applied sciences

MDPI

Article

Evaluation of Active Shoulder Exoskeleton Support to Deduce Application-Oriented Optimization Potentials for Overhead Work

Johannes Sänger [1,†], Zhejun Yao [2,†], Tim Schubert [2], Alexander Wolf [3], Carla Molz [3], Jörg Miehling [3], Sandro Wartzack [3], Thomas Gwosch [1], Sven Matthiesen [1,*] and Robert Weidner [2,4,*]

[1] IPEK-Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstraße 10, 76131 Karlsruhe, Germany
[2] Laboratory of Manufacturing Technology, Helmut-Schmidt University Hamburg (HSU), Holstenhofweg 85, 22043 Hamburg, Germany
[3] Engineering Design, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Martensstraße 9, 91058 Erlangen, Germany
[4] Chair for Production Technology, Institute of Mechatronics, University of Innsbruck (UIBK), Technikerstraße 13, 6020 Innsbruck, Austria
* Correspondence: sven.matthiesen@kit.edu (S.M.); robert.weidner@hsu-hh.de (R.W.)
† These authors contributed equally to this work.

Citation: Sänger, J.; Yao, Z.; Schubert, T.; Wolf, A.; Molz, C.; Miehling, J.; Wartzack, S.; Gwosch, T.; Matthiesen, S.; Weidner, R. Evaluation of Active Shoulder Exoskeleton Support to Deduce Application-Oriented Optimization Potentials for Overhead Work. *Appl. Sci.* **2022**, *12*, 10805. https://doi.org/10.3390/app122110805

Academic Editor: Antonio Sarasa Cabezuelo

Received: 30 September 2022
Accepted: 20 October 2022
Published: 25 October 2022

Abstract: Repetitive overhead work with a heavy load increases the risk for work-related shoulder disorders. Occupational exoskeletons supporting arm elevation are potential solutions to reduce that risk by lowering the physical strains on the shoulder. Many studies have reported a reduction in shoulder stress in various overhead tasks by using such exoskeletons. However, the support demand can vary in each phase of motion as well as in each individual task. This paper presents a laboratory study with five participants to evaluate the influence of the support level of an active shoulder exoskeleton in different motion phases (e.g., arm lifting, screw-in, and arm lowering of two overhead tasks) to identify the potential optimization of support at each phase. Results show that the support level of the exoskeleton should be adapted to the motion phase of the two chosen tasks. A higher support force is desired for the screw phase compared to the arm lifting and lowering phases, and the support level needs to be reduced immediately for arm lowering after the screw phase. The time for switching the support levels can be recognized by the electric current of the screwdriver.

Keywords: human–machine interaction; biomechanical analysis; sEMG; interaction forces; user experience; power tool; exoskeleton

1. Introduction

Overhead work is one of the greatest risk factors for work-related musculoskeletal disorders (WMSD) [1]. Sixty percent of workers in the EU with health problems have reported WMSD as their most serious health problem [2]. In Germany, 22.8% of the total sick days at work are caused by "musculoskeletal and connective tissue disorders" [3]. An exoskeleton is a potential solution to reduce the physical load on workers that affects the stress on, for example, the shoulder region [4,5]. The most commercialized shoulder exoskeletons are passive, for example, Paexo shoulder (Ottobock, Duderstadt, Germany), ShoulderX (SuitX, Emeryville, CA, USA), and Airframe™ (Levitate Technologies, San Diego, CA, USA). Passive systems use mechanical energy and have no need for an additional powered actuator, energy source, or electronic components, which demand more space and weight. Active systems (e.g., shoulder exoskeleton S700 (exoIQ, Hamburg, Germany)), on the other hand, have the potential to regulate the support level during the use itself, adapting to the requirement of the manual task and individual wishes. Many studies have shown the effect of load reduction on workers with an exoskeleton [6–8]. Otten et al. showed a possible reduction in shoulder muscle activity of up to 58.2% with the Lucy exoskeleton during overhead activities [9,10]. Kim and Nussbaum simulated an overhead drilling procedure using an arm support exoskeleton and were able to demonstrate a reduction in the physical demand on the upper extremity [5]. Further simulative approaches have shown the potential reduction in the user's muscle activity through the implementation of different support concepts [11].

For the evaluation of exoskeletons, methodological approaches have been proposed using both objective (e.g., muscle activity) and subjective (e.g., perceived exertion) measurements to demonstrate the reduction in the physical demands of the user [12,13]. These approaches are particularly suitable for validating exoskeleton designs when ensuring that the same workload is applied to the user. Exoskeleton testing setups are usually designed in such a way by assuming the participants have the same workload under different test conditions through the standardized task definition [14]. Many studies have investigated the influence of the support force on the user's movement [15]. However, the use of exoskeletons can also lead to a different behavior of the user, which can result in different interaction forces or process forces of the task (e.g., the push force of screw-in task) [14]. The process force of the test task is hardly measured by exoskeleton evaluation. Furthermore, earlier research indicates that the support requirement of a task depends on its workload and the relevant movement [16]. Thus, the optimization of an exoskeleton is always application-related.

To identify the optimization potentials of an active shoulder exoskeleton for selected overhead tasks with a cordless screwdriver, the influence of two different support levels (50% support, and 100% support) were investigated in this paper. Two screw-in tasks with different workloads were replicated from the industrial manual works. The user's physical strain and the human–exoskeleton interaction force were measured and analyzed in three key motion phases (lifting arm, screw, and lowering arm) of the tasks. Additionally, the push forces of the tasks were also recorded to monitor the workload. Based on the evaluation, an adjustment in the support level related to the key motion phases and a switching time detection approach are proposed.

2. Materials and Methods

First, the participants and technical systems as well as the work task are introduced. This is followed by the explanation of the method for performing the study, the description of the observed variables, and the method of data analysis.

2.1. Participants

The study was conducted with five voluntary male participants, resulting in a mean age of 29 (SD 9) years, mean weight of 73 (SD 11) kg, and a mean height 182 (SD 4) cm. Further information on the participants can be found in Table 1. The participants reported no acute diseases or pain of the muscular system, no restrictions in the range of motion in the shoulder due to known degenerative diseases, and no treatment of the shoulder or back pain, upper extremity injury, or surgery within the last six months. Three participants were right-handed and two were left-handed. All participants were college members with basic experience using a cordless screwdriver in industrial tasks and their experience with the investigated exoskeleton was less than two tests. Before the experiment, the participants were informed about the procedure of the study and signed the informed consent form. The study could be stopped by the participants at any time.

Table 1. The weight and anthropometric data of the participants.

		Age [Years]	Body Height [cm]	Weight [kg]	Shoulder Width [cm]	Upper Arm Length [cm]
participant	P1	29	180	74.2	43	37
	P2	44	178	69.3	40	35
	P3	23	188	93.0	47	41
	P4	21	184	65.2	40	38
	P5	28	182	65.0	40	38

2.2. Test Apparatus

In the study, a cordless screwdriver (Festool cordless impact drill PDC 18/4, Festool GmbH, Wendlingen, Germany) and power tool datalogger [17] with a total weight of 2.5 kg were used. The datalogger was placed in the interface between the screwdriver and the battery pack, as can be seen in Figure 1.

Figure 1. Festool screwdriver. Datalogger was placed in the screwdriver's battery interface to record the electric current and voltage during the tasks.

The exoskeleton Lucy (see Figure 2 left) is an active shoulder exoskeleton that is mainly designed to reduce the physical strains on the shoulder when the user works at head level or above [10]. The width of the shoulder bar, length of the back part, and the location of the armrest are adjustable to fit the shoulder width and upper arm length of the user. Lucy is actuated by a pneumatic cylinder that is integrated into the arm bar. The cylinder is regulated by the elevation angle of the upper arm, which is measured by a joint sensor, and helps the user to lift the arm up, at, and above the shoulder level (see motion phases lifting arm, positioning, and screw in Figure 3). The cylinder is activated first when the arm elevation angle is over 15°, and then its pressure supply increases proportionally from zero to the set support level until the arm elevation reaches 25° (see Figure 2 right). The level of support can be manually adjusted by the user through a potentiometer. For standardization of the tests, two levels of support (50% and 100%) were selected as the two test conditions.

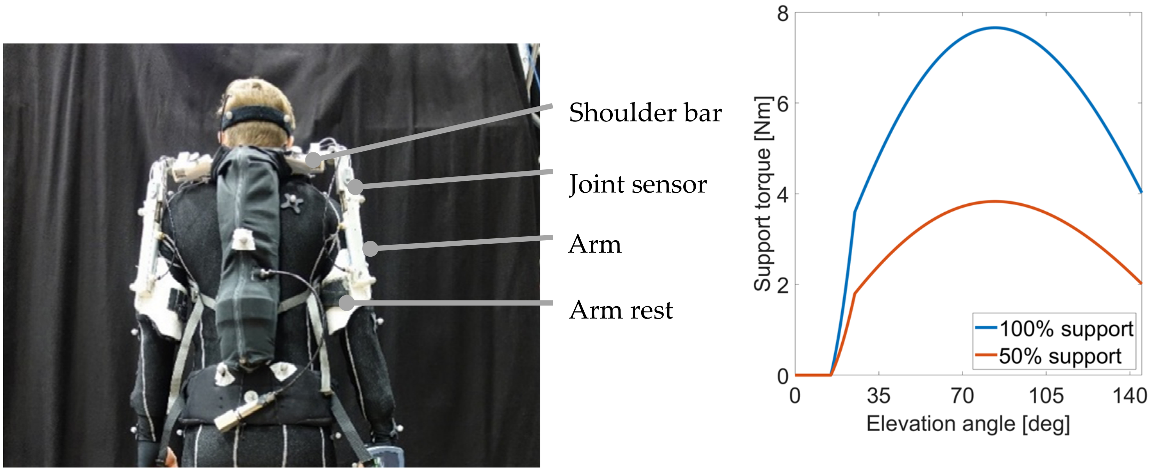

Figure 2. (**Left**) exoskeleton Lucy. (**Right**) Torque–elevation curve for two different support levels: 50% and 100%.

