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Article

Influence of Exoskeleton Use on Cardiac Index

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Abstract: This study aims to assess the whole-body physiological effects of wearing an exoskeleton during a one-hour standardized work task, utilizing the Cardiac Index (CI) as the target parameter. $N = 42$ young and healthy subjects with welding experience took part in the study. The standardized and abstracted one-hour workflow consists of simulated welding and grinding in constrained body positions and was completed twice by each subject, with and without an exoskeleton, in a randomized order. The CI was measured by Impedance Cardiography (ICG), an approved medical method. The difference between the averaged baseline measurement and the averaged last 10 min was computed for the conditions with and without an exoskeleton for each subject to result in $\Delta CI_{without\ exo}$ and $\Delta CI_{with\ exo}$. A significant difference between the conditions with and without an exoskeleton was found, with the reduction in CI when wearing an exoskeleton amounting to 10.51%. This result corresponds to that of previous studies that analyzed whole-body physiological load by means of spiroergometry. These results suggest a strong positive influence of exoskeletons on CI and, therefore, physiological load. At the same time, they also support the hypothesis that ICG is a suitable measurement instrument to assess these effects.

Keywords: exoskeletons; manual welding; hemodynamics; cardiac index

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1. Introduction

According to the ASTM International Technical Committee on Exoskeletons and Exosuits (ASTM F48), "an exoskeleton is defined as a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity" [1]. Exoskeletons can be grouped by the way they create support, the supported body region, and their use case [1–3]. Exoskeleton support can be either passive, with force created by springs, levers, or elastic elements, or active, with force created by a power source. Another possibility is a mix of passive and active elements [4]. The supported body region could be any region of the body, although the most common are back, shoulder, and lower-limb exoskeletons [5].

The development and research on exoskeletons for the industrial use case has recently gained great momentum [2,3,5–7] due to the prevalence of work-related musculoskeletal diseases (MSD) resulting from heavy physical work [8]. MSD can lead to a decreased quality of life, increase in sick leave, incapacity to work, and therefore results in the absence of skilled workers. Industrial exoskeletons for back and shoulder support have been shown to reduce the muscle activity and perceived strain in the target body region as well as the overall perceived strain [9–14]. These effects of exoskeletons on the target region are the focus of a majority of the research [2]. Effects on whole-body unloading have not yet been studied sufficiently, and the results are inconsistent [15–17]. While a reduction in heart rate from using an exoskeleton could not be shown for either upper or lower body exoskeletons, a reduced metabolic cost could be found for upper-body exoskeletons [6,18].

This paper focuses on assessing the whole-body physiological effects of exoskeletons instead of isolated areas. It is indispensable to show the effect of assistance systems such as exoskeletons on cardiovascular load. One useful approach to study the effect of exoskeletons on whole-body loading, measured in oxygen consumption, was made by Knott et al. [19]. We want to build on this approach but utilize more realistic work scenarios [20] as well as a measurement method which is easier to use, more portable, and more comfortable for the worker.

Thus, this paper aims to demonstrate the physiologically relieving effects of exoskeletons in a realistic work task by means of hemodynamics. Hemodynamic parameters describe the dynamics of blood flow, while oxygen is transported by blood. This means that oxygen consumption and the dynamics of blood flow are interrelated.

According to the literature, the Cardiac Output (CO) is very closely correlated to the maximum oxygen consumption (Pearson's Correlation of r = 0.88–0.92) [21]. The regulatory system of the cardiac pump function is designed to meet the body's demand for oxygen at all times. CO represents a parameter that is indicative of acute physical stress, especially during moderate workload [22]. Stegemann describes the increase in CO as a consequence of sympathetic tone caused by physical work as a function linear to oxygen uptake [23,24]. To date, the conventional invasive methods for determining CO include cardiac catheterization and arterial punctures using the Fick's method or the dye dilution method, according to Hamilton. The standard invasive procedures also include pulmonary arterial thermodilution. The invasive nature of these procedures makes them unsuitable for use outside medical diagnostics. Likewise, non-invasive Doppler echocardiography or esophageal Doppler monitoring offers few possibilities of application in everyday work due to the need for a sonograph or an oesophageal catheter and the prerequisite of a resting patient [21,25,26]. Using spiroergometry, CO can be computed by calculating the arteriovenous oxygen difference, but it cannot directly be measured. Regardless of its accuracy, the use of this method is also not practical in an industrial setting due to the need for a breathing mask.

