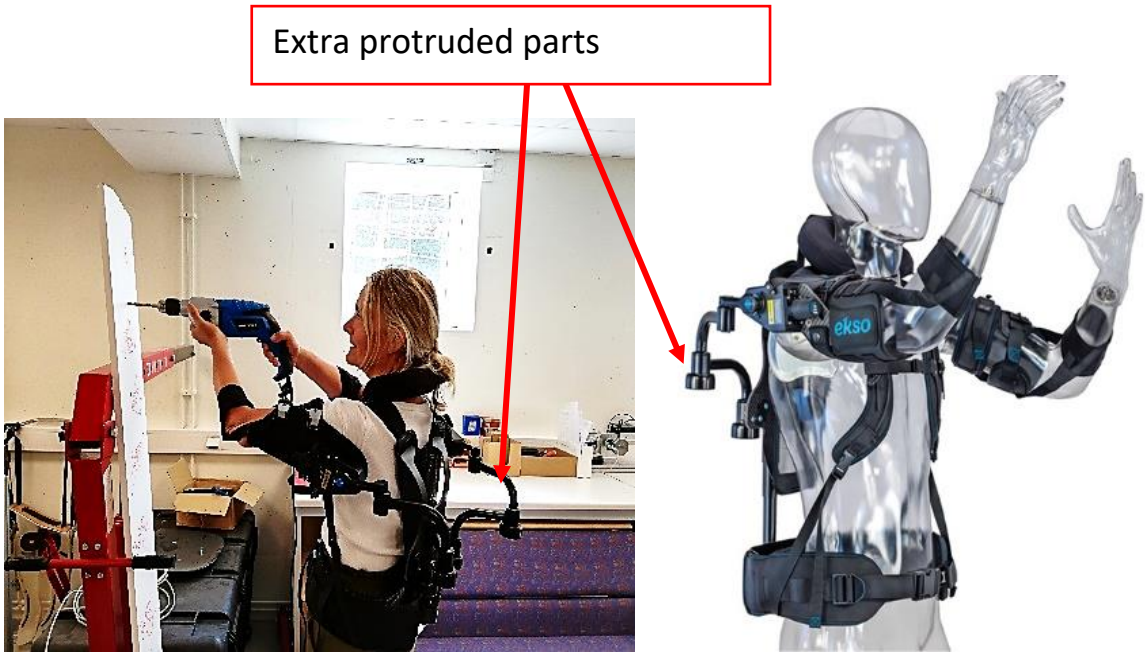


Figure 1. Eksovest with Extra Protruded Parts as marked by the Red Arrows

Eksovest is a passive upper-body exoskeleton that has been assisting workers in their jobs by reducing muscular stresses. It is mainly used in the assembly lines of Automotive industry. It is quite effective in performing repetitive overhead and shoulder-level tasks.

The research team of the University of Gävle, Sweden, has tested Eksovest extensively in their field lab as well as in four pilot testing labs. The pilot sites were set up at the actual sites of Swedish SMEs, construction, and logistic companies. There is no doubt that Eksovest has reduced the muscle activity of the workers by more than 60%. We have recorded the muscle activity, by using EMG sensors, of the workers while performing the same task with and without wearing Eksovest.

The workers unanimously agreed that Eksovest provided significant level of support while performing overhead and shoulder-level tasks. However, Eksovest creates mobility challenges, for example, in

narrow work-places due to the extra protruded parts (as marked by the arrows in Figure-1). These protruded parts might pose serious safety hazards for construction workers, for example, it can stuck with scaffolding during the work.

Furthermore, these extra protruded parts contributes heaviness to the vest. These parts can be shortened and metallic parts can be replaced by non-metallic Carbon-Fiber materials having equivalent strength.

The University of Gävle team has communicated its concerns to the manufacturer of Eksovest, the Eksobionics, and we have received positive acknowledgment of our suggestions. The manufacturers have assured us that our design improvement suggestions will be considered in their future design.