2.3. Tasks

Two different tasks with a cordless screwdriver were performed. In task T1, the participants had to fix a predrilled wooden component with a screw to an overhead plywood board. This task required precision and coordination from the participants. Task T2 consisted of the screw-in process of a wood screw, which required a high force during the screw phase. Both tasks were performed with the same experimental setup. For the experiment, a wooden beam and plywood board were mounted in a fixture for the overhead drilling and screw-in task. The wood-type of the beam was structural solid wood. The height of the wooden beam was adjusted to achieve a shoulder elevation angle for task T1 (130°) and task T2 (100°) for the arm, which held the cordless screwdriver (dominant side). The speed and torque stages (SS, TS) of the screwdriver were set according to the task (see Table 2). During the tasks, participants stood on a force measuring plate (see Table 3).

Table 2. Task specifications and details.

	Cycles (Duration/Cycle)	Task Apparatus	Shoulder Elevation Angle [°]	Screwdriver Adjustments
task T1	10 (10 s/cycle)	plywood board (size: 400 × 600 × 55 mm) wooden component (size: 50 × 50 × 10 mm with central borehole) wood screw (5 × 60 mm, T-STAR plus T20, SPAX International GmbH & Co. KG, Ennepetal, Germany)	0–130	SS 2: 0–850 rpm TS 10: 5.3 Nm
task T2	10 (15 s/cycle)	solid structural timber (size: 400 × 400 × 160 mm) wood screw (10 × 100 mm, TX40, Fischerwerke GmbH & Co. KG, Waldachtal, Germany)	0–100	SS 1: 0–400 rpm TS 12: 11.5 Nm

The complete motion sequences of both tasks are illustrated in Figure 3. For task T1, participants were told to fasten a wooden component to a plywood board with a single screw in a given time of 10 s. By hearing an acoustic signal, the participants took a screw and placed it on the screwdriver bit, the screwdriver being held in the dominant hand. They then took a wooden component with their non-dominant hand and raised their arms to position the wooden component on the plywood board overhead. Finally, they had to tighten it with the screw, lower their arms, and wait for the next acoustic signal. This motion cycle was repeated ten times.

For task T2, the participants were told to screw in a wood screw above their head in 15 s. Starting with an acoustic signal, the participant picked up a screw and placed it on the screwdriver bit, then raised their arms to position the screw onto a marked position on the wooden beam, and tightened it. Here, the participants were allowed to use their non-dominant hand to hold and guide the screw. Finally, the participants lowered their arms and waited for the acoustic signal triggering the next cycle. After ten screws, the task was completed.

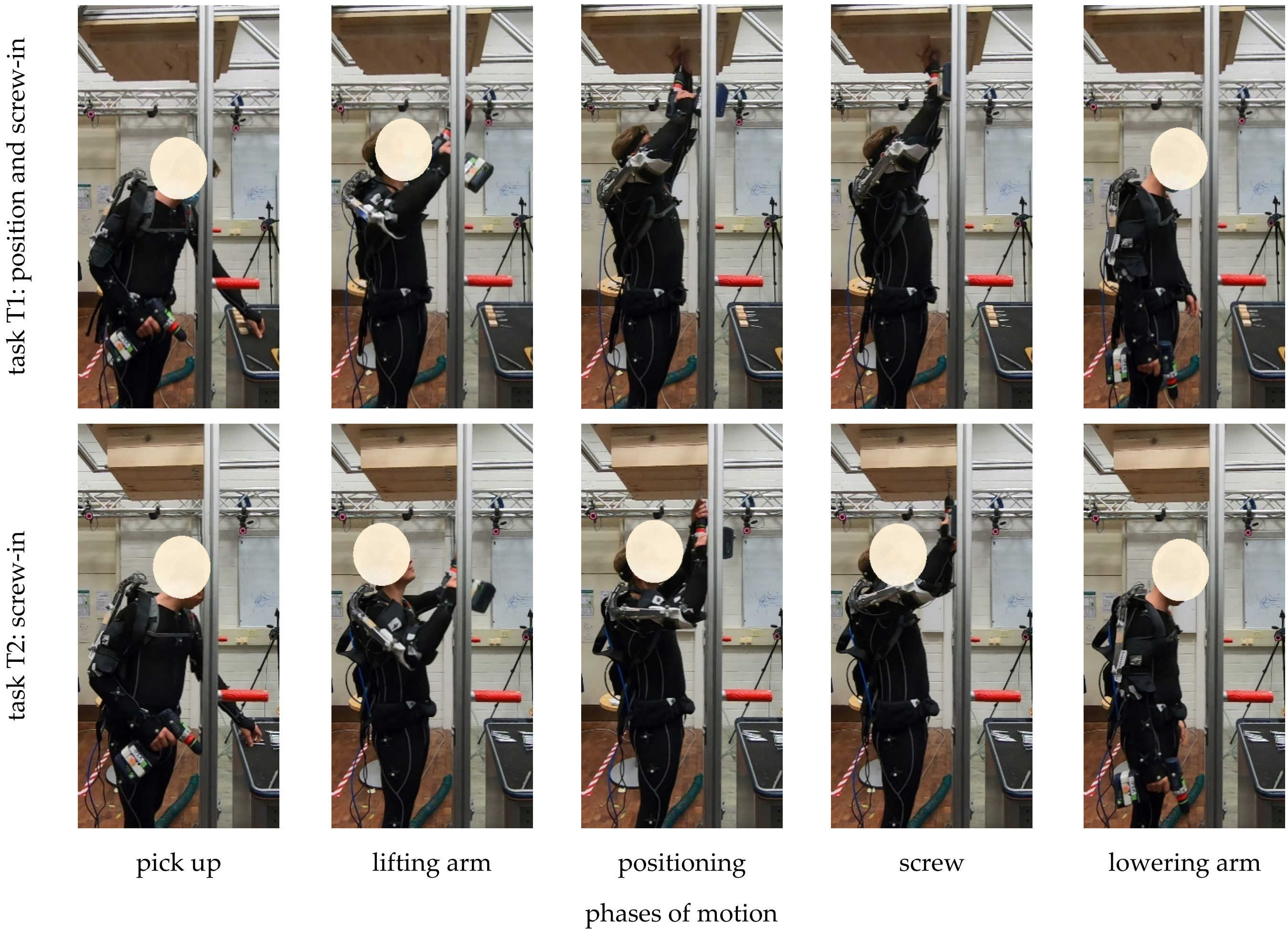

Figure 3. The definition of one motion cycle and its motion phases.

2.4. Test Procedure

Each task was conducted in a randomized manner under three test conditions: (S0) without the exoskeleton as the baseline, (S50) exoskeleton with 50% support level, (S100) exoskeleton with 100% support level.

The main steps of the test are summarized in Figure 4. It started with the anthropometric measurements including the weight, body height, and body segment length, and the necessary preparation of the electromyography (EMG)-measurement. For more details on the muscles that were considered in the study, see Section 2.5. After placing the EMG surface electrodes on the eight muscles, the maximum voluntary contraction (MVC) of each muscle was measured following the SENIAM recommendations [18]. The participant was then fitted with the exoskeleton and adjusted to their shoulder width and upper arm length. The passive-reflective markers of the Vicon system (see Section 2.5) were then attached to a motion capture suit worn by the participant. This was followed for about five minutes for the participant to become familiar with the exoskeleton and the work process of both tasks. All combinations of the task and support conditions (two tasks x three conditions) were examined. The experimental design was full factorial with six repetitions. The order of the repetitions was randomized. Participants filled out three questionnaires on the subjective perceptions of strain and support between each repetition (see Table 3). The questionnaires took about three minutes, followed by a two minute rest break between each combination.

