Intelligent Information Management, 2023, 15, 216-241
https://www.scirp.org/journal/iim
ISSN Online: 2160-5920
ISSN Print: 2160-5912

An Investigation of Exoskeleton Robotic Systems in Assisting Construction Tasks*

Xiu-Tian Yan[1#], Jenna Browne[1], Cameron Swanson[2], Cong Niu[1], Graeme Bisland[2], Youhua Li[1], Alan Johnston[3]

[1]Robotics and Autonomous Systems Group, The University of Strathclyde, Glasgow, UK
[2]National Manufacturing Institute Scotland, The University of Strathclyde, Glasgow, UK
[3]Build Environment-Smart Transformation (BE-ST), Edinburgh Napier University, Edinburgh, UK
Email: #x.yan@strath.ac.uk

How to cite this paper: Yan, X.-T., Browne, J., Swanson, C., Niu, C., Bisland, G., Li, Y.H. and Johnston, A. (2023) An Investigation of Exoskeleton Robotic Systems in Assisting Construction Tasks. *Intelligent Information Management*, **15**, 216-241.
https://doi.org/10.4236/iim.2023.153011

Received: March 21, 2023
Accepted: May 28, 2023
Published: May 31, 2023

Abstract

Whilst industrial robots have been widely used in many industrial sectors, they are predominantly used in a structured factory environment. In recent years, off-site robotics have been investigated extensively and there are some promising candidates emerging. One such category of robots is exoskeleton robots and this paper provides an in-depth assessment of their suitability in assisting human operators in undertaking manual operations typically found in the construction industry. This work aims to objectively assess the advantages and disadvantages of these two suits and provide recommendations for further improvements of similar system designs. The paper focuses on the passive exoskeleton robotic suits which are commercially available. Three types of activities are designed and a mechatronic methodology has been designed and implemented to capture visual data in order to assess these systems in comparison with normal human operations. The study suggests that these passive suits do reduce the effort required by human operators to undertake the same construction tasks as evidenced by the results from one focused study, though a number of improvements could be made to improve their performance for wider adoption.

Keywords

Exoskeleton, Robotics, Construction Manufacturing

1. Introduction

As a whole, the construction industry is still very much labour focused involving many human operators to undertake various tasks, in particular on-site con-

*Exoskeleton Robotics for construction.

struction tasks, however the industry is slowly moving toward more automated operations. Construction workers' tasks are currently often repetitive and strenuous and can involve lifting heavy objects. Due to tight deadlines and long working hours, these tasks can be performed when energy levels are low and fatigue high, resulting in a lack of good form and correct posture. Also, a minimal active inspection of effective use and handling could lead to injury.

Within the last 10 years, improvement in construction safety performance has been diminishing, approaching a stagnant state internationally [1]. Exploring a variety of methods here to focus on the worker's safety behaviour and acceptance of procedures, as unsafe construction worker behaviour causes over 80% of accidents [2] [3]. High accident rates are often correlated with corporations' lack of process for prevention, due to financial considerations and extended work hours caused by high demands [4].

Low back pain (LBP) is a spinal disorder that affects up to 80% of the population at some point in their life and can harm work capabilities and well-being [5] [6]. Construction workers who operate on roofs, on uneven terrain and in awkward working postures daily can expose themselves to LBP. Many physical factors have been recognised as indicators of LBP, such as frequent bending, twisting, over-stretching, heavy lifting, heavyweight pulling and pushing, prolonged standing and prolonged sitting [7].

Lower back pain is common among construction workers, particularly for those working on floors or roofs [8] [9]. Construction workers are often working on uneven terrain where mechanical loading on the spine can lead to sudden loading and cause injury [10] [11]. Work-caused lower back pain (LBP) was identified as one of the top three world occupational health problems by the World Health Organisation (WHO) [2]. Work LBP causes significant absenteeism and lower productivity, resulting in financial burdens on employers, employees, and the healthcare system [8].

It is clear there is an urgent need for a technological solution to address the challenges both construction workers and employers face relating to work LBP. Among many solutions, exoskeleton robots in general or exoskeleton suits as the passive form of the general terminology could be one solution. This paper focuses on the assessment of such technology in addressing the work LBP challenge. The paper reveals initial findings from a number of field lab tests of two exoskeleton suits and these findings are aimed to help disseminate the results to promote the wider use of such exoskeleton robotic solutions in addressing the LBP challenges faced in construction industry.

An exoskeleton robot can be defined for this study as a mechanical wearable structure that enhances the power of the wearer and reduce the stress on the wearer at the same time. Exoskeletons robots can be categorised as passive or active. Passive exoskeleton robots are devices that can be worn to assist the wearer without the need of an external power source such as a battery, whereas the active exoskeletons robots work on the principle of providing the assistance of power and other support relying on an external power source. This study focuses on passive exoskeleton robots with active exoskeleton robots to be investigated in future studies. The passive exoskeleton robots support the user's posture and motion and can help take the weight off them when they are doing a task. Passive exoskeletons have rarely been tested in a real work scenario, only in simple laboratory tasks that do not effectively mimic construction worker tasks. These passive exoskeletons need to be tested in the field to measure their effectiveness in a real-life scenario. This paper provides a detailed assessment of the effectiveness of these passive exoskeleton robots, or passive exoskeletons, or passive exoskeletons suits, which are equally used to refer to the same passive exoskeleton robots for convenience. The paper's novelty lies in the reporting of these new testing of passive exoskeleton robots in real construction work.

2. A Mechatronic Assessment Approach and Research Methodology

For the purpose of a robust assessment of two selected exoskeleton passive robots, it is necessary to define a methodology through which such assessment can be undertaken. The methodology proposed is shown in Figure 1 and consists of three main components namely field lab design, data capture system design and implementation, and finally post processing of data captured. Three field labs have been designed in order to cover a range of typical construction manufacturing operations. The first field lab is for the operators to lay tiles on a purpose-built roof. The second field lab is to design for operators to undertake plaster boarding activities. The final field lap is designed for operators to assemble furniture within a factory environment.

2.1. Selected Passive Exoskeletons Robot

2.1.1. Passive Exoskeleton Robot (PER) PER-A

Two commercially available passive exoskeletons suits have been selected for this study and they have been anonymised as passive exoskeletons robot—PER A

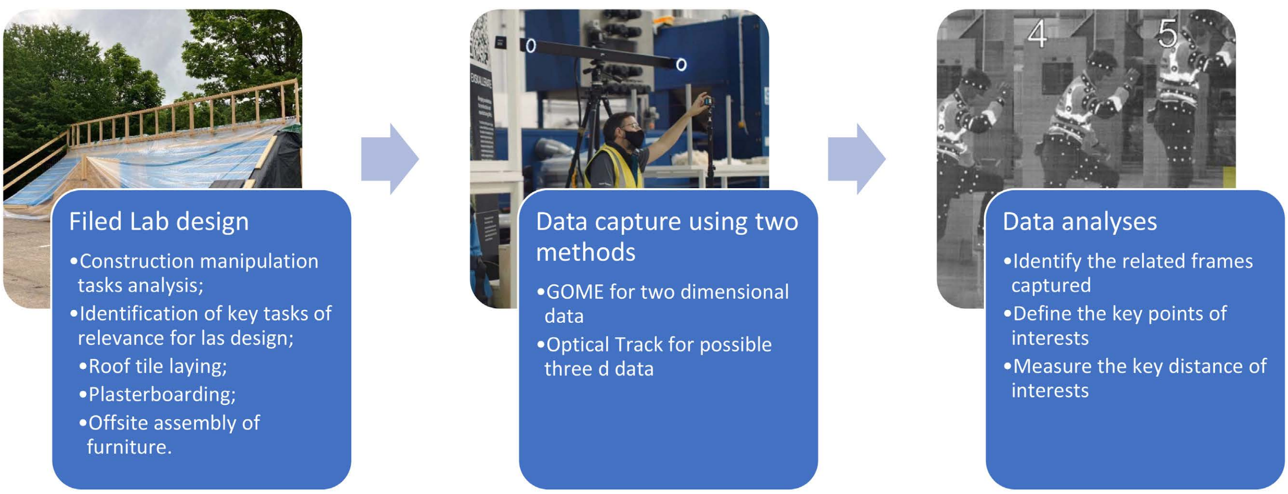

Figure 1. A mechatronic methodology for investigating passive exoskeleton suit.

suit. The PER-A suit is a passive textile exoskeleton suit designed to support back and hip muscles when lifting objects from below hip level, or when working in a forward-leaning position. The suit can be sized to fit the user through adjustment of straps and buckles. Tension is stored and released by elasticated material on the suit. In these labs users were shown how to fit the PER A suit and fitted and adjusted the PER A suit themselves for each lab.