The target value CO can be determined non-invasively by Impedance Cardiography (ICG) and shows a high correlation with conventional methods. Lorne et al. [27] could show a Pearson Correlation of r = 0.84 between the oesophageal doppler procedure and ICG in a study with 32 subjects. A similar result was found by Scherhag et al. [28] when comparing ICG to pulmonary arterial thermodilution (ATD). A Pearson correlation of r = 0.83 at rest and r = 0.85–0.87 during exercise was shown in a study with 20 patients. These results were confirmed by Yung et al. [29], who verified the correlation between ICG and ATD (Pearson's r = 0.80) as well as the correlation between ICG and the Fick method (Pearson's r = 0.84) in a population of 20 subjects.

Therefore, we hypothesize that the effect of exoskeletons can not only be examined by means of oxygen consumption but also by means of hemodynamics, utilizing the CO, measured by ICG, as the main parameter to describe acute physical stress.

2. Materials and Methods

2.1. Participants and Ethical Approval

A total of $N = 42$ subjects participated in the study. The following criteria were considered:

Inclusion criteria:

- Trained professional welder
- Professional welding experience
- physically healthy

Exclusion criteria:

- musculoskeletal diseases
- cardiological diseases
- neurological diseases
- acute or chronic diseases

All subjects were professionals with welding experience. All subjects were healthy, had no contraindicating musculoskeletal or cardiovascular diseases and gave written informed consent to participate in the study.

$N = 39$ of total $N = 42$ participant datasets could be used for this evaluation. Subject 0305, 0308, and 0323 could not be taken into account due to weak signals of the ICG derivation, see Table 1. For these subjects an elevated BMI and body-fat percentage lead to a base-impedance that was outside of the working range of the system.

Table 1. Body Mass Index of unsuitable participants.

Subject ID	BMI	Age
0305	48	20
0308	36	20
0323	34	17

The average age of the study population was 23.3 years. 36 of the participants were male (92.3%), 3 were female (7.7%). Body mass index (BMI) averaged at 26.

The experiment received prior approval by the ethical committee of the University of Stuttgart on 20 September 2021 with the protocol code Az. 21-018.

2.2. Experimental Design

In order to ensure a safe experimental procedure, welding simulators "Soldamatic" from the company Seabery (Seabery Soluciones, Huelva, Spain) as well as grinding simulators designed by the Institute of Industrial Engineering and Management at the University of Stuttgart and the Fraunhofer IPA were used. These simulators accurately mimic the task of welding a seam and reworking the piece with an angle grinder under laboratory conditions. Standard DIN EN ISO 9606-1 for welding education served as a basis for the simulated workplaces, allowing to define real processes under authentic framework conditions. DIN EN ISO 9606-1 describes and defines welding in constrained positions. Since it is the welding process with the highest industrial impact, the metal active gas (MAG) welding process was chosen for this study. The following welding positions for this experiment were defined in cooperation with the SLV Nord welding research institute, Hamburg:

1. PF Position—vertical uphill (workpiece located in front of the body, end position slightly below eye level) (see Figure 1).
2. PE Position—overhead (workpiece positioned above head, approximately 300 mm in front of the eyes) (see Figure 2).

Each subject welded a 250 mm seam in PF position, moving the welding torch along the workpiece with a speed of 3.5 mm/s, followed by simulated grinding in this position. For the grinding task, the prepared grinder is moved up and down along the simulated weld until a time of 20 s is reached. This is an inherent part of the realistic welding task and simulates the physical load arising from the weight of the grinder as well as the grinding pressure. This procedure was repeated 10 times. Directly following, each subject completed the same process in the PE position (10 times welding and grinding of the seam). The total time for the workflow was approx. one hour. Each study participant completed the defined workflow twice resulting in a randomized crossover study design: group one started with an exoskeleton and group two started without an exoskeleton. The assignment of subjects to the groups was randomized. 20 of the participants started without exoskeletons (51.3%), and 19 participants started with exoskeletons (48.7%). The subjects were given at least one hour to rest between the runs.