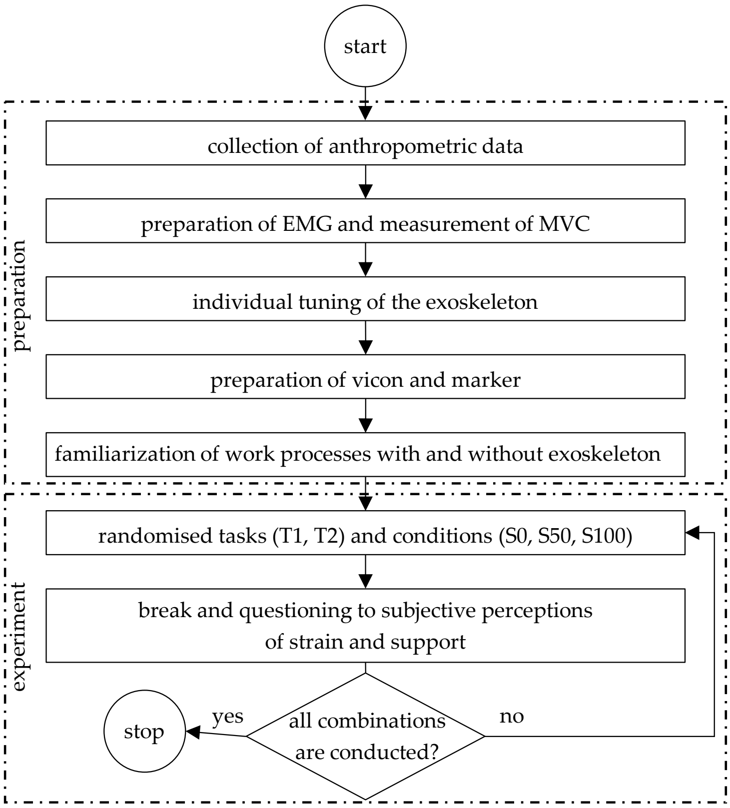

Figure 4. Test procedure.

2.5. Observed Variables

Eight variables were measured during the test (see Table 3). Five of them were metrics for evaluating the changes in physical strain on body, workload, human–exoskeleton interaction force, and subjective perception of the support force. The other three variables were assisting metrics, which helped to enable a determination of the different phases of motion not only by using motion data.

Table 3. Variables and measurement systems.

	Variable	Measurement System
evaluation metrics	Muscle activity (objective physical strain)	Surface EMG (Myon 320, 1.000 Hz, Myon AG, Schwarzenberg, Schweiz)
	Perceived exertion (subjective physical strain)	Questionnaire with body map and Borg Scale CR-10 [19]
		NASA-TLX questionnaire evaluated in six subscales [20]
	Push force (workload)	One force plate (AMTI OPT, 464 × 508 mm, Advanced Mechanical Technology Inc., Watertown, NY, USA)
	Human–exoskeleton interaction force	One pressure sensing mat (X3 Pro System, 127 × 254 mm, Xsensor Technology Corporation, Calgary, AB, Canada)
	Subjective perception of the support force	Questionnaire for user experience
assistant metrics	Electric current and voltage screwdriver	Datalogger on screwdriver [17]
	Elevation angle exoskeleton	Datalogger on Lucy
	Human motion	Vicon (Vicon Bonita, Oxford Metrics Ltd., Oxford, UK)

The activities of eight muscles were recorded with surface EMG: M. flexor carpi ulnaris (FCU), M. biceps brachii (BB), M. deltoideus anterior (DA), M. latissimus dorsi (LD), on both the dominant and non-dominant side. The physical exertion was also recorded with subjective questionnaires (NASA-TLX, body map) in order to compare the user's evaluation with the measured EMG data. The push force (F_{pu}) of the user was measured to ensure that the same workload was applied to the participants for the different support levels. The push force was indirectly measured from the vertical component ($F_{GRF,\ v}$) of the 3-axis ground reaction force F_{GRF}. This provided a good approximation of the push force during the screw phase, since the user was in a static posture and no inertial forces occurred. The pressure sensing mat was placed wrinkle-free between the dominant upper arm and the armrest of the exoskeleton. It measured the pressure on the complete surface of the armrest. The normal interaction force between the dominant upper arm and the armrest was calculated by the measurement software. A questionnaire was used to compare the measured interaction force with the subjective evaluation of the support level.

2.6. Data Analysis

The motion data, EMG-signal, and ground reaction force were measured when synchronized. The data from the exoskeleton and the screwdriver were synchronized with the motion data through predefined events during data processing. To divide the continuous data into motion cycles, the start and end times of each motion cycle were determined manually and visually based on the motion data captured by Vicon. One motion cycle started when the participant had just reached the first object (the wooden component in task T1 or the screw in task T2) to be picked up and ended when the dominant upper arm returned to its neutral position (0° elevation) (also see Figure 3). For the analysis of the EMG-signal and push force, one cycle was then split into three main motion phases. The start and end of the phase arm lifting and lowering were detected by the local minimum and maximum of the curve of the shoulder elevation angle. The starting point of the screw phase (trigger pressed) was detected when the screwdriver battery-current threshold of 2 A was exceeded. If the screwdriver electrical current dropped below this threshold, it was detected as the end of the screw phase (trigger released).

The collected EMG-signals were processed in the ProEMG (myon AG) software with a 20–200 Hz Butterworth bandpass filter 4th order, rectification, and smoothing with a 300 ms root mean square. For the normalization of EMG-signal amplitudes, the highest signal amplitude from the three MVC recordings was used. The EMG-signals were then divided into 10 motion cycles and each cycle was time normalized to a 0–100 percentage of the motion. For each participant, an average EMG curve was calculated from the 10 cycles. The mean EMG corresponded to the mean amplitude of the average curve. The mean EMG of each motion phase was then calculated from the sliced EMG curve. Because of the small sample size, an intra-individual comparison of the mean EMG was performed instead of a statistical analysis.

The calculation of the push force F_{pu} was based on the vertical component ($F_{GRF,\ v}$) of the measured 3-axis ground reaction force as follows: $F_{pu} = F_{GRF,v} - G_P + G_{sc}$. Here, G_{sc} is the weight force of the screwdriver and G_P is the weight force of the participant including the exoskeleton, screwdriver, and measurement systems. This can be seen as a good approximation of the push force, especially during the screw phase. The mean value of each of the 10 cycles was calculated and displayed as exemplary for participant P3. All further analyses of the push force were performed during the screw phase only by calculating the mean value of the push force for each of the 10 cycles and plotting it as a boxplot. The postprocessing and preparation of figures was conducted in MATLAB R2020b.

Due to a malfunction in the screwdriver datalogger, the start and endpoints of the screw phase of participant P2 were not detected. Thus, the measurement data of the push force were not evaluated and P2 was excluded for the evaluation of the push force during the screw phase.

3. Results

First, the load of the participants was analyzed by presenting the results of the push force during the screw phase. Subsequently, the physical strain of the participants during the tasks were evaluated by the subjective perceived exertion and the muscle activities. The analysis of the human–exoskeleton interaction based on the subjective perception of the support force as well as on the interaction force between the armrest of the exoskeleton and the upper arm of the participant.

3.1. Push Force during Screw Phase of the Motion

A typical mean push force curve of participant P3 for ten cycles is shown as an example in Figure 5. The standard deviation (Std. dev.) is marked as the blue area, the start and endpoint of the screw phase with black dashed lines. The mean push force started at a lower level between 10 N and 40 N from 0% to 50% of the motion cycle. This was then increased slightly from 40 N to 75 N until the start of the screw phase (62%) and reached a plateau at 110 N during the screw phase from 62 to 87% of the motion cycle. The push force dropped back to a lower level at the end of the screw phase (87%). All further evaluations of the push force were considered only the mean value during the screw phase of the motion for each cycle.

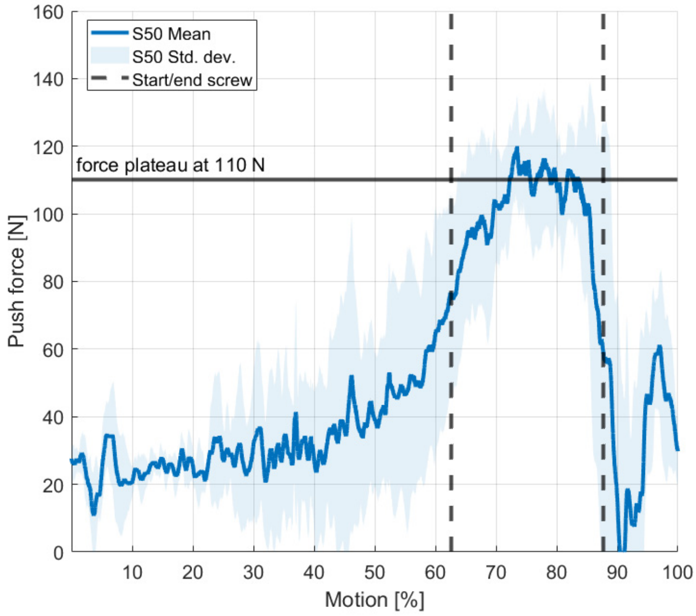

Figure 5. Exemplary course of the mean push force for participant P3, task T1, and support condition S50 with the start- and endpoint of the screw phase. A push force plateau could be recognized during the screw phase.

Considering task T1 in Figure 6, the mean push force of participants P1, P4, and P5 were at different levels between 83–93 N (P1), 88–100 N (P4), and 103–108 N (P5) for the different conditions S0, S50, and S100, respectively. Only participant P3 showed a larger dispersion of the mean push force between the support conditions (68–109 N). The dispersion of the push force was larger for participants P1 and P3 than for P4 and P5. A larger mean value of the push force at condition S50 compared to S0 could be observed for participants P3, P4, and P5. Subject P1 did not show this effect. However, P1 had two outliers for condition S50. All participants tended to show a lower push force at support condition S100 compared to S50, which was particularly evident for subject P3. Due to the overlapping of the boxes, no difference in push force was suggested between the support levels for participants P1, P4, and P5.