EXSKALLERATE Design improvement

Date
18-3-2023

Partner/Field lab: University of Twente
Exoskeleton tested: Auxivo LiftSuit
Design improvement 1: Reshaping padding/ leg straps

- The Auxivo liftSuit was tested by 10 subjects performing four lifting tasks: asymmetric, squatting, stooping and static bending (Figure 2). These tasks were designed to mimic real-life factory movement while also representing general types of movements.

*Figure 1**Error! Reference source not***

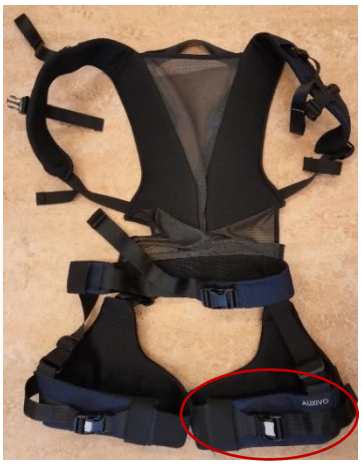


Figure 2: Uncomfortable leg straps

- Subject filled in a discomfort questionnaire which showed that the Auxivo LiftSuit was perceived as not comfortable, especially around the thighs (Figure 2), which corresponds to the findings of Goršič et al. [35]. This is mainly because the leg and shoulder straps should be tight for the elastics to have tension when standing in a neutral position. However, these leg straps could not be secured very tightly. This resulted in the movement of the leg straps upwards when tightening the shoulder straps, which caused friction in the groin.
- In a new design, the legs straps should be able to be secured tighter and a somewhat narrower at the inner side of legs, in order to relief friction in the groin. The Auxivo should facilitate thinner legs.
- We emailed Auxivo (the manufacturer) about this. We received a very positive reaction to our message.
- Our proposed design modification will result in a higher feeling of comfort during wearing the exoskeleton.
- There was one other design flaw communicated to the manufacturer:
    - Dropping of the spring load during wearing the exoskeleton due to loosening of the straps. See document *EXSK Design improvement 2 – UT - Auxivo*.
- Our design idea was already addressed and therefore implemented in the successor of the Auxivo LiftSuit. The LiftSuit 2 has improved leg straps/ padding.
- Auxivo really appreciated our ideas and were very interested in our study with exo's, more specific: in our kinetic motion. Analysis. We have been in contact.

EXSKALLERATE Design improvement

Date
20-3-2023

Partner/Field lab: University of Twente
Exoskeleton tested: Auxivo LiftSuit
Design improvement 2: Enhance strap anchor

- The Auxivo LiftSuit was tested (Figure 1) by 10 subjects performing four lifting tasks: asymmetric, squatting, stooping and static bending. These tasks were designed to mimic real-life factory movement while also representing general types of movements.

Figure 1: Auxivo duing experiment

Figure 2: Strap anchor tends to slide

- However, the fitting of the Auxivo could not be further improved for some participants. The leg straps could not get tight enough for them to tense the elastics properly. Besides, the fitting of the Auxivo got worse when more time was spent moving. The straps loosened; consequently, the elastic was tensed less and delivered less force (Figure 2). This would result in less assistance from the exoskeleton and, therefore, more muscle activity of the participant.
- In a new design, the straps anchors need to be improved by either a wider anchor and strap, or a another type such as the picture below (Figure 3). The amount of support will be optimal during use.


Figure 3: A different type of anchor

- This improvement was communicated with the manufacturer via email. We received a very

positive reaction to our mail.

- There was one other design flaw communicated to the manufacturer:
    - Uncomfortable leg straps. See document *Design improvement 1: Reshaping padding/ leg straps*.
- The design flaws were already addressed by other customers. Therefore, this design idea is not yet implemented in the development of the successor of the LiftSuit. However, they used smaller padding / leg straps at the inner leg in the LiftSuit 2 (design idea 1). Auxivo really appreciated our ideas.