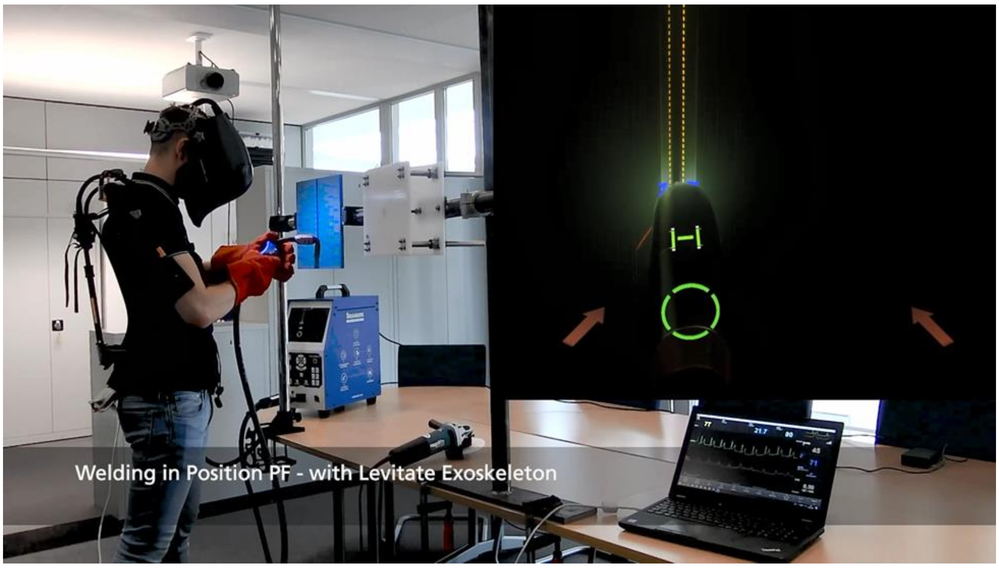


Figure 1. Exemplary illustration of the Position PF during the welding sequence including first-person perspective of the subject. Fraunhofer IPA.

Figure 2. Exemplary illustration of the Position PE during the grinding sequence. Fraunhofer IPA.

2.3. Target Ratio

In order to investigate the influence of the exoskeletons used on the hemodynamics during the defined one-hour activity, the Cardiac Index (CI) was observed. The CI is a normalized value, which is calculated by dividing the CO by the body surface area (BSA). The normalized CI has the unit L/min/m^2 and provides comparability among the test subjects [22].

$$CI = \frac{CO}{BSA}$$

$$CI = Cardiac\ Index \mid CO = Cardiac\ Output \mid BSA = Body\ Surface\ Area$$

2.4. Equipment

2.4.1. Exoskeletons

Different passive industrial exoskeletons were used in this study. Since the design of the workflow strains the arms and shoulder area, all exoskeletons aimed at supporting work in front of the upper body and overhead by supporting the upper arm. The ones used within this study were:

- Airframe®—Levitate Technologies, Inc., San Diego, CA, USA
  - Supporting force: 1.7 to 4.7 kg per arm
- HAPO MS—ErgoSanté, Anduze, France
  - Supporting force: up to 6 kg per arm
- Mate XT—Comau S.p.A., Grugliasco, Italy
  - Supporting force: 1.8 to 5.5 kg per arm
- Paexo Shoulder—Ottobock SE & Co. KGaA, Duderstadt, Germany
  - Supporting force: 1 to 4.5 kg per arm
- 360 XFR—Skel-Ex B.V., Rotterdam, The Netherlands
  - Supporting force: 1 to 4.9 kg per arm

The selection of exoskeletons was randomly determined. In order to be market-neutral and not to create a competitive advantage, no manufacturer-selective evaluation was conducted. This is possible because the design, the point of force application at the upper arm, and the supporting force of all three exoskeletons are similar.

We distributed the exoskeletons randomly to the subjects and tried to keep the model use as equally as possible among the test persons as shown in Figure 3.