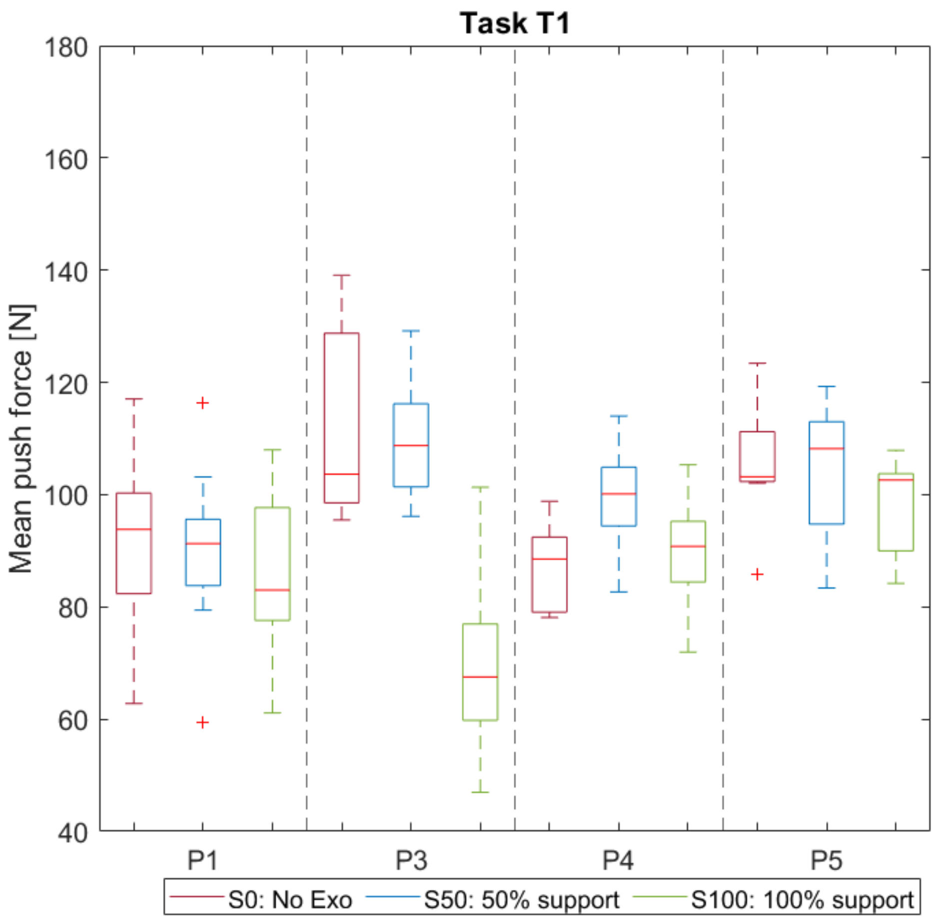

Figure 6. Mean push force of ten cycles for task T1 during the screw phase with all three support conditions (S0, S50, S100) of participants P1, P3, P4, and P5. The boxes represent the interquartile range (IQR). The length of whiskers is IQR*1.5. Outliers (>IQR*1.5).

Considering task T2 in Figure 7, the mean push force varied between the participants from 66 N to 135 N. Here, the participants showed different force levels. The push force was at different levels for participants P1 (66–74 N), P3 (70–89 N), P4 (124–135 N), and P5 (87–100 N) for the three support conditions. The dispersion of the mean push force was comparable for participants P1, P3, and P5. Participant P4 showed a larger dispersion for S100 and a decrease in dispersion at higher support levels. At the same time, there was a slight increase in the mean push force for participant P4 with a support level of S100 compared to S0. However, due to overlapping of the boxes, there was no difference in the mean push force of participants P2, P4, and P5 at different support conditions. Only participant P3 had a lower mean push force for support levels S50 (71 N) and S100 (70 N) compared to S0 (89 N).

3.2. Subjective Perception of the Strain

The participants completed a standard NASA TLX questionnaire after ten screw-in cycles under each test condition. The mean value of the ratings in the subcategories are plotted in Figure 8. The following scale was used: 0 corresponded to very low, 100 corresponded to very high.

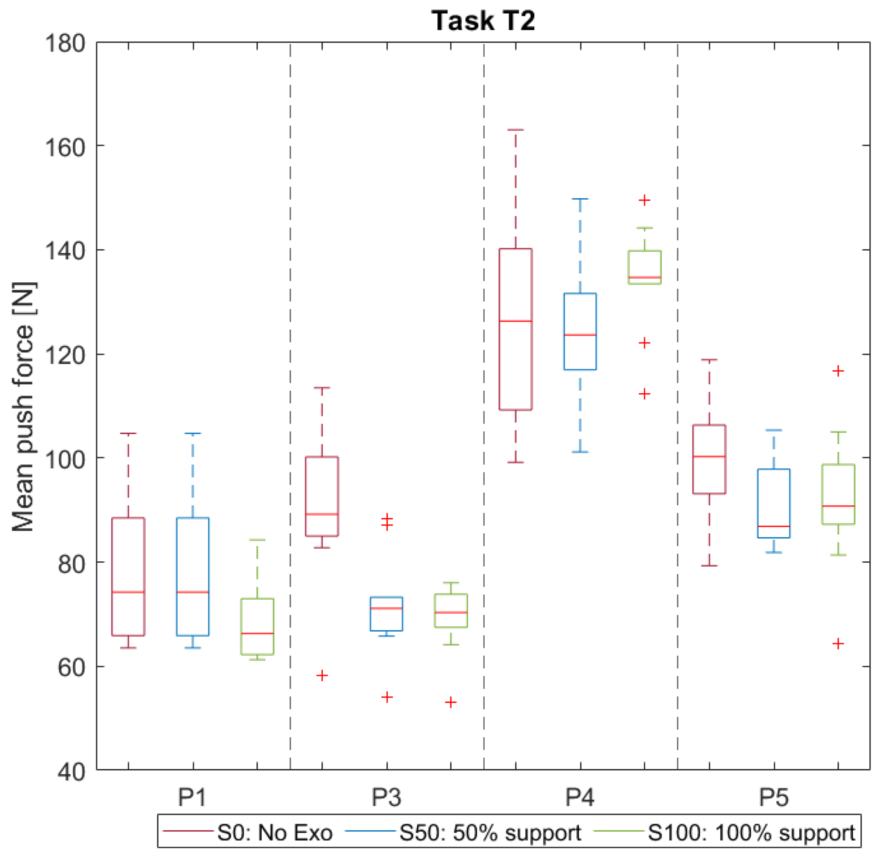

Figure 7. Mean push force of segment screw from T2 and all three support conditions (S0, S50, S100) of participants P1, P3, P4, and P5. The boxes represent the interquartile range (IQR). The length of whiskers is IQR*1.5. Outliers (>IQR*1.5).

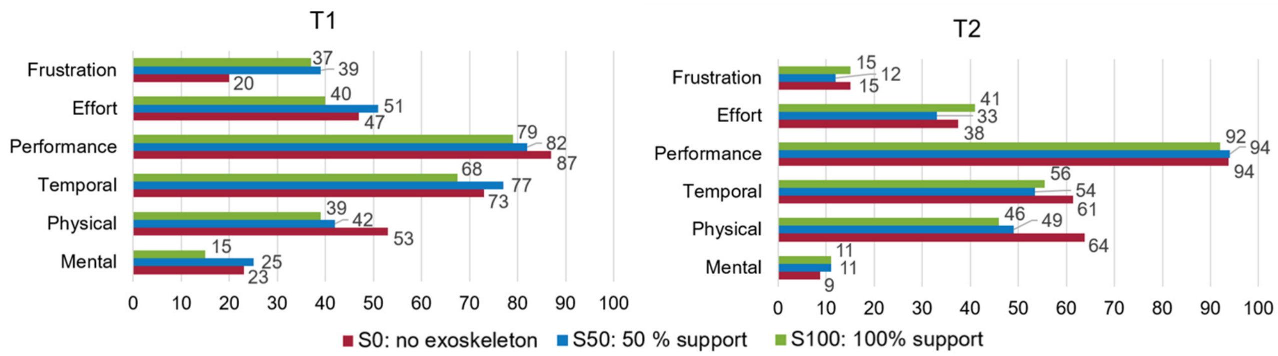

Figure 8. Mean values of NASA TLX of all participants for task T1 (**left**) and task T2 (**right**). The physical load on the user was reduced with an increasing support level of the exoskeleton.

The physical strain category was rated higher on average without support (S0) in both tasks (T1: 53, T2: 64) compared to support level S50 (T1: 42, T2: 49) and support level S100 (T1: 39, T2: 46).

Looking at the ratings of the category frustration, the participants showed a much higher value at support level S50 with 39 and S100 with 37, in comparison to the mean score for support level S0 with 20 in task T1. This was not evident in task T2. Here, frustration was rated the same at support level S0 and S100 with 15, and slightly lower at support level S50 with 12. Considering the categories effort, performance, temporal, and mental, there were only small differences between the support levels S0, S50, and S100 in both tasks T1 and T2. The performance was estimated lower here, with an increasing support level for task T1. Temporal and mental requirements of the task were not affected by the different support levels.

In Table 4, participants rated the exertion of task T1 (overall) with the help of the Borg scale CR-10 with an effort of S0 (4.4), S50 (4.6), and S100 (3.2). A relief in the dominant shoulder for support level S0 (6), S50 (5.7), and S100 (4.3) was mentioned.