2.1.2. Passive Exoskeleton Robot (PER) PER-B

The passive exoskeleton robot PER-B is also a passive textile exoskeleton suit designed to reduce strain on the back, with a function to switch the back assistance on and off with a clutch. The suit is a modular design, allowing for parts to be interchanged to tailor to the individual size. Tension is stored and released through the use of elasticated material on the suit. It also offers different strengths of elasticated material to suit the users need. In these labs users were shown how to fit the PER-B suit and fitted, adjusted, and selected their preferred tension strength for the PER-B suit themselves for each field lab tasks.

2.2. Monitoring Data Capturing

For data monitoring, inevitably it is essential to use some mechatronic technologies for a scientific measurement of the performance of those systems. These include two specific monitoring systems which can provide two dimensional performance measurement and possible three-dimensional performance measurement data.

A method of projecting human movements can be productive for later reviewing and analysing the data gathered. Real-time recording takes place through camera-capturing motion, a way of tracking specific joint movements to verify if the posture of the user is correct would be beneficial within this experiment.

2.2.1. GOM Aramis SRX

A commercial GOM system has been used to capture the typical factory environment body movement of a human operator in the designed field lab environment. It effectively works on the principle of tracking markers attached to several areas of the body of a human operator.

For motion tracking of the participant while conducting the tasks, the GOM ARAMIS SRX 1600 high speed dynamic measurement system was used. The camera uses tracking markers that are placed onto the participant. The coordinate system was established using markers in a plane-line-point arrangement, and was consistent across all tests. Using the markers, points can be identified and monitored on the participant's body to then analyse the change in the distance through the tasks. Motion was generally captured at 25 fps and reduced to 10 fps where the activity required prolonged recording time. The GOM Setup is shown in **Figure 2**.

The advantage of this approach is that a higher number of markers or points can be tracked and time sequencing positional data can be captured and stored for post processing. A potential disadvantage is that the system captures a higher number of position markers and it could potentially lead to a miss identification of markers to be measured. Markers can be lost while the worker is performing tasks *i.e.* twisting of the body. Markers come off easily when performing the task *i.e.* when user is putting tiles onto their shoulder, the markers fall off.

2.2.2. Optitrack System

An alternative technology is to use optical track system which works on the principle of tracking a smaller number of groups of clustered reflective spheres with 6 DoF information and this system is shown in **Figure 3**. This approach provides better three-dimensional information as a cluster of three reflecting balls are mounted on each plate attached to a critical point of interest in motion monitoring. The introduction of a cluster of these three ball marking plates reduces occlusion due to more points for possible tracking and can be very useful if some of the ball markers are rotated which can still be visible partially by the cameras. In these cases, for flat markers used in systems such as the first technology GOM critical position information will be lost.

Finally, a number of data analysis techniques have been used in order to provide

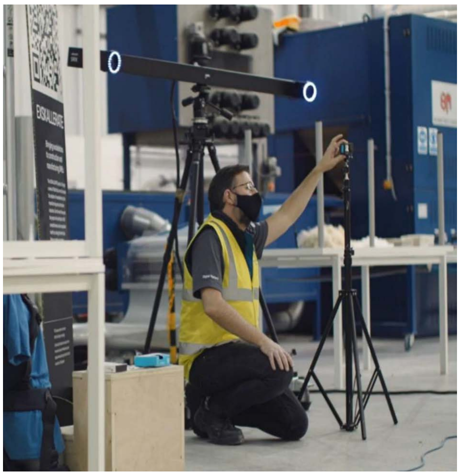

Figure 2. GOM ARAMIS SRX 1600.

Figure 3. A multiple 3-D point tracking system.

rapid and reliable analysis of the visual information captured.

2.3. Monitoring Data Capturing

The above methodology has been extended to include a human model. This study will help to locate precisely the markers using both monitoring technologies. A method of projecting human movements can be productive for later reviewing and analyzing the data gathered. Real-time recording takes place through camera-capturing motion, a way of tracking specific joint movements to verify if the posture of the user is correct would be beneficial within this experiment.

2.3.1. Gazebo Modelling and Simulation

Gazebo is used to model a human representation and it is a simulation programme which allows for human models to be created or inputted into the software, and physics principles to be associated with the model. A basic human model is generated and each part of the body is shown as a separate component with its own starting coordinates shown in **Figure 4**. Gravity can be put onto the model meaning it can mimic a real-life environment with the model used.

Additional functions can be developed to enable Gazebo to use high-performance physics engines to generate real-time simulations on models. Models in Gazebo can react with others to simulate real-life interaction between objects. Gazebo can run a simulation repeating an active task to discover the effects of repeating multiple iterations. For example, repeating the activities discussed later in the paper of a roofer laying tiles to analyse how their performance and body

Figure 4. A high level of human model.

movements will change over a prolonged period. This can help with showing the effect workers can impact on themselves by working a physically strenuous trade.

2.3.2. Proportional Integral Derivative

To allow the joints in the body to be controlled and manipulated, they are monitored through a proportional-integral-derivative (PID) of each critical join point.

$$
\begin{aligned}
&e(t) = SP - PV \\
&u(t) = u_{bias} + K_c e(t) + \frac{K_c}{\tau_I}\int_0^t e(t)\,\mathrm{d}t - K_c \tau_D \frac{\mathrm{d}(PV)}{\mathrm{d}t}
\end{aligned} \tag{1}
$$

where SP is a Set point; PV is a Process variable; $u(t)$ is Controller output; u_{bias} is Constant ($u(t)$ value when the controlled is in automatic mode); K_c is Controller gain; T_D is Derivative time constant; and $e(t)$ is Error from the set point.

A PID controller is suited for processes where the output eventually returns to the initial input. These initial inputs can be set as desirable moments within the human simulation, to be noted as the ideal scenario. From this, the data can be inputted and highlighted when it strays from the ideal scenario identified. This enables the modelling of the human in performing manual manipulation tasks to be investigated to assist the evaluation of passive exoskeleton robots in a virtual environment in future.

2.3.3. Armature

An armature is used to relate the joints of the body to one another to operate as a human body would. **Figure 5** shows the relationship between various body parts of the body. The parent-child relationship between parts ensures that when one body part moves the other follows. For example, if the thigh moves, the calf will then follow. These relationships defined among different body regions provide suitable framework for modelling a human body movement and will be further investigated.

3. Data Analyses of Planned Field Trials

Based on the understanding of human body movement and the data captured, a high level of measurement of effort made by a human operator is defined as the primary performance measurement for the passive exoskeleton robot system. This also reflects a lack of experimental work found in the literature review that there is very little scientific measurement work or few approach indeed used for such a measurement of human operators in the construction industry. In this research it is therefore proposed to effort as a generic measurement of performance of an operator in undertaking a particular construction task. Similar to the generalised effort definition used in the bond graph theory [12], an effort for this study is defined as energy required for an operator to perform a manufacturing task which involving moving a component either with bare hands or with a tool

Figure 5. Armature configuration of a human model.

per unit of displacement. For the same manufacturing tasks, as the mass and gravity remain the same, the focus will therefore be on the distance travelled by the operator in performing the task. The distance is mostly reflected on the body movements for the tasks designed. It is therefore reasonable to focus on the analyses on the distance individual part of the body moves during a task execution. Given the availabilities of multiple marker tracking approaches taken in the experimental design and the nature of this first attempt analysis, selected markers have been used to measure the effort. For the simplicity and effectiveness of this study, it is decided to measure the following key distances:

- Upper body moving distance: this initially measures the distance of a fixed point on an operator's head to a marker on the operator's waist to represent the effort required to bend their upper body by measuring this distance reflecting the amount of complex bending motion including their head driven by and connected to the neck and torso or upper body. For simplicity the neck movement including both bending and turning are included in the upper body measurement;

- Lower body moving distance: This defines a measurement of effort made by the operator in manipulating their muscles to bend, move or lift the lower extremity of the body, excluding the foot movement.

Detailed analysis of body movements, key stress-related movements are detailed in the next section.