EXSKALLERATE Design improvement

Date
18-4-2023

Partner/Field lab: University of Twente
Exoskeleton tested: Paexo Back
Design improvement: Larger range of motion

- The Paexo Back was tested by 10 subjects performing 4 lifting tasks: asymmetric, squatting, stooping and static bending (Figure 1). These tasks were designed to mimic real-life factory movement while also representing general types of movements. The Paexo Back was set to the static mode during all tasks.
- During the experiment it appeared that persons were not able to perform squats to lift heavy gear from a low table. Apparently, the maximal range of motion of the joint (Figure 2) of the Paexo Back is limited when bending during a squatting movement. During squatting, the Paexo Back tends to lift. In this situation, the straps are not able to hold the exo in place.

Figure 1: Paexo Back used

Figure 2: Joint with limited range of motion

- In order to facilitate bending in a squatting manner, the range of motion of the Paexo back should be increased, either by changing the load v. displacement characteristics or the shifting the position of the 'endstop'.
- Additionally, in a new design, the Paexo Back should have an extra strap running below the buttocks in order to prevent lifting of the exo. This could be similar to the strap used in the Laevo Flex (Figure 3).

Figure 3: straps at the bottom of the side cuffs (similar to Laevo Flex)

- We emailed Orrobock (the manufacturer) about this. We did not yet receive a reaction to our message but we will expects this any moment.

- Our proposed design modification will result in a better fitting of the exo and an increased functionality during use of the exoskeleton.
- There is one other design flaw communicated to the manufacturer:
    - Leg cuff redesign. See document *EXSK Design improvement 4 – UT – Paexo Back*.
- Since we did not receive a reaction from the manufacturer yet, we can assume that our proposal was not implemented yet in a new design.

EXSKALLERATE Design improvement

Date
1-5-2023

Partner/Field lab: University of Twente
Exoskeleton tested: Paexo Back
Design improvement: Leg cuff redesign

- The Paexo Back was tested by 10 subjects performing four lifting tasks: asymmetric, squatting, stooping and static bending (Figure 1). These tasks were designed to mimic real-life factory movement while also representing general types of movements. The Paexo Back was set to the static mode during all tasks.
- Participants experienced discomfort at the front of the legs when wearing the Paexo. This is because the leg pads are made of hard material and are curved (Figure 2). However, this was not a good fit for everybody due to the large difference in thigh circumference.
- The Paexo is suitable for stoop-like tasks; however, due to the high discomfort, it might not be suitable to wear for a long time.

Figure 1: Paexo Back that was used

Figure 2: Uncomfortable cuffs

- In a new design, the Paexo Back should have 'less curved' cuffs at the upper legs. In practice this would mean the radius of the curve must be much larger to facilitate different leg sizes (Figure 3). Additionally, either a soft padding may be added inside the cuff or the cuff may be changed for a more flexible structure that can shape itself better around the thigh.

Figure 3: Fit of a small radius cuff (black) vs. large radius cuff around leg (orange)

- We emailed Orrobock (the manufacturer) about this. We did not yet receive a reaction to our message but we will expects this any moment.
- Our proposed design modification will result in a more comfortable fitting of the exo which will result in a longer wearing time.

- There is one other design flaw communicated to the manufacturer:
    - Uncomfortable side padding. See document *Design improvement 3 – UT – Paexo Back*.
- Since we did not receive a reaction from the manufacturer yet, we can assume that our proposal was not implemented yet in a new design.

15/05/2023

Partner/Field lab: VUB

Exoskeleton tested: German Bionics CrayX
Design improvement: Interference and range of motion

- The German Bionics CrayX had been subjected to a range-of-motion analysis experiment where we collected objective measurements, and has been used in demo's and communication events where we were able to collect subjective feedback from people able to compare several commercially available exoskeletons. They give feedback about the biggest assets and the biggest drawbacks of each of the devices.

- The main concerns about the CrayX are regarding the weight and the width. While it is reported that the weight is well proportioned, still the device feels heavy when moving around. Besides this, when moving in tight spaces or through open doors, the width of the device is particularly cumbersome. The objective measurements show that the main limitation in range of motion is regarding trunk rotation and lateral flexion. Indeed, the device is quite rigid, and this limits the movement of the torso with respect to the legs in most directions.

- This specific need has not been communicated to the manufacturer, however the device itself is collecting data as well as allows for feedback (“how likely are you to recommend this device”).
- An improved range of motion will allow for a higher wearability, reducing the disadvantages of exoskeletons compared to the advantages. Any step in this direction can improve the adoption and acceptance of exoskeletons.