Table 4. Borg ratings [CR10] of perceived exertion on tasks T1 and T2. The perceived exertion for tasks T1 and T2 was rated lower with increasing support force.

	Mean Value [CR10]		
	Support level	Task overall	Dom. shoulder
task T1	S0: no exoskeleton	4.4	6.0
	S50: 50% support	4.6	5.7
	S100: 100% support	3.2	4.3
task T2	S0: no exoskeleton	5.8	6.3
	S50: 50% support	4.4	5.0
	S100: 100% support	4.2	4.7

Considering task T2, a higher exertion compared to T1 was observed. The participants rated the overall exertion with support level S0 as the highest (5.8), followed by S50 (4.4), and S100 (4.2). The exertion on the dominant shoulder was rated lower with increasing support level (S0: 6.3, S50: 5, S100: 4.7).

3.3. Muscle Activities

3.3.1. Muscle Activities for the Whole Motion Sequence

The baseline (S0) average EMG curves of the participants (Figures 9 and 10) showed that, in both tasks, on the dominant side, DA and LD were activated at the beginning of arm lifting while FCU and BB were activated first at the beginning of the screw phase of the motion. In task T2, the non-dominant DA and LD had similar activity patterns to the dominant side, but with lower activity level. The same applied to LD in task T1. In comparison to the dominant DA, the non-dominant DA in T1 not only had a lower activity, but also a different pattern: the dominant DA curve climbed from arm lifting to screw while the non-dominant DA curve declined. During the screw phase of task T1, on the non-dominant side, an increase was observed in the FCU curve, but not in the BB curve. In the screw phase of task T2, both non-dominant FCU and BB had increased EMG activity, but less than the increase in the dominant ones. By comparing the baseline (S0) EMG curves between the two tasks, the FCU and BB on the dominant side and the BB, DA, and LD on the non-dominant side suggested higher activities in task T2 than in T1, especially during the screw phase. Overall, DA was the most active muscle and LD had the lowest activity in both tasks on both sides. The arm lifting phase was dominant in T1 with 33% of the motion and the screw phase with 19%, while the screw phase took the most time of the motion in T2 with 42% and the arm lifting phase with 20%. It was worth noting that, in both tasks, the arm lowering phase started simultaneously at the end of the screw phase.

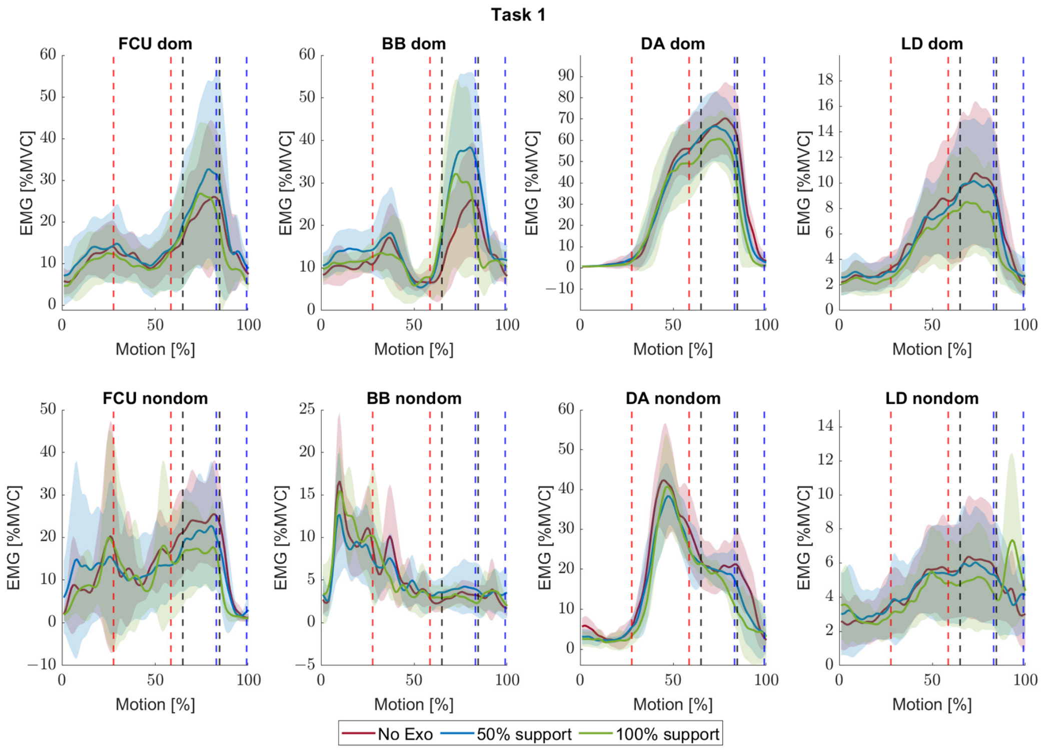

Figure 9. The participants' average EMG curves during the complete motion sequence, in task T1, under three test conditions. The shadows represent the standard deviations. Three motion phases are marked from left to right on the graphic: (1) arm lifting was between two red dashed lines; (2) screw was between two black dashed lines; (3) arm lowering was between two blue dashed lines.

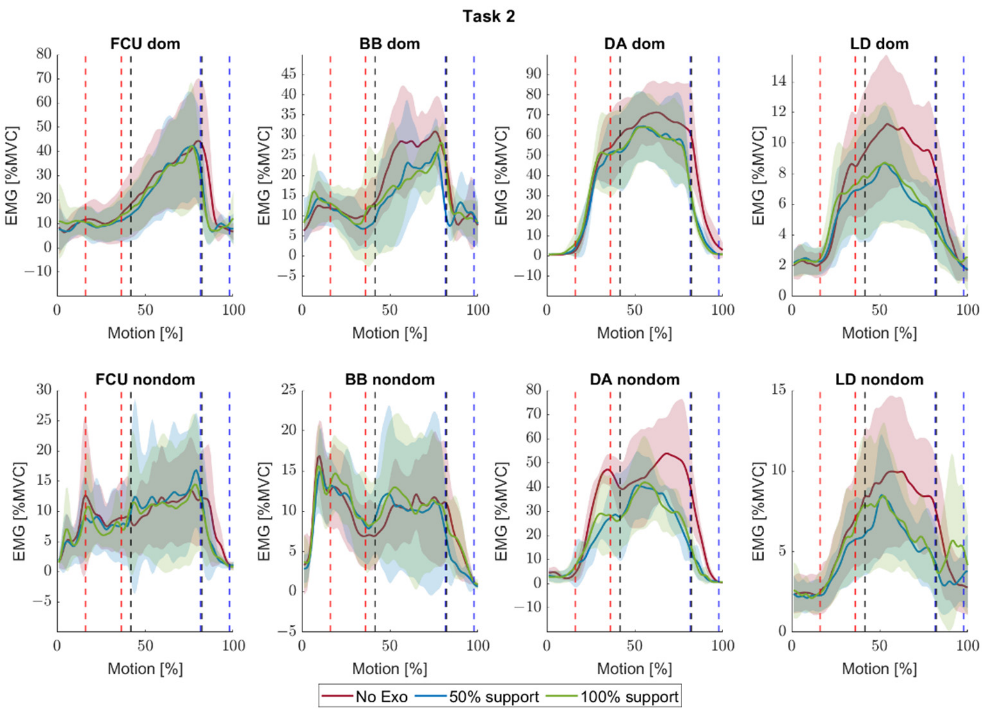

Figure 10. The participants' average EMG curves during the complete motion sequence, in task T2, under three test conditions. The shadows represent the standard deviations. Three motion phases are marked from left to right on the graphic: (1) arm lifting was between two red dashed lines; (2) screw was between two black dashed lines; (3) arm lowering was between two blue dashed lines.

Comparing the average EMG curves of the participants between the three conditions, a lower EMG level was observed in dominant DA and LD during 50–100% of the motion in T1 only in condition S100 and 30–100% in T2 in both condition sS50 and S100. The average EMG curves of non-dominant DA suggested a lower activity under the two supported conditions during 75–100% of the motion in T1 and 25–100% in T2. During the screw phase, the non-dominant LD had a lower EMG level only in S100 in T1 and on both supported conditions in T2. It should be noted that there was an obvious increase in EMG of the non-dominant LD in condition S100 in the arm lowering phase of both tasks. During the screw phase of task T1, the average EMG curves of dominant FCU and BB on S50 were over their baseline curves (S0). The dominant BB had a lower EMG level in both supported conditions during the screw phase of T2.

Based on the observations from the average EMG curves, an intra-individual comparison of mean EMG values was further conducted in each motion phase. Since the influence of support on FCU and BB were mainly discovered during the screw phase of the motion, their mean EMG was not compared for the other two motion phases. For each participant, the mean EMGs under conditions S50 and S100 were compared to the mean EMG at baseline. Their differences in percent are summarized in Figures 9–11.