3.1. Field Lab 1—Roofing Operations

Field lab 1 involved the users conducting roofing activities of laying concrete tiles over a pitched roof. Three trained roofers performed these activities while being observed and recorded however only one of these participants was used for dimensional motion analysis. The PER-A and PER-B suit were both tested throughout the activity. The roofing activity was broken down into three sub-activities based on the variance in motion, allowing each sub-activity to be captured in full. The three sub-activities selected were:

1) Lifting six tiles from a stack onto their shoulder;
2) Stepping up onto the roof and lowering the tile stack to the roof;
3) Laying the six tiles from the stack into two rows.

3.1.1. Activity 1—Lifting Tile Stack from the Ground

The first activity involved a significant back bend to retrieve the tiles, a heavy load rotated onto their shoulder with a squat to lift the tiles into place. The individual tiles weighed 5.1 kg, with the stack of tiles weighing 30.6 kg. The dimensions of the tiles were 418 × 344 × 31 mm. This activity is repeated three times by the same operator.

Building on the effort definition and effort to move three main body regions head and neck, torso and lower extremity, four specific metrics have been identified to support the effort measurement and they were measured during this activity: head height, hip height, lean angle, and bend angle, as shown in Figure 6. These measurements focus on two vertical movements measured from the head and hip and two angles between the torso and the lower extremity, and the lower

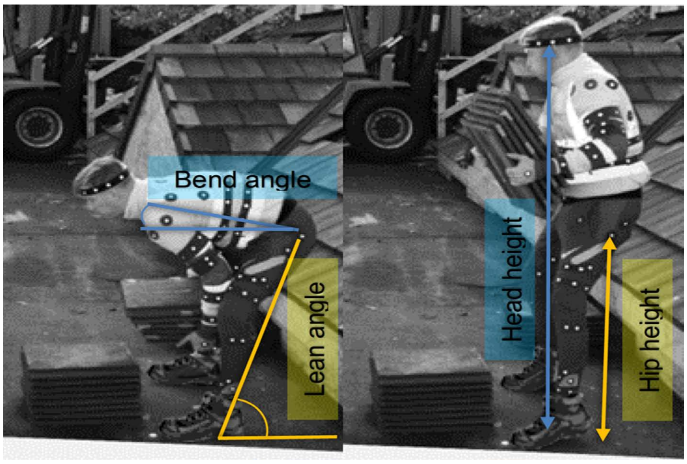

Figure 6. Measurement metrics used in field lab 1—activity 1.

extremity to the ground level. These are intended to measure both translational movement of the body as well as the rotational movement between two key body regions. The exact definitions of these measurements are described below and schematic illustration of these measurement are shown in:

- Head height—The height of the centre of the head to the ground;
- Hip height—The height of the lower hip to the ground;
- Lean angle—Backwards lean of the legs against the X-axis (vertical);
- Bend angle—Angle of back relative to the Y-axis (horizontal).

Three sets of experiments have been undertaken for each of the following cases, namely the experiment with an operator wearing no exoskeleton suit at all shown in **Figure 7**, the one with an operator wearing PER-A exoskeleton suit captured in **Figure 8**, and finally an operator wearing PER-B exoskeleton suit illustrated in **Figure 9**. For these three experiments, the same operator performed the same activity type and the same number of operations. This is intended to

Figure 7. Measurement metrics used in field lab 1 – activity 1.

Figure 8. Worker 1 (roofer) performing field lab activity 1 with a PER-A suit.

Figure 9. Worker 1 (roofer) performing field lab activity 1 with a PER-B suit.

provide a minimal deviation if not zero deviation, caused by other controllerable variations in the experiments, such as tiles weight variation, operator's person height difference and so forth. It is also worth to highlight that all these experiments have been performed by professional roofers and it is therefore can be assumed that they would have repeated the same operation in a professional style with minimal deviation from one experiment to the others apart from wearing different exoskeleton suits or not wearing at all.

It was planned to capture the same sequence of operations of each experiments for easy comparison and the same number of 5 images have been selected for analyses purpose of each of the experiments shown in, Figure 7, Figure 8 and Figure 9. Each image is marked with a number starting from image 1 to image 5 in each of the above three figures. The general motions, shown in Figure 7, Figure 8 and Figure 9, are described as follows: the participant, from a standing position (0) shown in image 1 of each figure bends down to grip the underside of the sixth tile (1). The participant holds the bend while the tiles are tipped slightly backwards at an angle and positioned for a firm grip (2). The tiles are then partially lifted to knee level where they are brought in closer to the body (3). The tiles are then lifted directly upwards along a small arc with the rear of the feet lifted (4). The tiles are then planted on the shoulder in preparation for carrying to a location (5).

1) Lean and Bend Angles

The no suit and PER-A suit results show similarities in form and repetition. Overall, the PER-A result shows the greatest consistency in motion and duration across the three repetitions. The following specific observations have also been made.

Figure 10 is labelled with the motions within the activity that creates the chart results. When comparing the three charts, the PER-A suit shows the most variance

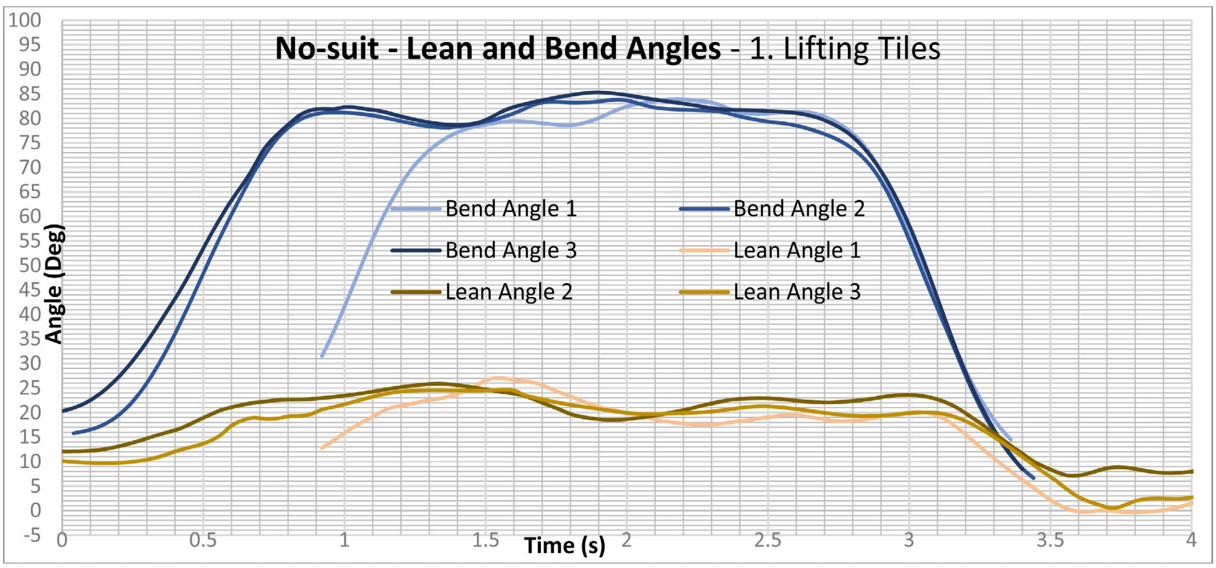

Figure 10. Worker 1 (roofer) lean and bend angles for field lab activity 1 with no suit.

in motion. Across all three iterations of lifting the tiles, each result within the PER-A chart is very different, especially at the point of the initial bending and lifting of the tiles. Whilst Worker 1's bend angle varies as they were performing different stages of the activity, it is worth noting that the maximum bend angle with No-suit is measured to be approximately 85˚; the profile patters are similar for all three repeated experiments. The maximum lean angle is measured to be 25˚ again with very similar patterns.

For experiment 2 when the worker 1 wears the PER-A suit, it is observed that the Worker 1's bend angle also varies as expected when he was performing different stages of the activity. It is however observed that the maximum bend angle is measured to be approximately 90˚ with three bending angle profile patters are similar. The maximum lean angle is measured to be about 30˚ with very similar patterns shown in Figure 11.

Experiment 3 involved the use of PER-B suit by the Worker 1. Similar to experiment 2 it is observed from results shown in Figure 12 that the Worker 1's bend angle also varies as expected and the maximum bend angle is measured to be also approximately 90˚ with three similar bending angle profiles. The maximum lean angle is measured to be about 25˚ with very similar patterns.

The above measurements are summarised and explained below. Worker 1's maximum bend angle with No-suit was approximately 85˚, with the PER-A and PER-B suit the worker conducted the lift with a maximum bend angle of approximately 89˚ to 90˚. The large angle shows that less back bending has occurred while wearing the suits compared to without the suits. These consistent measurement of larger bending angles when the operator wears an exoskeleton robot suit suggest that the suit does provide support to enable the operator to bend about 5˚ less in each operation. In other words, the operator requires less effort equivalent to rotating his torso by 5˚.