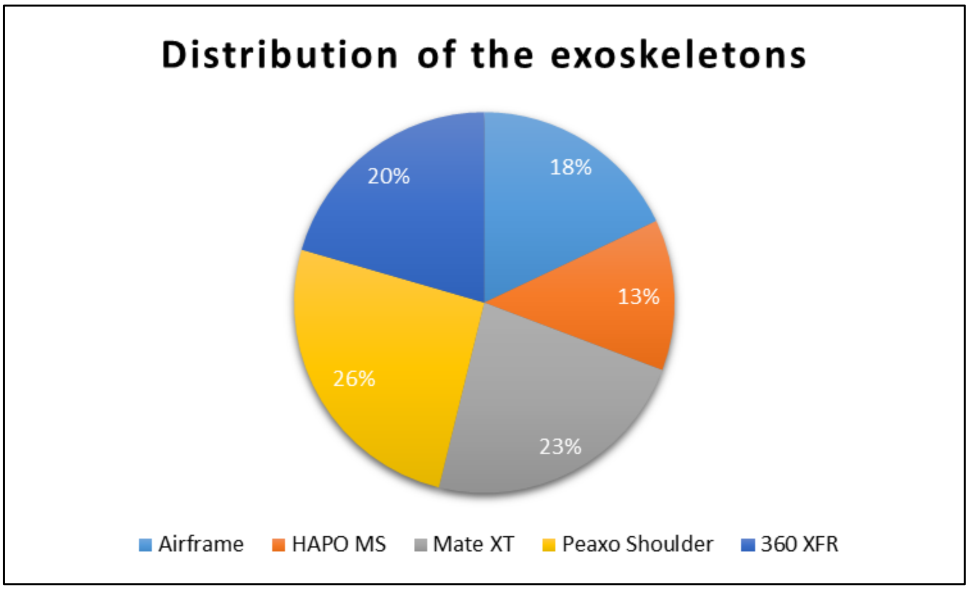


Figure 3. Illustration of the distribution of the exoskeleton use. Fraunhofer IPA.

2.4.2. Impedance Cardiography

The ICG measurements were recorded with the Medis Cardioscreen 1000 (medis Medizinische Messtechnik GmbH, Ilmenau, Germany; REF CG1000)

For the measurements, two pairs of electrodes were placed at the neck and the thorax. An additional Arterial Compliance Modulation (ACM) sensor was placed at the earlobe. Hemodynamics and cardiac conduction were recorded over the complete duration of the trial. A baseline measurement was taken before the start of each trial. The subjects were finally prepared for the run and standing in front of their working space. For the run with exoskeleton, the baseline measurements were taken with the exoskeleton on.

2.4.3. Grinding Simulator

In a grinding experiment 35 N of axial force were measured in order to grind a welded seam appropriately. Based on this finding a grinding simulator was developed by the author to ensure appropriate force on the workpiece of 35 N in z-direction. This working point is based on a welding experiment conducted and analyzed in preparation of this study.

The welding parameters in accordance with DIN EN ISO 9606-1 were physically welded in an internal test workshop and processed using an angle grinder. The forces occurring during grinding were determined and simulated using force transducers. The constructed test stand consists of a force-absorbing linearly mounted plate of polyoxymethylene that provides visual led feedback when a force of 35 N is reached in z-direction (see Figure 4).