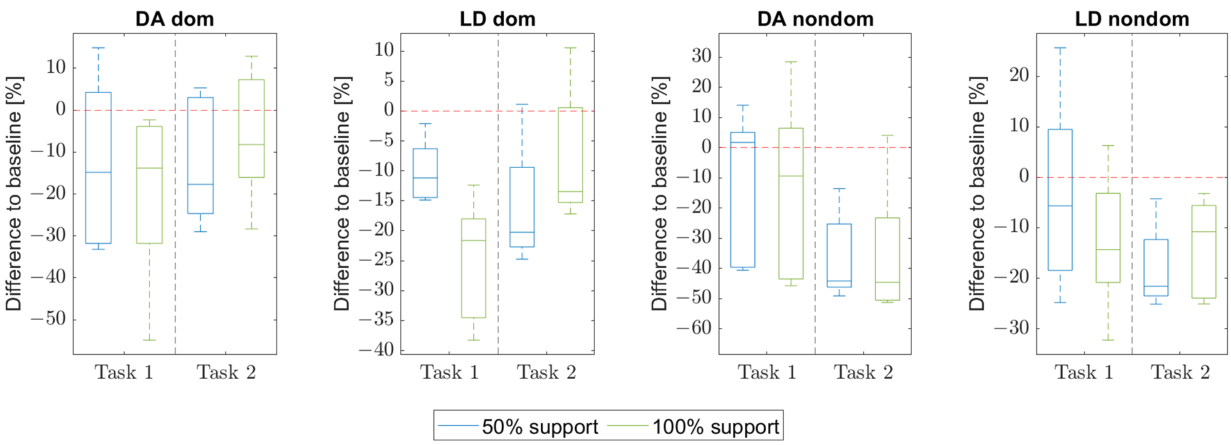

Figure 11. Differences in the mean EMGs of DAs and LDs under conditions S50 and S100 compared to S0 during arm lifting in both tasks.

3.3.2. Muscle Activities during the Arm Lifting Processes

In the arm lifting phase of task T1 (see Figure 11), the influence of the support on dominant DA and LD was more obvious in condition S100 than on S50. The mean EMG of dominant DA under condition S50 reduced in three participants and increased in two participants. However, all participants had reduced mean EMG in the dominant DA under condition S100. The mean EMG of dominant LD reduced in all participants under both the supported conditions and the reduction in S100 was stronger than in S50. In task T2 during arm lifting, the influence of the support on DA and LD was obvious on the non-dominant side but not on the dominant side. There was no clear difference between the conditions S50 and S100 in T2. Reduced mean EMGs in non-dominant DA and LD were observed under both conditions S50 and S100 for all participants with one exception for DA in S100. The dominant LD showed a reduced mean EMG during arm lifting in T2 in both S50 and 100, except for one participant. An intra-individual difference indicated a higher EMG activity of dominant LD on S100 than on S50 in T2.

3.3.3. Muscle Activities during Screw Phase of the Motion

In task T1 during the screw phase (see Figure 12), the dominant FCU and BB suggested increased activities in condition S50 compared to baseline S0. Their activities in S100 were lower than on S50 but comparable to S0. There was a recognizable reduction in non-dominant FCU with support in T1, and the reduction in S100 was stronger than in S50. The differences in mean EMGs of the two DAs had large inter-individual variance and showed no clear reduction under the supported conditions in T1. However, their mean EMG on S100 were smaller than on S50 at each participant. A reduction in the mean EMG of the LDs was only recognized under condition S100 in T1. During the screw phase of task T2, a reduction in the mean EMG of FCU was obvious under supported conditions, but only for the dominant side. Reduced activity was recognized by dominant BB in T2 under both supported conditions, with one exception in S100. The mean EMGs of DAs showed reductions from conditions S0 to S50 and S100 in T2, except for one participant. The LDs on both sides had recognizable reductions due to support.

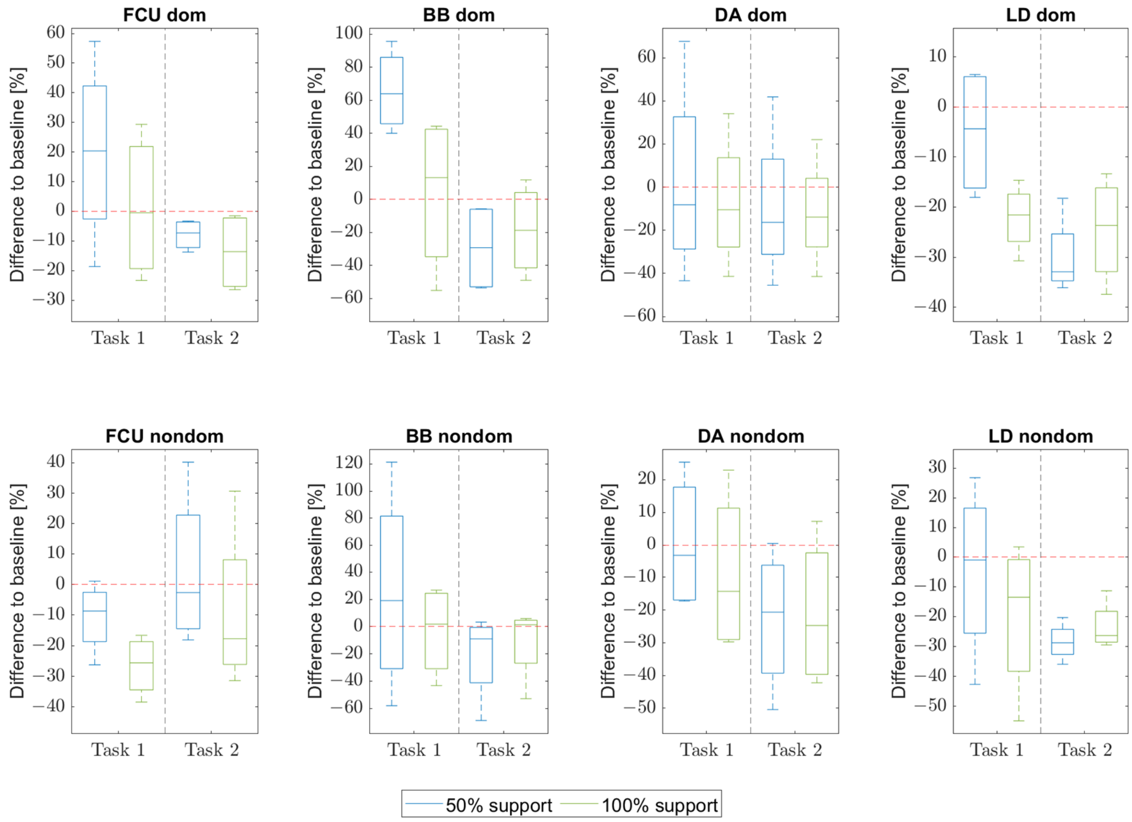

Figure 12. Differences in the mean EMGs of the eight muscles under conditions S50 and S100 compared to S0 during the screw phase in both tasks.

3.3.4. Muscle Activities during the Arm Lowering Processes

Similar to the arm lifting phase, during the arm lowering phase of task T1 (see Figure 13), the relief effect of the support on dominant DA and LD was stronger under condition S100 than in S50. Two participants had increased mean EMG of the two muscles in S50, while all participants had reduced mean EMG in S100 except for the LD of one participant. However, the mean EMGs of dominant DA and LD in S100 were lower than in S50 for each participant. The non-dominant DA had a clear reduction in the mean EMG on both supported conditions during arm lowering in T1, and its activity in S100 was lower than in S50. The mean EMG of non-dominant LD suggested higher activity with support, especially under condition S100. During arm lowering in T2, the dominant DA and LD as well as the non-dominant DA had reduced mean EMG with support. However, a difference in the mean EMG between S100 and S50 was not observed. The non-dominant LD had reduced activity in S50 in T2, but a higher mean EMG in S100 than in S50 for the participants.

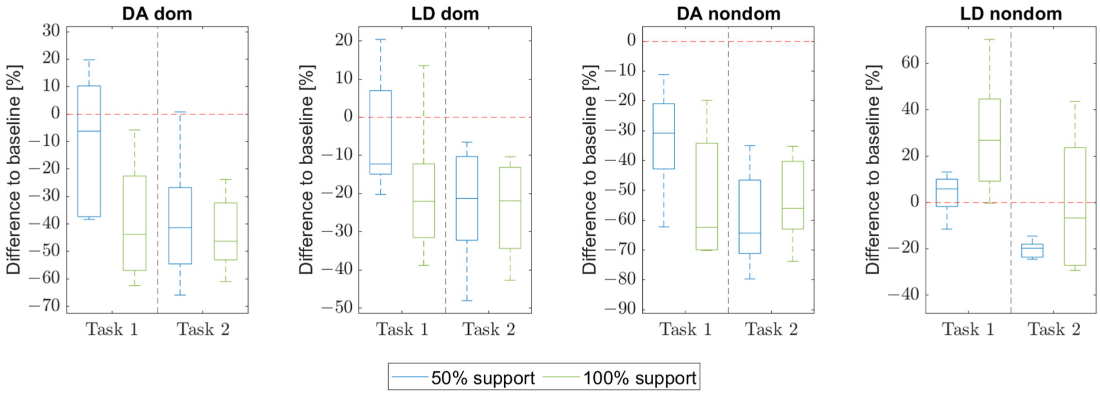

Figure 13. Differences in the mean EMGs of the DAs and LDs under conditions S50 and S100 compared to S0 during the arm lowering phase of the motion in both tasks.