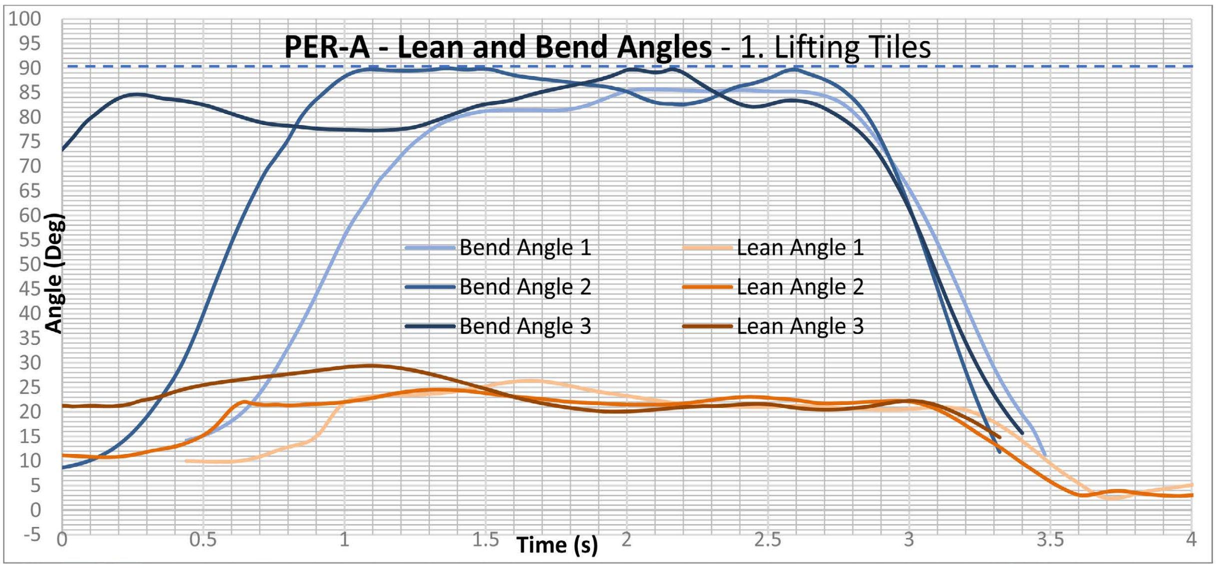

Figure 11. Worker 1 (roofer) lean and bend angles for field lab Activity 1 with PER-A suit.

This preliminary conclusion can be verified within the head and hip height measurements in next section.

It is observed that Worker 1 was on average, able to conduct the lifting activity within a slightly shorter time while wearing the PER-A suit, average lift time of 1.24 seconds when compared to no-suit 1.29 seconds. The PER-B suit took marginally longer with a lift time of 1.32 seconds.

2) Hip Heights

Hip heights are selected to measure the effort exerted on the lower extremity by rotating around both the knee joints and hip joints of an operator. Generally speaking, the higher the hip height, the less effort is required to rotate the lower extremity. Figure 13 shows three hip height profiles for three repeated lifting tile

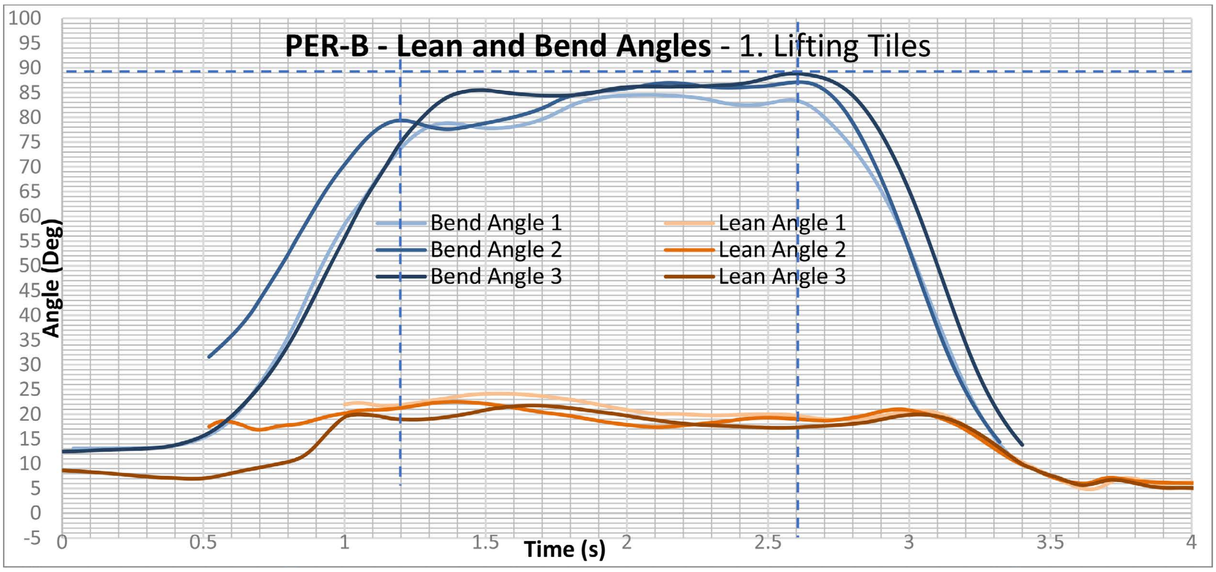

Figure 12. Worker 1 (roofer) lean and bend angles for field lab activity 1 with PER-A suit.

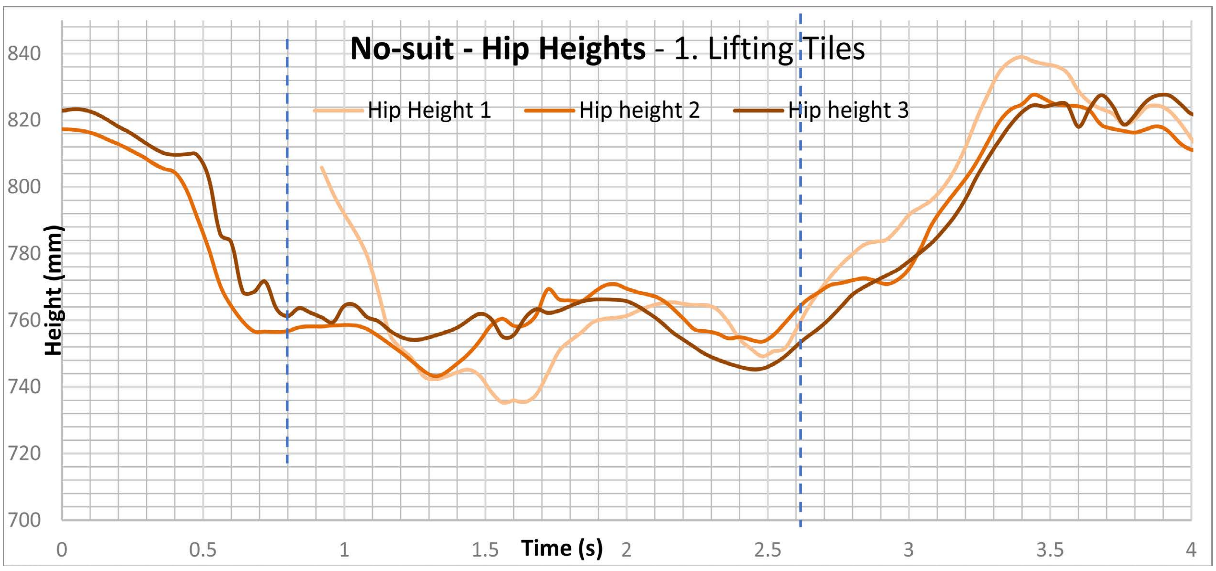

Figure 13. Worker 1 (roofer) hip heights for field lab activity 1 with no suit.

stack activities when the operator wears no suit. It can be observed that from 0.5 second to 2.53 second of this 4 second operation, the operator has a lower hip height about 760 mm for all three repeated activities.

Figure 14 plots three hip height profiles for three repeated lifting tile stack activities when the operator wore PER-A suit. It can be observed from three similar profiles of hip heights that during the entire 4 second operation, the operator has a high hip height about 800 mm from the ground for activity 2 and 3 and slightly lower hip height at 780 for the duration from 1 second to 2.5 second for activity 1.