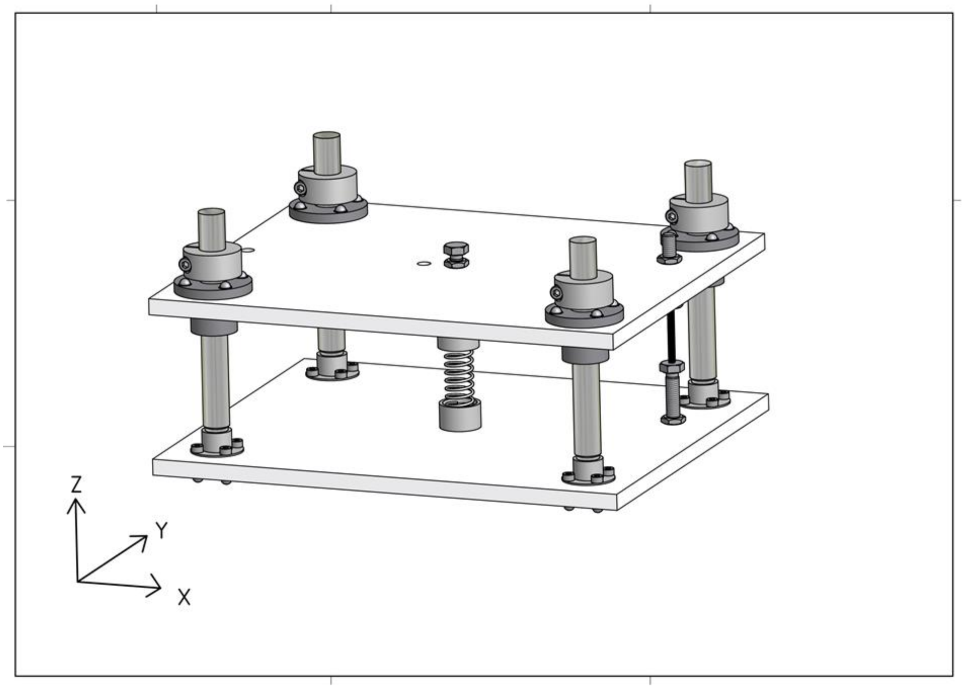


Figure 4. Grinding Simulator CAD illustration. Fraunhofer IPA.

The operating point is not rigid and leaves around 5 mm space for movement as in real grinding. The counterpart is a commercially available angle grinder. Its functionality is deactivated by isolating the power connector. The grinder is combined with a dummy cutting disc manufactured of polyoxymethylene with the identical dimensions of a 125 mm cutting disc.

2.5. Data Analysis

All data were analyzed using Minitab statistics software, version 20.1.2 (64 bit). For the statistical analysis, the last 10 min of each one-hour trial are used and compared with a previous baseline measurement that was taken directly before the start of the trial. Afterwards, the differences between the baseline measurement and the last 10 min of each trial were investigated as illustrated in Figure 5.

Therefore, the distributions of the two samples, consisting of the differences between the averaged baseline measurement and the averaged last 10 min of all subjects ($\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$) were tested with an Aderson–Darling test. Though the samples are non-normally distributed, we decided to use parametric statistics because, on the one hand, we obtained continuous data on the other hand, the sample size of $N = 39$ is large enough that the robustness of the methods is given. As Rasch and Guiard [30] as well as Gangestad and Thornhill [31] describe, this method is reasonable under the given conditions. The Levene method was used to analyze the variances of the two samples. The comparison of the variances was visualized using interval plots associated with the confidence interval of both samples. Finally, an unpaired t-test was used to examine significant differences of the samples in their mean values.

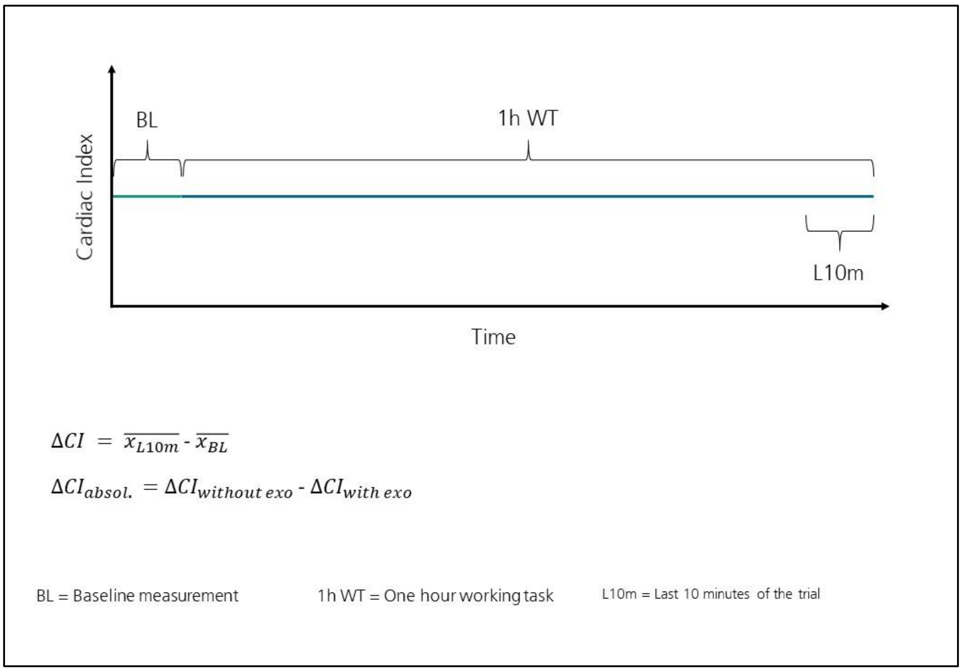


Figure 5. Schematic representation of the data preparation. Fraunhofer IPA.