02/05/2023

Partner/Field lab: VUB

Exoskeleton tested: Otto Bock Paexo Back
Design improvement: Range of motion and adjusting complexity

- The Otto Bock Paexo Back has been tested in our field lab in a range of motion experiment. Overall, the Paexo back performed very well in these, preserving the range of motion of the user, however in the lateral flexion there is quite a reduction noticeable. As this is a movement that is also associated with asymmetric lifting and several ambulation tasks, it can be considered very unfavourable for the wearability of the exoskeleton.

- The second main issue that has been identified during demo's and events is the adjustability of the settings of the exoskeleton 'dead zone' determining the threshold of hip angle at which the exoskeleton automatically switches between locked and unlocked. While the mechanism should be one of the major USP's for the exoskeleton, users seem to often use the exoskeleton 'fully open' or 'fully closed'. This obviously reduces the versatility of the device.

- This specific need has not been communicated to the manufacturer. However, it seems like the manufacturer is aware of the complexity of the settings as they offer a training session with every purchase of exoskeletons, where they explain not only the sizing and adjustments, but also the way to use the settings.

- An improved range of motion will allow for a higher wearability, reducing the disadvantages of exoskeletons compared to the advantages. Any step in this direction can improve the adoption and acceptance of exoskeletons.

15/05/2023

Partner/Field lab: VUB
Exoskeleton tested: Innophys Muscle Suit
Design improvement: Range of motion/rigidity

- The Innophys Muscle Suit, like a few other commercially available exoskeletons, has its effect on the range-of-motion of the users tested, as well as more subjective testing during communication events where attendees could experience the exoskeleton and provide feedback. As they could compare the device to other commercially available exoskeletons, they could pinpoint the most important differences between all of them. The Mucle Suit's most notable disadvantage is it's high rigidity. Because of the rigid structure connected to the back of the user, which is quite high from between the shoulders all the way to the low back, as well as wide on the low back, the range of motion of the torso is quite restricted. This also showed from the objective measurements we performed, showing a reduction in range of motion of more than 30% for some movements. A decrease in the rigidity of the structure could greatly improve this.

- Despite the torso/legs range of motion that is restricted, also the arms range of motion and the encumbrance of the device. The latter is mostly important when combining the exoskeleton with sitting tasks or driving, where the exoskeleton will obstruct the

- This specific need has not been communicated to the manufacturer.
- An improved range of motion will allow for a higher wearability, reducing the disadvantages of exoskeletons compared to the advantages. Any step in this direction can improve the adoption and acceptance of exoskeletons.

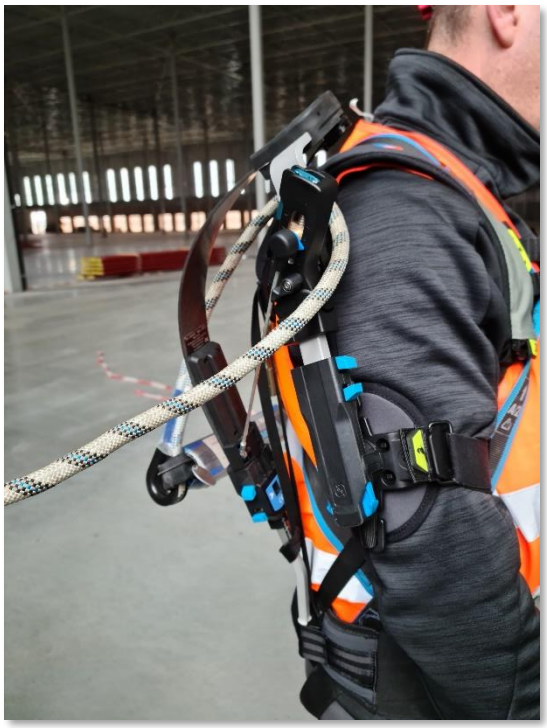
EXSKALLERATE Design improvements

22 March 2023

Partner/Field lab: TNO

Exoskeleton tested: Skelex 360

Design improvement: Avoiding trapped lines



Due to the specific design of the Skelex exoskeleton, there is a risk of entrapment between the shoulder and the exoskeleton. This can be a nuisance as in the left picture where loop of cables, that are installed in overhead ducts, are 'snatched' by the exoskeleton. The operator stated that this was a reason not wanting to wear the exoskeleton in these types of activities.