Three hip height profiles for three repeated lifting activities are illustrated in Figure 15 when the operator wore PER-B suit. It can be observed from three

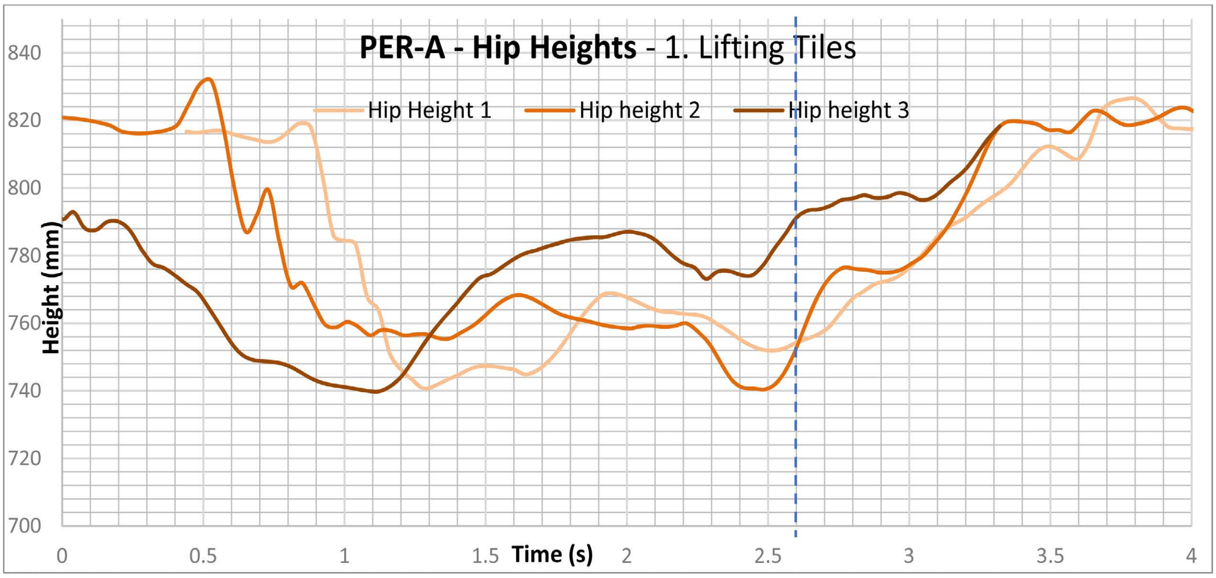

Figure 14. Worker 1 (roofer) hip heights for field lab activity 1 with PER-A suit.

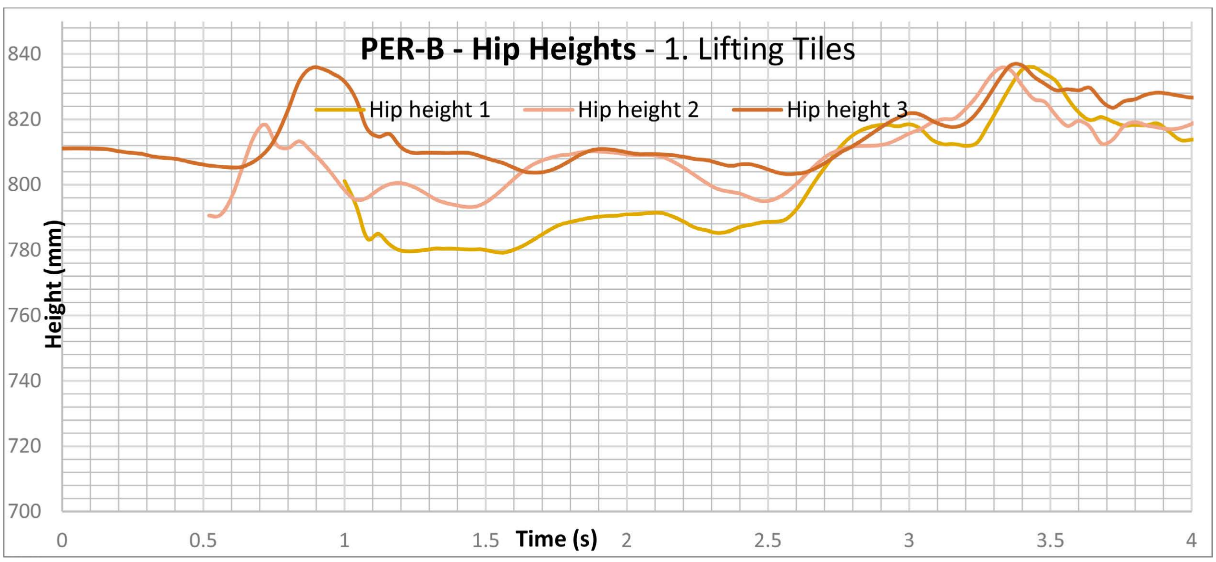

Figure 15. Worker 1 (roofer) hip heights for field lab activity 1 with PER-B suit.

similar profiles of hip heights that during the entire 4 second operation, the operator has a high hip height about 800 mm from the ground for activity 2 and 3 and slightly lower hip height at 780 for the duration from 1 second to 2.5 second for activity 1.

If these heights are shorter for the suits compared to without the suit, this appears to suggest that the less back bending was due to the support from restraining torso movement and also possible from the extra bend in the knees. Ensuring sufficient bending of knees lessens the opportunity for overly bending the back.

A lower hip height value of 760 mm from Figure 13 with no suit suggests that the operator had to lower his torso and hip significantly more than the cases where the operator wore either PER-A or PER-B suit with a hip height values of 780mm and 780 to 800 mm respectively shown in Figure 14 and Figure 15. It is clear a cumulative of shorter lowing distance, when many repetitive activities are carried out, can lead a significant reduction in stress on associated muscles.

The above shows a high level observation. It is also necessary to note the results from the hip height analysis, showing varying distances and irregular patterns across the 3 trials. The no suit and PER-A suit results show the greatest similarity, with the range of movement from 730 - 830 mm and 740 - 830 mm respectively. The results with the PER-A suit show a smaller range of measurement with only 780 - 830 mm range. Further investigation is therefore necessary to draw more conclusive findings.

3) Head Height

Similarly, the head height is also measured for three roofer tile lifting operations. Figure 16 shows the head height during the operation when no suit was worn.

When PER-A suit was used, the head height motion profile is captured and

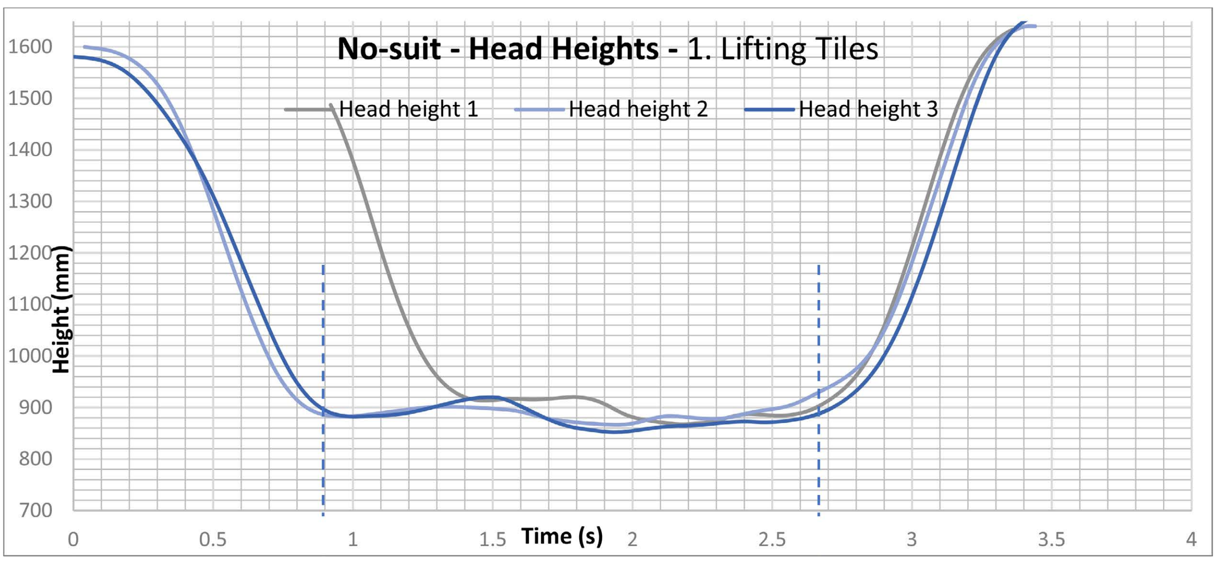

Figure 16. Worker 1 (roofer) head heights for field lab activity 1 lifting tiles with no suit.

shown in **Figure 17** during the operation. This profile shows a similar profile but with a reduced head height from 865 mm to 790 mm. the head height is further reduced to 750 mm shown in **Figure 18** which plots the results of the same activity in lifting tiles when PER-B suit was used. These results suggest that PER-B suit helps an operative to bend less in terms of head height.