3. Results

3.1. Distribution of the Two Samples $\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$

Both samples $\Delta CI_{with\ exo}$ ($p < 0.005$) and $\Delta CI_{without\ exo}$ ($p < 0.005$) are non-normally distributed. As described in Section 2.5, parametric statistics are used despite the non-normal distribution of both samples. The method is robust against asymmetric distribution and is more powerful than nonparametric statistics.

3.2. Analysis of Variances of the Two Samples $\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$

The analysis of variance showed a similar scatter of the sample with the exoskeleton and the sample without the exoskeleton (see Figure 6). The Levene test resulted in a non-significant difference in the standard deviation of the two samples.

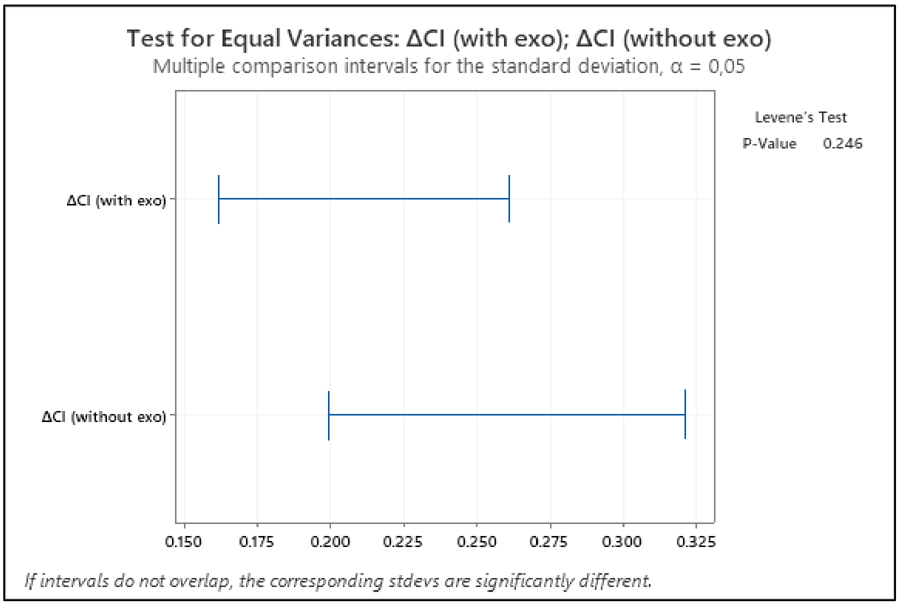
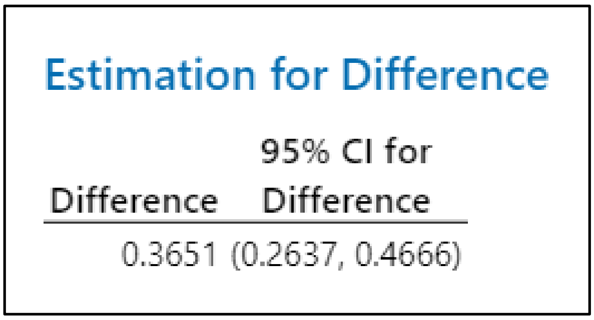


Figure 6. Test for equal variances of the samples $\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$ ($p = 0.246$). Fraunhofer IPA.

3.3. Analysis of Means of the Samples $\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$

An unpaired *t*-test was used for the comparison of means of the samples' $\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$. The *t*-test resulted in a significant difference of the two samples with a *p*-value of $p = 0.000$.