3.4. Subjective Perception of Support Force

The subjective perceptions of the support force in the three motion phases were carried out with the help of a survey (see Figure 14). Sixty percent of the participants rated the support force during arm lifting as appropriate. Forty percent of them wished for stronger support force during lifting of the arm for condition S50 for both tasks. For one participant, the support force during the arm lifting process for condition S100 for task T2 was still too low. One participant was indecisive and was unable to give a ruling. Forty percent rated the support during arm lifting in task T1 condition S100 as too strong. The resistance during arm lowering was generally evaluated as low to appropriate by 60% of the participants. In both tasks, 40% of the participants rated the resistance during arm lowering in condition S100 as high or very high.

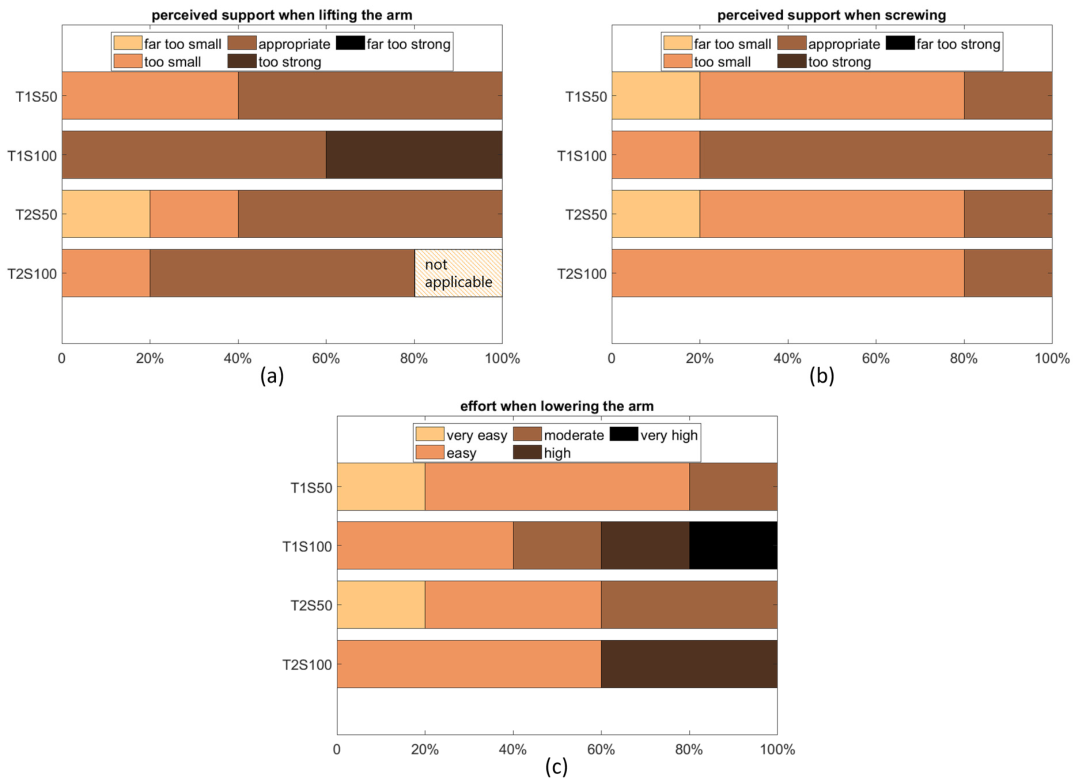

Figure 14. Subjective perception of (**a**) the support force when lifting the arm, (**b**) support when screwing-in, and (**c**) effort when lowering the arm.

The support force during the screw phase in task T2 was either too low, or way too low for 80% of the participants under both supported conditions (S50 and S100). In task T1, condition S50 was evaluated as too low or way too low by 80% of the participants. After increasing the support level to S100, 80% of the participants rated the support force as appropriate, but 20% still stated that it was too low.

3.5. Human-Exoskeleton Interaction Force

Unlike the homogeneous support force, the interaction force of the participants under the same support condition was heterogeneous. However, they showed similar patterns. The interaction force under condition S100 was higher than under condition S50. The interaction force increased during the arm lifting phase and had an additional increase when the screw phase began. In most cases, it was observed that the interaction force increased briefly at the beginning of the arm lowering phase (see red circles in Figure 15) and then decreased with the shoulder elevation angle. Interestingly, participant P4 had a higher interaction force at the start and finish of the motion sequence in comparison to the other participants. This could be explained by the shoulder elevation angle. At the beginning and end of the motion sequence, participant P4 extended their upper arm at baseline S0 more than on the two supported conditions, which resulted in a countermovement of the upper arm against the armrest of the exoskeleton.

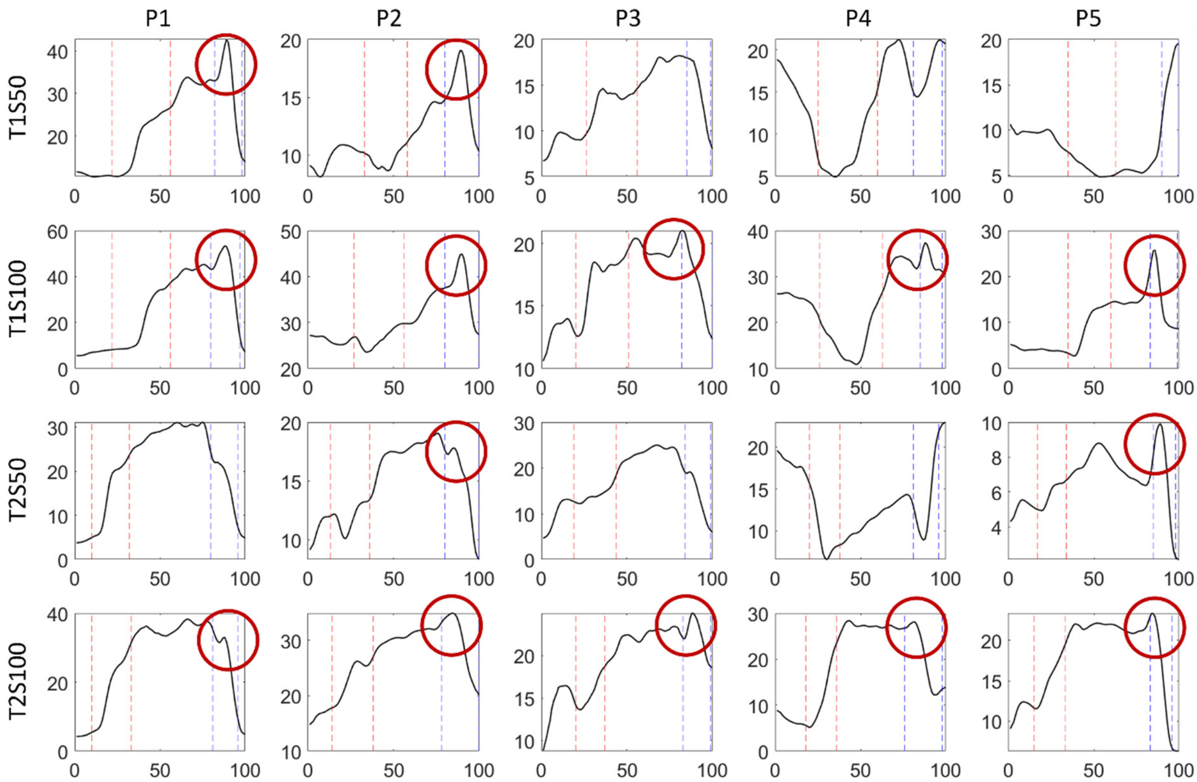

Figure 15. An overview of the interaction force (y-axis in N, x-axis in%-Cycle) between the arm and armrest. Two red dashed lines enclose the arm lifting phase, while two blue dashed lines bound the arm lowering phase. The red circles highlight the peaks of the interaction forces, which were observed at the beginning of the arm lowering phase.

4. Discussion

The evaluation results of the physical strain and human–machine interaction showed that an adaption of the support level to the motion phases was expected for the two selected tasks. The screw phase was the most strenuous and required the highest support level compared to the arm lifting and lowering phases, while the maximum support level was not always necessary in the other two phases and was even perceived as resistance by some participants, especially when arm lowering. It was interesting to note that aside from the arm elevation angle, the electric current of the screwdriver was also a promising means of determining the switching time between the motion phases to adjust the support level.

Both the subjective perception and the EMG activities showed the overall exertion and the exertion of the dom. shoulder during the two overhead tasks. The screw phase was the most strenuous in both tasks. There were different push force levels of the participants and a general higher push force level in task 2 due to the higher torque compared to task T1. The mean push force was generally not affected by the support level of the exoskeleton for participants P1, P4, and P5 during the screw phase in both tasks. Only participant P3 showed a lower mean push force with increasing support levels. This indicated that the participants experienced the same load for all three support levels in both tasks, which was a precondition for the comparability analysis.

The relative reductions in the shoulder muscle activities as well as the reduction in the perceived exertion under the supported conditions indicated a positive effect of the shoulder exoskeleton Lucy on the user, which is consistent with previous studies of similar overhead tasks [10,16]. The perceived physical strain reported by the participants revealed a stronger relief in S100 than in S50 in both tasks. However, support level S100 led to a stronger reduction in shoulder muscle activity than support level S50 only in T1, and not in T2. This may be related to the different physical loads of the two tasks and their required support. Task T2 was more physically demanding than T1 because of the higher torque needed and the longer duration of the screw phase. The perceived support during the screw phase indicated that improving the support level from S50 to S100 was sufficient for T1 but still not enough for T2. Some participants rated the support level S100 as too high when lowering the arms. This was also observed in previous studies for other manual activities [16]. An increase in the activation of the non-dominant LD was particularly noticeable for condition S100 when lowering the arms. Furthermore, an increase in the interaction force between the dominant arm and the armrest of Lucy was observed in most cases.