The results show similarities across each of the trials, visually the graphs follow the same pattern. The maximum distance across each suit is the same at 1600 mm, this distance is the total height of the user. The suit with the most variance in result is the PER-B suit (820 - 1600 mm) compared to the PER-A and no suit (840 - 1600 mm and 860 - 1600 mm respectively).

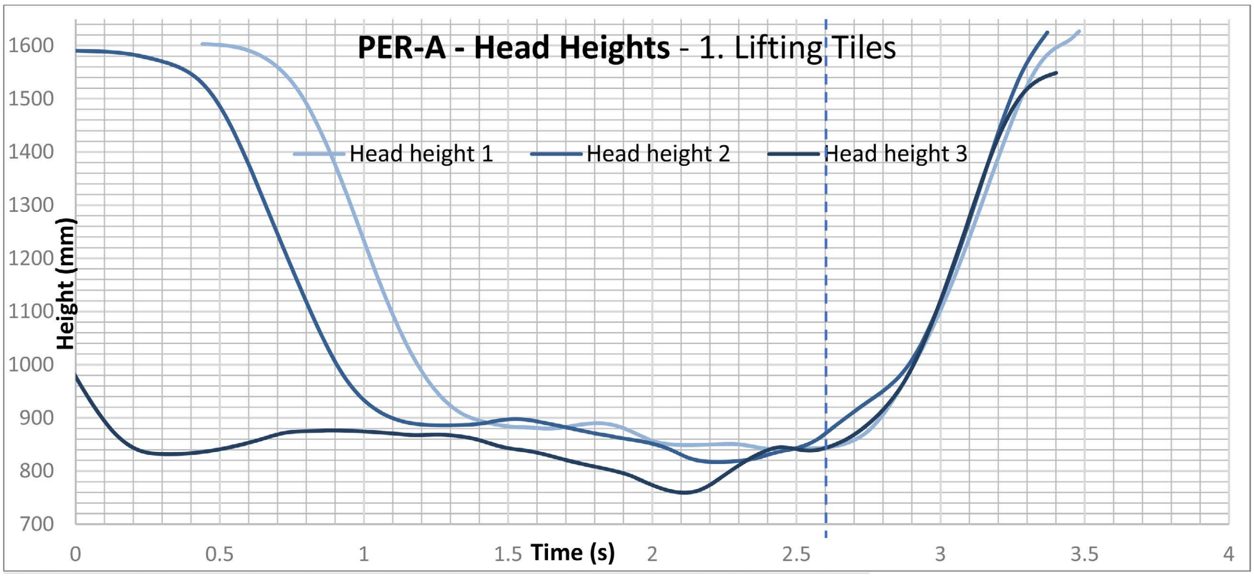

Figure 17. Worker 1 (roofer) head heights for field lab activity 1 lifting tiles with PER-A suit.

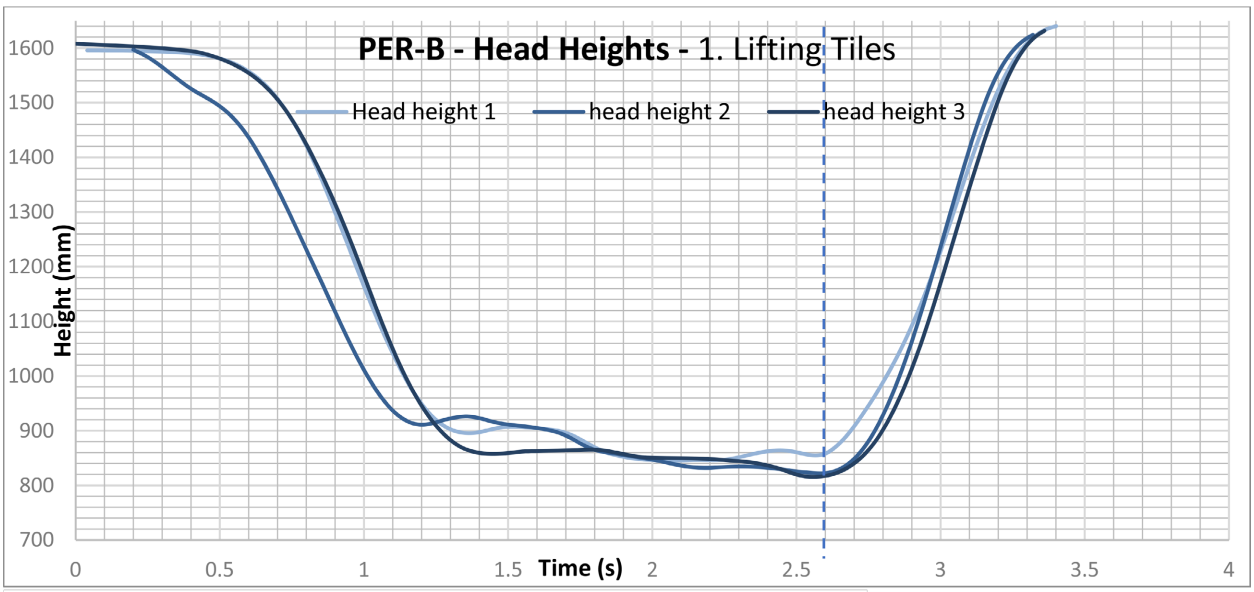

Figure 18. Worker 1 (roofer) head heights for field lab activity 1 lifting tiles with PER-B suit.

4) Duration

Overall, the time to complete the activity detailed in Table 1 is not heavily affected by the use of the suits. The PER-B suit showed the longest average time, followed by no suit and then PER-A. The bend time gives the greatest variance, with both suits showing a longer bend time compared to no suit. Lift times across all suits show very little difference.

3.1.2. An Alternative Measurement

Due to the nature of dynamic movements of different body regions, an alternative set of measurement parameters have also been identified in order to measure the effort directly. Instead of measuring the heights of three critical regions of the operators body movement, it is desirable to measure the relative movement of each body region to other body region. It is believed these measurements will provide an alternative relative measurement of effort made by the operator in order to manipulate or rotate body regions during the activity operation. In this approach, two measurements have been identified: head to hip distance, and hip to foot distance. Head to Hip (HtH) distance is to measure the movement of upper body including head, neck and torso and this measurement provides an objective and relative indication the amount of effort made by the operator. Hip To Foot (HtF) distance monitors the effort made in leg movements. Markers used for these two measurements are shown in Figure 19 during tile laying operations.

For this field lab tests, an operator is asked to lay 6 tiles in 2 groups with each location with each tile laid three times. These captured videos are then analysed and a resultant table for Head to Hip distance measurement is show in Table 2.

These data are presented in a chart shown in Figure 20 and it is clear that the distance between Head to Hip is consistently larger when the operator wore PER-B suit in comparison with the same operations when he wore no suit. The average HtH distance when using PER-B in laying tile is 746.9 mm in comparison

Table 1. Times to complete roofing activity 1 (lifting tiles) for all suits.

		Bend time (s)	Lift time (s)	Total time (s)	Average total time (s)
PER-A	1	0.92	1.2	3.32	3.35
	2	0.92	1.24	3.40	
	3	0.96	1.28	3.32	
PER-B	1	0.76	1.2	3.24	3.81
	2	0.84	1.4	3.68	
	3	0.88	1.36	4.52	
No-Suit	1	0.68	1.28	3.00	3.43
	2	0.68	1.28	3.56	
	3	0.80	1.32	3.72	

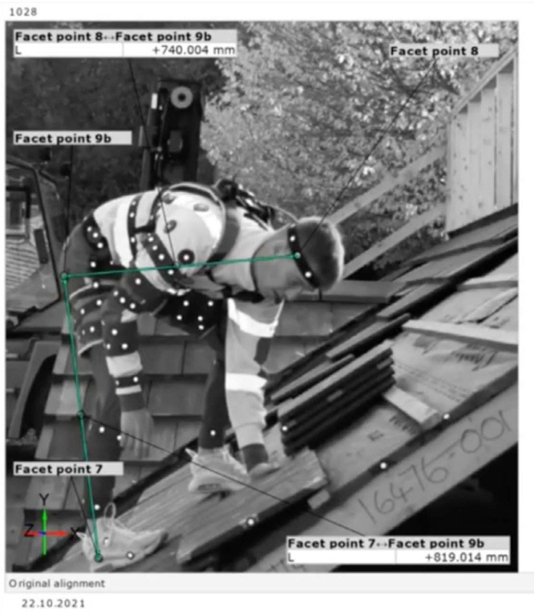

Figure 19. An alternative measurement of effort made in tile laying operation.