The estimated absolute difference between the means of the two samples $\Delta CI_{absol.}$ amounts to 0.365 L/min/m^2 (see Figure 7). If compared to the average CI of the last 10 min of the sample without exoskeletons ($\overline{x_{L10m,\ without\ exo,\ total}} = 3.470$ L/min/m^2) this corresponds to a 10.51% reduction in CI. An overview of the individual results for each subject can be found in Table A1 (Appendix A).



Estimation for Difference

Difference	95% CI for Difference
0.3651	(0.2637, 0.4666)

Figure 7. Estimation for differences of $\Delta CI_{absol.}$ and the associated 95% confidence interval. Fraunhofer IPA.

4. Discussion

The analysis of variance using the Levene test shows no significant difference between the samples and therefore indicates a similar standard deviation. It can be assumed that wearing an exoskeleton does not influence the accuracy of the measurement method and does not produce outliers or measurement errors. Thus, both samples can be compared in a comparison of means.

The samples $\Delta CI_{with\ exo}$ and $\Delta CI_{without\ exo}$ showed a significant difference (*t*-test, $p = 0.000$) in means. This means that wearing an exoskeleton for the defined task leads to a significant decrease in the CI. Due to the correlation of CI to oxygen consumption [21], a significant reduction in the physiological load can be concluded.

A reduction in CI of 0.365 L/min/m^2 when wearing an exoskeleton compared to the same one-hour task without using an exoskeleton indicates reduced physical stress. The reduction amounts to a 10.51% decrease in CI from wearing one of the available upper-body exoskeletons. Therefore, wearing an exoskeleton during a one-hour simulated welding task, consisting of in front of the body and overhead welding and grinding, reduces the acute physical stress by over 10%.

A reduction in CI of more than 10% with the aid of an exoskeleton is consistent with the results of Schmalz et al. [32], where a reduction in the oxygen consumption during a defined task of up to 12% was found with the use of an upper-body exoskeleton.

Considering the size of the population, the representative range of age, and BMI, but especially the use of different exoskeleton systems, which were not considered selectively, the result is very powerful. Several previous findings on the relieving effects of exoskeletons during physical work can be confirmed by these results. These results should further be confirmed in different standardized working scenarios as well as with a broader range of exoskeletons, i.e., a logistics task with back supporting exoskeletons or overhead assembly with upper-body exoskeletons.

As described in the introduction, modern impedance cardiographic measurements are highly reliable [27–29], and there is a linear relationship between CO and oxygen consumption [21,22]. Considering these two factors, the results found here indicate a strong benefit of exoskeletons regarding the metabolic relief and indicate that ICG is a highly suitable method to study these effects.

Nonetheless, the scaling of the shown reduction in CI has to be clarified. Further studies are needed to verify the relationship between the measured hemodynamics and the oxygen consumption and put them in relation to the absolute performance. Furthermore, the acceptable range regarding health and safety has to be clarified.

The idea of using ICG for the evaluation of exoskeletons or even for performance physiological determination of work-related loads brings comfortable advantages. It seems to be promising based on the obtained evidence. However, the correlations must be specified and further confirmed in extended studies.

5. Conclusions

The effects of exoskeletons on different physiological, biomechanical, and subjective parameters have been increasingly studied in the past few years. Relieving effects have been shown for subjective effort, muscle activity in the target region, and joint moments. However, these studies mostly focus only on the target area of the exoskeleton and provide little to no understanding of the effects on the whole body. Whole-body relief has been shown through reduced energy expenditure or reduced heart rate, whereas these results are not consistent between studies. As heart rate does not seem sensitive enough to accurately analyze the effects of exoskeletons and spiroergometry is not suitable during real working scenarios, further methods to investigate whole-body loading are necessary.

As several studies have shown a clear correlation between oxygen consumption and CO [22–24], which can reliably be measured by ICG [27–29], we hypothesized this to be an adequate parameter and corresponding measurement instrument to investigate the effects of exoskeletons. We set up a one-hour standardized work task which included overhead welding and grinding, using several different exoskeletons for overhead work, and measured the CO and the CI. Results showed a significant reduction in the CI when wearing an exoskeleton, which amounted to an over 10% reduction compared to not wearing an exoskeleton. Therefore, we can confirm the relieving effects of exoskeletons on the cardiovascular system as well conclude the suitability of the CI as a parameter to study these effects.