According to the results, some potential optimization can be made for motion phases of screw and arm lowering to extend the use cases of Lucy. An additional or an enhanced support force to supplement the push force during the screw phase was expected for T2. An additional mechanical structure for coupling the exoskeleton and the screwdriver or a stronger cylinder are possible approaches. The mechanical coupling could allow for further application-oriented optimization of the support performance of the exoskeleton. However, it must be investigated how a stronger support force affects the load on the wrist. First, simulative studies on new support concepts already exist and are so far quite promising [11]. The mechanical structure should apply additional support forces directly to the power tool during the screw phase. For the phase arm lowering, a lower support level compared to the screw and arm lifting phases can improve the user experience. The detection of the start and end of the screw phase is important for the timely increase and decrease in the support level for screw and arm lowering phases, respectively. An additional trigger button on the power tool for the user to switch the support level manually was presented in previous work [10]. An automated detection of the switching time based on the current of the screwdriver may be a promising way. Furthermore, different settings of support level for the dominant and non-dominant sides could enhance the user experience if the workload on either side had a significant difference. Considering the inter-individual variety in the perception of physical strain and support, it is important for the user experience to allow the user to pre-set the support level according to their own perception.

Limitations of the Study

The study allowed us to determine the potential optimization of the exoskeleton for selected use cases. Nevertheless, there were some limitations of the study that need to be considered in dealing with the results. First of all, the sample size of this study was relatively small for quantitative analysis. Thus, it is mainly used for qualitative analysis. The task definition and the experimental setup tried to reproduce real scenarios in the industry. However, the participants were college members and not workers in the industry. The difference in experience in these tasks could lead to small deviations with regard to the exact movements made and push forces applied. For instance, in real working scenarios, the experts may stand with one foot forward and one back and change their standing position during the task. The participants, on the other hand, were not able to move due to the limited surface of the force plate.

5. Conclusions

This study evaluated a shoulder exoskeleton Lucy for two overhead tasks with a screwdriver in a lab environment to identify the potential optimization of the exoskeleton for the selected use cases. The objective and subjective assessments suggest that Lucy can reduce physical strain on the shoulder. An additional analysis of each phase of motion indicates that a higher support force is desired for the screw phase, while the support level during the lowering of the user's arms can be reduced for a better user experience. This suggests an adaptive control of the support level according to the motion phase. In order to adjust the support level effectively, it is important to identify the start and end of the screw phase. To increase the maximum available support force during the screw-in action, there are two potential solutions: equipping the current exoskeleton with a stronger cylinder or adding a mechanical structure to create a force parallel to the user's push force. The possible solutions will be evaluated through simulation in the next stage.

Author Contributions: J.S., Z.Y. and C.M. designed the study. J.S., Z.Y. and T.S. performed the study. J.S. and Z.Y. abstracted the data and wrote the first manuscript draft. A.W., C.M., J.M., S.W., T.S., T.G., S.M. and R.W. revised and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Research Foundation (DFG). The authors gratefully acknowledge the financial support of project 435242218 (WA 2913/41-1, MA 5940/11-1, and WE 6430/3-1).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Ethics Committee of the Department of Psychology of Helmut-Schmidt University Hamburg (HSU).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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

References

1. Fritzsche, L.; Wegge, J.; Schmauder, M.; Kliegel, M.; Schmidt, K.-H. Good ergonomics and team diversity reduce absenteeism and errors in car manufacturing. *Ergonomics* **2014**, *57*, 148–161. [CrossRef]
2. European Commission. *EU Labour Force Survey 2020: Module on Accidents at Work and Other Work-Related Health Problems: Assessment Report*, 2021 ed.; Publications Office of the European Union: Luxembourg, 2021; ISBN 9789276420040.
3. BAuA/BMAS. Sicherheit und Gesundheit bei der Arbeit—Berichtsjahr 2016. Bundesministerium für Arbeit und Soziales (BMAS) 2017. Available online: https://www.baua.de/dok/8732292 (accessed on 1 June 2022).
4. De Looze, M.P.; Bosch, T.; Krause, F.; Stadler, K.S.; O'Sullivan, L.W. Exoskeletons for industrial application and their potential effects on physical work load. *Ergonomics* **2016**, *59*, 671–681. [CrossRef] [PubMed]
5. Kim, S.; Nussbaum, M.A. A Follow-Up Study of the Effects of an Arm Support Exoskeleton on Physical Demands and Task Performance During Simulated Overhead Work. *IISE Trans. Occup. Ergon. Hum. Factors* **2019**, *7*, 163–174. [CrossRef]
6. Bär, M.; Steinhilber, B.; Rieger, M.A.; Luger, T. The influence of using exoskeletons during occupational tasks on acute physical stress and strain compared to no exoskeleton—A systematic review and meta-analysis. *Appl. Ergon.* **2021**, *94*, 103385. [CrossRef] [PubMed]

7. Miehling, J.; Wolf, A.; Wartzack, S. Musculoskeletal Simulation and Evaluation of Support System Designs. In *Developing Support Technologies: Integrating Multiple Perspectives to Create Assistance that People Really Want*; Karafillidis, A., Weidner, R., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 219–227. ISBN 978-3-030-01836-8.
8. Moeller, T.; Krell-Roesch, J.; Woll, A.; Stein, T. Effects of Upper-Limb Exoskeletons Designed for Use in the Working Environment-A Literature Review. *Front. Robot. AI* **2022**, *9*, 858893. [CrossRef] [PubMed]
9. Otten, B.; Weidner, R.; Linnenberg, C. Light weight support systems with inherent biomechanic compatibility for tasks at or above head level. In *Proceedings of the 2nd Transdisciplinary Conference "Technical Support Systems, That People Really Want"*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 495–505.
10. Otten, B.M.; Weidner, R.; Argubi-Wollesen, A. Evaluation of a Novel Active Exoskeleton for Tasks at or Above Head Level. *IEEE Robot. Autom. Lett.* **2018**, *3*, 2408–2415. [CrossRef]
11. Molz, C.; Yao, Z.; Sänger, J.; Gwosch, T.; Weidner, R.; Matthiesen, S.; Wartzack, S.; Miehling, J. A Musculoskeletal Human Model-Based Approach for Evaluating Support Concepts of Exoskeletons for Selected Use Cases. *Proc. Des. Soc.* **2022**, *2*, 515–524. [CrossRef]
12. Hefferle, M.; Lechner, M.; Kluth, K.; Christian, M. Development of a Standardized Ergonomic Assessment Methodology for Exoskeletons Using Both Subjective and Objective Measurement Techniques. In *Advances in Human Factors in Robots and Unmanned Systems*; Chen, J., Ed.; Springer International Publishing: Cham, Switzerland, 2020; pp. 49–59. ISBN 978-3-030-20466-2.
13. Maurice, P.; Camernik, J.; Gorjan, D.; Schirrmeister, B.; Bornmann, J.; Tagliapietra, L.; Latella, C.; Pucci, D.; Fritzsche, L.; Ivaldi, S.; et al. Objective and Subjective Effects of a Passive Exoskeleton on Overhead Work. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2020**, *28*, 152–164. [CrossRef]
14. Alabdulkarim, S.; Nussbaum, M.A. Influences of different exoskeleton designs and tool mass on physical demands and performance in a simulated overhead drilling task. *Appl. Ergon.* **2019**, *74*, 55–66. [CrossRef]
15. McFarland, T.C.; McDonald, A.C.; Whittaker, R.L.; Callaghan, J.P.; Dickerson, C.R. Level of exoskeleton support influences shoulder elevation, external rotation and forearm pronation during simulated work tasks in females. *Appl. Ergon.* **2022**, *98*, 103591. [CrossRef] [PubMed]
16. Argubi-Wollesen, A. Entwicklung und Biomechanische Evaluation eines Körpergetragenen Unterstützungssystems (Exoskelett) für Arbeiten in und über Kopfhöhe. 2021. Available online: https://ediss.sub.uni-hamburg.de/handle/ediss/9166 (accessed on 3 June 2022).
17. Dörr, M.; Ries, M.; Gwosch, T.; Matthiesen, S. Recognizing Product Application based on Integrated Consumer Grade Sensors: A Case Study with Handheld Power Tools. *Procedia CIRP* **2019**, *84*, 798–803. [CrossRef]
18. Hermens, H.J. (Ed.) *European Recommendations for Surface ElectroMyoGraphy: Results of the SENIAM Project*; Roessingh Research and Development B.V.: Enschede, The Netherlands, 1999; ISBN 978-90-75452-15-0.
19. Borg, G. *Borg's Perceived Exertion and Pain Scales*; Human Kinetics: Champaign, IL, US, 1998; ISBN 0-88011-623-4.
20. Hart, S.G.; Staveland, L.E. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Human Mental Workload*; Elsevier: Amsterdam, The Netherlands, 1988; pp. 139–183. ISBN 9780444703880.