Table 2. A summary table of Head to Hip distances when laying tiles by an operator with PER-B and No Suit.

	PER-B				No Suit			
	Min	Max	Mean	Standard deviation	Min	Max	Mean	Standard deviation
Group 1	668.8	854.3	725.1	49.8	576.5	844.6	681.5	97.3
	697.3	843.8	735.4	38.4	611.4	850.8	727	82.6
	715.7	866.9	776.3	40.4	560.2	836.9	688.5	92.4
Group 2	734.9	794.2	755.3	20.2	642.5	725.7	680	28.4
	732.1	806.9	766.5	27.2	648.3	736.6	685.9	31.4
	719.7	800.3	751.1	27.9	604	726	684.2	31.2
Group 3	736.6	778.6	751.9	12.5	657.2	769.1	707.6	40.2
	728.2	761.3	743.2	11.2	661.5	750.2	695.2	29.9
	737.7	797.7	762.5	17.8	663.3	771.4	712.2	31.6
Group 4	701.7	783.4	728.6	22.9	595.2	778.3	670.5	60.1
	676.5	780.2	733.6	33.9	527.3	736.3	621.9	61.7
	695.5	774.9	753.3	15	624.4	742	675.4	42
Group 5	728.8	772.7	743.8	13.9	614.5	708.8	662.8	29.8
	704.6	744.4	727.7	9.9	588.5	666.2	642.6	13.4
	707	799.2	744.4	30.9	615.5	708.6	666.6	32.2
Group 6	742.9	798.6	760.3	13.7	618.5	744.1	670.1	32.1
	727.8	800.9	743.4	15.1	606.1	694.4	659	30.5
	714.9	804.9	743.5	19.5	630.3	764.8	679.2	33.6

with 678.3 mm when no suit was used. This shows a difference of 68.6 mm for each of these 54 tile laying operations. From the charts, it is also clear that the HtH distance for the cases when the operator wore either PER-B is around 746.9 mm, whereas the HtH distance for no suit case is centred around its mean value, consistently below the blue line. This clearly suggests that passive exoskeleton robot suit PER-B does reduce the distance between head and hip by an average of 68.6 mm for each tile laying operation, or reducing the effort of bending of head and torso during activity 1.

The point between the foot and the hip shows the length of the leg when performing the task. As the knee is bent, this length decreases. For effective lifting without straining the back, bending of the knee is desirable for correct posture.

Similarly, when the distances between hip and foot are compared for two scenarios visa part be suit and without the suit, it is clear that the HtF distance when the PER-B was worn is also consistently larger then that one no suit was worn as visually shown in **Figure 21**. In fact the difference between those two distances are bigger at 21.22 mm as for PE-B the average of the mean distances is 813.4 mm whereas the distance for no suit is 792.1 mm when this operator undertook the tile laying operations.

3.1.3. Field Lab 1 Other Result Analyse Summary

Overall, from the roofing field lab, some differences were noted in the timing of tasks and range of motion with and without the suits both ***positive*** and negative

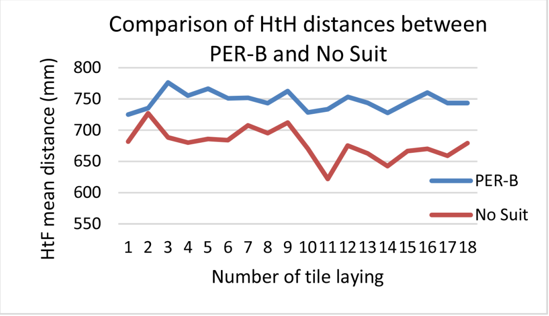

Figure 20. Head to Hip distance (mm) measurement of no suit vs average distance with PER-A and PER-B suits.

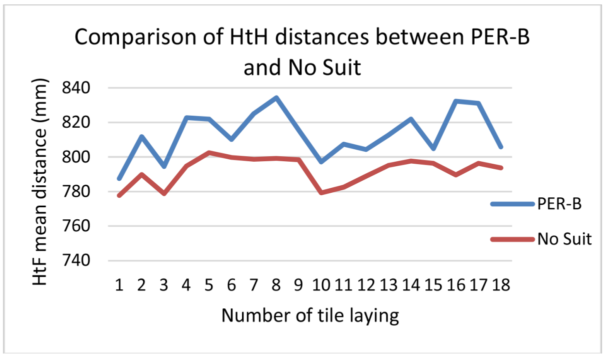

Figure 21. Head to Hip distance comparison of no suit vs PER-B suits when laying tiles.

depending on the activity and the suit. This was most notable in Activity 2, and with the PER-B suit, a greater inconsistency of motion between repeated activities was seen. The similarities in results of No-suit vs PER-A across the activities were reflected when comparing the user feedback from Worker 1 where the PER-A suit was rated higher than the PER-B suit.

1) Duration of tile laying operations

Time of each operation has also been recorded and one example set of data is shown in **Table 3** with detailed times recorded of each case for laying tiles for two rows respectively and in their total times.

The average time shows that both PER-A and PER-B are both under 16 second with PER-A leading by 15.01 on average total time to lay both Row 1 and 2. The comparison of total durations to lay six tiles (3 tiles per row) shows that the fastest single time was seen with the PER-A (12.84 seconds), followed by PER-B suit (14.68 seconds) and then No-suit (15.92 seconds), although all times are very close as can be seen in the average total times recorded. The slowest total duration to lay six tiles (3 tiles per row) is the PER-A (17.84 seconds), followed by the PER-B and No-suit (both at 16.68 seconds).

2) Heart rate data monitoring and analysis

Throughout the trial for the PER-B suit and without the suit, a Garmin watch was worn and used to measure the heart rate in beat per minute (BPM) of the participant. The watch was started as the task began, and stopped directly after the experiment finished. The data is plotted in **Figure 22**. The BPM is measured on the y-axis and the time for the activity is along the x-axis.

From observing the trends in the graph, the overall pattern of the change in heartbeat rate (HR) data throughout the activity matches for both the PER-B suit and without the suit. To analyse the data further the minimum, maximum, mean and standard deviation are presented after calculation for comparison. This data is shown in **Table 4**. Overall, the PER-B average is higher than those of the no suit across the majority of the activity. From this table it is clear that the heart

Table 3. Times recorded for completing two rows of tile laying in three scenarios.

Activity 3 times		Row 1 (s)	Row 2 (s)	Total (s)	Average total (s)
No Suit	1	8.12	9.08	17.84	16.77
	2	7.20	8.16	15.92	
	3	7.04	8.96	16.56	
PER-A	1	7.60	7.56	15.52	15.01
	2	7.84	7.96	16.68	
	3	6.32	6.12	12.84	
PER-B	1	7.32	8.92	16.68	15.69
	2	7.40	6.64	14.68	
	3	8.32	6.88	15.72	

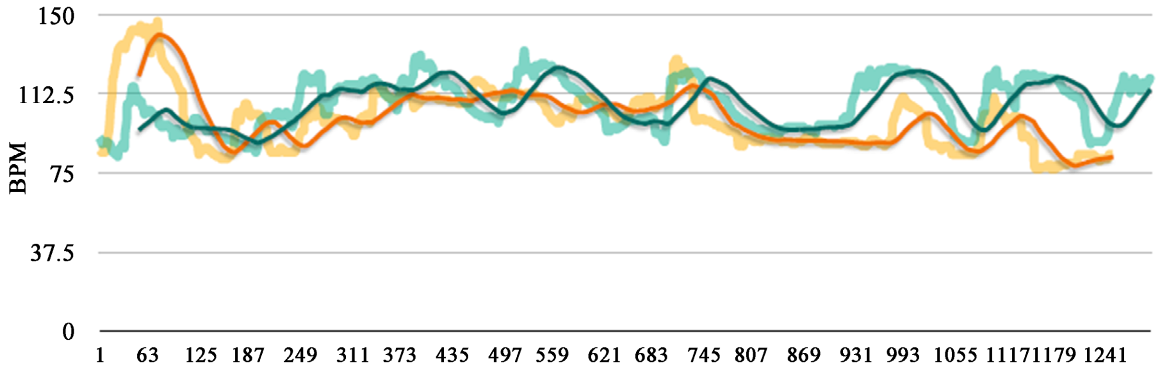

Figure 22. Heart beat rate records of three senarios for the same activities monitored.