Author Contributions: U.S. co-organized planning and implementation. M.S. planned and carried out the study, performed statistical analyses and wrote the article. I.S. supported the data gathering and writing of the article. T.B. and J.S. provided the resources and sourcing of measuring instruments and contributed scientifically. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of University of Stuttgart (Kommission Verantwortung in der Forschung), protocol code Az. 21-018, approved 20 September 2021.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, M.S. The data are not publicly available due to the privacy of research participants.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Averaged CI at baseline $\overline{x_{BL}}$, last ten minutes $\overline{x_{L10m}}$ and difference ΔCI with and without exoskeleton for all subjects.

	With Exoskeleton			**Without Exoskeleton**			$\Delta CI_{absol.}$ **L/min/m^2**
ID	$\overline{x_{BL}}$ **L/min/m^2**	$\overline{x_{L10m}}$ **L/min/m^2**	$\Delta CI_{with\ exo}$ **L/min/m^2**	$\overline{x_{BL}}$ **L/min/m^2**	$\overline{x_{L10m}}$ **L/min/m^2**	$\Delta CI_{without\ exo}$ **L/min/m^2**	
0301	3.628	3.308	−0.320	3.779	4.116	0.337	-
0302	3.795	3.904	0.109	4.406	4.560	0.154	-
0303	3.153	3.105	−0.048	3.420	3.458	0.038	-
0304	3.178	3.231	0.053	3.350	3.426	0.076	-
0306	3.832	3.473	−0.359	3.694	3.832	0.137	-
0307	4.174	4.193	0.019	3.811	4.381	0.570	-
0309	2.608	2.742	0.135	3.031	3.389	0.358	-
0311	3.481	3.461	−0.020	3.410	3.904	0.494	-
0312	2.918	2.912	−0.006	2.889	2.978	0.089	-
0313	3.406	3.229	−0.176	3.057	3.094	0.037	-
0314	3.022	2.861	−0.161	2.700	2.782	0.082	-
0315	3.205	3.186	−0.019	3.128	3.187	0.059	-
0316	4.086	4.392	0.306	4.714	5.141	0.427	-
0321	4.452	4.302	−0.150	4.441	4.421	−0.020	-
0322	3.280	2.924	−0.356	2.317	2.756	0.440	-
0324	3.387	3.176	−0.210	3.322	3.403	0.081	-
0325	3.277	3.243	−0.034	2.953	3.142	0.190	-
0326	2.631	2.591	−0.040	2.805	2.849	0.044	-
0327	4.554	3.742	−0.812	3.571	4.385	0.814	-
0328	3.686	3.852	0.166	3.833	3.930	0.096	-
0329	3.811	3.697	−0.113	3.700	4.652	0.952	-
0330	3.567	3.160	−0.407	3.127	3.195	0.068	-
0331	3.910	3.706	−0.204	3.321	3.554	0.233	-
0332	3.552	3.557	0.005	2.365	3.233	0.868	-
0333	3.339	3.330	−0.009	3.038	3.226	0.189	-
0334	3.494	2.931	−0.564	2.560	2.752	0.192	-
0335	2.553	2.445	−0.108	2.729	2.738	0.009	-
0336	3.130	3.128	−0.002	2.732	3.106	0.375	-
0337	3.132	2.978	−0.153	3.036	3.007	−0.029	-
0338	3.194	3.002	−0.192	3.536	3.524	−0.013	-
0339	3.438	3.305	−0.132	3.213	3.548	0.335	-
0340	2.694	2.702	0.008	2.406	2.716	0.310	-
0341	3.846	3.752	−0.094	3.500	3.826	0.326	-
0342	3.175	3.085	−0.090	3.185	3.524	0.339	-
0343	2.854	2.812	−0.042	2.993	3.248	0.255	-
0344	2.224	2.009	−0.214	2.580	2.715	0.135	-
0345	3.473	3.456	−0.017	3.264	3.449	0.185	-
0346	3.591	3.548	−0.042	2.793	3.421	0.628	-
0347	2.769	2.776	0.007	2.664	2.760	0.096	-
-	-	-	-	-	-	-	0.365

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