It also poses a danger, as shown in the right picture. Here a fall protection line can become trapped in the wedge that is formed between the exoskeleton and the shoulder. This very quickly became apparent in a short test of combining an exoskeleton with fall protection gear.

This was communicated with the manufacturer, who responded very positive to the feedback we supply on their exoskeleton. In fact, they had already created a solution for the problem in the form of a fabric that covers the gap. It was demonstrated to us in an online meeting with Skelex.

We have not yet been able to test the suitability of the cover, especially with regards to it being strong enough to divert a fall protection line away from the wedge. This may be done in the near future.

Partner/Field lab: TNO
Exoskeleton tested: general
Design improvement: price reduction

Exoskeleton cost-benefit analysis tool v1.1

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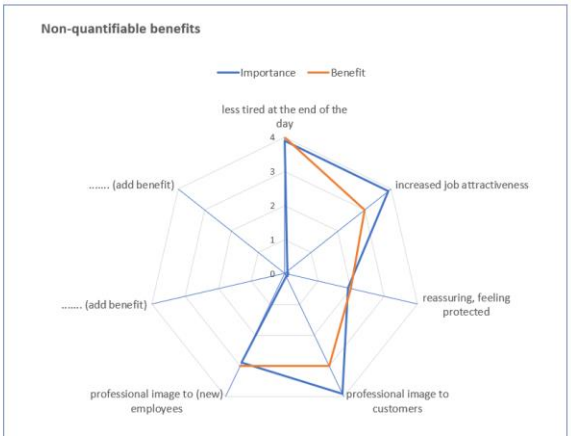
Overview

Quantifiable benefits

Yearly costs	**€ 1.216**	based on: 5 year depreciation period
	€ 966	purchase
	€ 250	service and maintenance
Yearly benefits	**€ 980**	
	€ 1.200	productivity
	N/A	quality
	-€ 220	damage costs
	€ 0	occupational health
Costs/benefits	**-€ 236**	
IF business case is negative		
Yearly costs as % of worker costs (1 exoskeleton/worker)	0,49%	
Required increase in hourly rate	€ 0,15	

Non-quantifiable benefits	benefit score	importance score
less tired at the end of the day	4	4
increased job attractiveness	3	4
reassuring, feeling protected	2	2
professional image to customers	3	4
professional image to (new) employees	3	3
..... (add benefit)		
..... (add benefit)		



In construction industry, tasks often vary on a day to day or project to project basis. Tasks also often vary during the day. An exoskeleton generally does not have an added value for all tasks. Therefore the exoskeleton may only be used for certain projects and specific tasks during a working day.

Because of this, the companies that already have exoskeletons, have a limited number of them, often only one or two, which can be borrowed from the company's central tool supply.

From a business case point of view, this is not surprising. Current passive arm support exoskeletons and rigid back support exoskeletons are in a price range between approximately €2500 and €4500. Because the exoskeleton is not a prerequisite to be able to do the work, such as e.g. electric tooling, and because they are not always needed, companies choose to have a few in stock to minimize the amount of exoskeletons lying around.

This system could hinder adoption because it draws up extra barriers for potential use, on top of discomfort and hindrance issues. First of all, planning is needed to make sure the exoskeleton is on-site when needed. Second, because the exoskeleton is shared, it needs to be adjusted to the user. From office chairs in flexible offices we know that making sure users adjust them properly, is a challenge[1]. A maladjusted exoskeleton easily leads to a user's dissatisfaction about the product.

For optimal adoption of exoskelet use, it is our opinion that the exoskeleton should be personal equipment. The likelyhood of becoming personal equiment would greatly increase if their price would fall in the range of high end office chairs.

[1] Office chairs are often not adjusted by end-users, Vink et al., 2007