Table 4. Heart rate monitored in beats per minute for two cases.

	PER-B	No Suit
Min	83	78
Max	133	148
Mean	107.9	100.7
Standard deviation	11.53	14.28
Time	1298	1252

beat rate is higher when a passive exoskeleton is worn by the same user at a mean rate of 107.9 compared with 100.7 when no suit was worn. This may be due to the PER-B activity occurring after the no suit. Therefore, the heart rate of the participant may have been resting at a higher BPM than when the participant started the no suit trial.

It is worth noting that the maximum HR reached by the no suit is a lot higher than with the suit, with a difference of 15 BPM or 11.3% increase. This spike in HR occurred at the beginning of the no suit trial. The time taken to carry out the trials with the PER-B suit was longer than the no suit, a difference of 46s (1298-1252). Even though the PER-B suit trial took longer to complete than the no suit trial, the heart rate was however lower, suggesting less stress on the heart of the operator.

Due to space limit the details of the other two field lab activities in lowering the tile stack and laying tiles onto the roof will not be described in this paper and will be further reported later.

4. Design Improvement

Whilst both passive exoskeleton robot suits show some advantage in reducing the effort of a human operator in undertaking similar tasks, there is scope for improvements and they are summarised below.

4.1. Customisable/Modular Solution

The PER-B suit came with a “fit kit” which provided alternately sized thigh and shoulder straps as well as alternate strength tension straps. Minor adjustment could also be achieved through an adjustment to straps on the suit.

The PER-A lift suit 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 PER-A suit during the field lab. The level of customization and adjustment of the PER-B suit meant that it was impossible to use during the 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.

4.2. Suit Padding and Comfort

Within the Offsite Field Labs that were conducted at a partner's Innovation factory, it was identified that both the PER-A and PER-B suits used throughout the field lab were creating significant discomfort for the users and causing bruising/irritation.

Through discussion with the offsite participants, 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 leads 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 spend 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 operator's shoulder and collarbone while in these positions. A lot of the work done by the operators involves rotating their shoulders 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 collarbone 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. Continued/persistent pain will cause users to stop wearing the suit which will stagnate its adoption.

4.3. Tool/Accessory and PPE Accommodation

Within the Roofing and Offsite Field Labs that were conducted at the partner's Innovation factory, it was identified that neither of the passive back support 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.

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 exoskeleton suit.

Any changes to accommodate the typical PPE and tool accessories worn by users will encourage adoption of the 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.

4.4. Suit Toughness and Cleanliness

Within the Offsite Field Labs that were conducted, 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.

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 PER-B suit and the suit being exposed to underarm and back sweat during use.

The PER-A 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 PER-A 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. The PER-A suit allows for machine washing up to 30 ˚C. The PER-B 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 PER-B suit (this will depend on the handling 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 PER-B and PER-A) 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 suits could stagnate.

4.5. Disengagement of a Suit

Within the Roofing, Plasterboard and Offsite Field Labs that were conducted, two suits PER-A and PER-B were trialled, Each participant of the field lab got to spend time in each suit. Each of PER-A and PER-B has different temporary release mechanisms. The PER-B has a one handed clutch release whereas the PER-A suit is a slightly more involved strap release.

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 these 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 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.

In 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.

5. Conclusions

This paper discusses the use of exoskeletons in assisting to reduce the effort in performing typical construction tasks by manual workers equipped with two types of passive exoskeleton robotic suits. To assess these systems in comparison with humans without these suits effectively, a mechatronic methodology for capturing motion data effectively and analysing them to verify effectiveness of the suits was developed. A large amount of visual data has been captured with suitable markers to enable quantitative analyses. The analysis results suggest that the selected passive exoskeleton suits do provide support in reducing the effort required from a worker in performing typical tasks designed. Tile laying and lifting tile stacks from ground operations have been focused in this paper whilst the other operations designed in other two field lab activities such as plaster boarding, lowering the tile stack are briefly mentioned. There are a number of areas in which two suits show deficiencies. The improvements recommended to both suits are a customisable sizing system, focus on padding and comfort, acknowledgment to work around current PPE standards, cleanliness of the suit and how to disengage the suit.

Based on observations and interview of participants, a number of recommendations have been made relating to the customisation of the passive exoskeleton robotic suits in particular in responses to different tasks as well as working environment. Further investigations were undertaken to understand the improvement on passive suit's interaction with human operators in ensuring to achieve adequate level of comfort. Easiness in cleaning the suits for different person and tasks usage has also been examined. Finally a dynamic engagement and disengagement when required is examined and recommendations have been made with regards to the mainstream methods.

Acknowledgements

The authors of the paper would like to thank Interreg North Sea Region for its financial support under the project title EXSKALLERATE 'ACCELERATE adoption of EXOSKELETONS for construction and manufacturing applications in the North Sea Region, The authors would also like to acknowledge contribution made by all participants in three field lab trails.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Chen, Y., McCabe, B. and Hyatt, D. (2017) Impact of Individual Resilience and Safety Climate on Safety Performance and Psychological Stress of Construction Workers: A Case Study of the Ontario Construction Industry. *Journal of Safety Research*, **61**, 167-176. https://doi.org/10.1016/j.jsr.2017.02.014

[2] Choi, B., Ahn, S. and Lee, S.H. (2017) Construction Workers' Group Norms and Personal Standards Regarding Safety Behavior: Social Identity theory Perspective. *Journal of Management in Engineering*, **33**, Article ID: 04017001. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000511

[3] Willamson, A. and Feyer, A.M. (1990) Behavioural Epidemiology as a Tool for Accident Research. *Journal of Occupational Accidents*, **12**, 207-222. https://doi.org/10.1016/0376-6349(90)90107-7

[4] Huang, X. and Hinze, J. (2006) Owner's Role in Construction Safety. *Journal of Construction Engineering and Management*, **132**, 164-173. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:2(164)

[5] Manchikanti, L., Singh, V., Falco, F.J., Benyamin, R.M. and Hirsch, J.A. (2014) Epidemiology of Low Back Pain in Adults. *Neuromodulation: Technology at the Neural Interface*, **17**, 3-10. https://doi.org/10.1111/ner.12018

[6] Walker, B.F., Muller, R. and Grant, W.D. (2004) Low Back Pain in Australian Adults. Prevalence and Associated Disability. *Journal of Manipulative and Physiological Therapeutics*, **27**, 238-244. https://doi.org/10.1016/j.jmpt.2004.02.002

[7] Manchikanti, L. (2000) Epidemiology of Low Back Pain. *Pain Physician*, **3**, 167-192. https://doi.org/10.36076/ppj.2000/3/167

[8] Forde, M.S., Punnett, L. and Wegman, D.H. (2005) Prevalence of Musculoskeletal Disorders in Union Ironworkers. *Journal of Occupational and Environmental Hygiene*, **2**, 203-212. https://doi.org/10.1080/15459620590929635

[9] Goldsheyder, D., Weiner, S.S., Nordin, M. and Hiebert, R. (2004) Musculoskeletal

Symptom Survey among Cement and Concrete Workers. *Work*, **23**, 111-121.

[10] Giustetto, A., Vieira Dos Anjos, F., Gallo, F., Monferino, R., Cerone, G.L., Di Pardo, M. and Micheletti Cremasco, M. (2021) Investigating the Effect of a Passive Trunk Exoskeleton on Local Discomfort, Perceived Effort and Spatial Distribution of Back Muscles Activity. *Ergonomics*, **64**, 1379-1392. https://doi.org/10.1080/00140139.2021.1928297

[11] Zhou, J., Ning, X., Nimbarte, A.D. and Dai, F. (2015) The Assessment of Material-Handling Strategies in Dealing with Sudden Loading: The Effect of Uneven Ground Surface on Trunk Biomechanical Responses. *Ergonomics*, **58**, 259-267. https://doi.org/10.1080/00140139.2014.965229

[12] Karnopp, D.C., Margolis, D.L. and Rosenberg, R.C. (2012) System Dynamics: Modeling, Simulation, and Control of Mechatronic Systems. John Wiley & Sons Ltd., Chichester. https://doi.org/10.1002/9781118152812