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ARTICLE

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The impact of an active and passive industrial back exoskeleton on functional performance

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ABSTRACT

Due to differences in actuation and design, active and passive industrial back exoskeletons could influence functional performance, i.e., work performance, perceived task difficulty, and discomfort, differently. Therefore, this study investigated and compared the impact of the active CrayX (7 kg) and passive Paexo Back (4.5 kg) on functional performance. Eighteen participants performed twelve work-related tasks with both types of exoskeletons and without (NoExo). The CrayX hindered work performance up to 22% in multiple tasks, compared to the Paexo Back and NoExo, while work performance between NoExo and the Paexo Back condition was more comparable, except for stair climbing (13% hindrance). Perceived task difficulty and discomfort seldomly varied between both exoskeletons. Although the CrayX shows promise to benefit workers, limitations in hindrance and comfort should first be addressed. The Paexo Back has demonstrated an advantage in certain static tasks. However, increasing its potential across a broader range of tasks seems warranted.

Practitioner Summary: Differences between industrial back exoskeletons with regard to functional performance, i.e. work performance, discomfort and perceived task difficulty, were investigated by evaluating the active CrayX and passive Paexo Back back exoskeletons. The CrayX significantly hindered functional performance, while the Paexo Back seldomly affected functional performance.

Abbreviations: WMSD: Work-related musculoskeletal disorder; NoExo: No Exoskeleton; GD: General discomfort; PTD: Perceived task difficulty; BMI: Body Mass Index

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Exoskeletons; wearable assistive device; device evaluation; human factors

1. Introduction

Work-related musculoskeletal disorders (WMSDs), defined as impairments of the musculoskeletal system that are primarily caused by work tasks and/or the direct work environment (European Agency for Safety and Health at Work 2019), continue to form one of the most important occupational health problems. With an estimated 12-month prevalence of 47% in the manufacturing industry, lower-back WMSDs are one of the most reported disorders (Govaerts et al. 2021). These disorders negatively affect the quality of life of employees (de Carvalho, Schmidt, and Soares 2016; Roux et al. 2005) and are deleterious for corporations, due to long-term work absenteeism or even permanent work incapacity of skilled employees (Bevan 2015; European Agency for Safety and Health at Work 2019). These implications form a strong impetus for managerial decision making in companies' structural policies regarding implementing effective prevention strategies. For example, a commonly used prevention strategy is to ergonomically optimise manufacturing workstations (e.g. adjusting work table height, rearrangement of tools or minimising lifting time) in an attempt to limit specific risk factors associated with the development of back-related WMSDs (e.g. repetitive movements, heavy lifting, and awkward postures) (da Costa and Vieira 2010).

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Despite pursuing ergonomic improvements, there are manufacturing tasks that cannot be sufficiently adjusted (e.g. lifting heavy loads in awkward postures). Therefore, to also mitigate WMSD-risks when conventional prevention strategies have reached their limit, researchers and practitioners are developing and implementing new technological approaches, such as exoskeletons, that focus on providing physical assistance during ergonomically suboptimal working tasks (de Looze et al. 2016). Focusing on back exoskeletons, studies have shown that the use of these devices can decrease the physical load on the back (Koopman, Kingma, et al. 2020; de Looze et al. 2016; Koopman, Kingma, Näf, et al. 2020), hereby mitigating the risk for developing back-related WMSDs. Two main categories of back exoskeletons exist: (i) active back exoskeletons that are usually electrically or pneumatically powered e.g. the CrayX (German Bionic Systems GMBH, Augsburg, Germany), and (ii) passive back exoskeletons which do not incorporate a power source but use deformation of springs or other elastic materials to store and return kinetic energy e.g. the Paexo Back (Ottobock SE & Co., Duderstadt, Germany), LifSuit (Auxivo, Schwerzenbach, Switzerland), and Laevo FLEX (Laevo B.V., Delft, Netherlands) (de Looze et al. 2016). Despite numerous studies investigating back exoskeletons, systematic comparisons between different categories are lacking (De Bock et al. 2022).

Moreover, although showing promise towards reducing back-related WMSDs, it is important that these devices do not hamper functional performance. Functional performance is defined as the ability of individuals to efficiently and effectively carry out relevant functional tasks in their work environment, encompassing work performance related metrics such as performance time and repetition count, and subjective metrics such as perceived task difficulty and discomfort (Baltrusch et al. 2018; Pesenti et al. 2021). It is important to minimise hindrance to users' functional performance as this could negatively impact user experience and hinder the adoption of the technology (Elprama, Vanderborght, and Jacobs 2022; Elprama et al. 2020; Pesenti et al. 2021). Since the level of support and actuation mechanism differ between passive and active exoskeletons, effects on physical load and functional performance could differ to a certain extent. In general, it is expected that active exoskeletons, using the advantage of mechanical motors and smart actuation, can provide more physical support compared to passive exoskeletons (Poliero et al. 2022). On the other hand, active devices are often bulkier in design and typically heavier compared to passive back exoskeletons, potentially hampering the net-gain for the user and decreasing functional performance. Furthermore, rigid exoskeleton designs, often associated with active exoskeletons, may have more difficulty fitting different body types, which can affect the device's effectiveness, user's comfort and thereby functional performance compared to more flexible designs. This highlights the underlying link between exoskeletal design and functional performance. Each with their unique features in terms of weight, level of support and design, the impact that both active and passive back exoskeletons pose on functional performance must be investigated, and compared to correctly consult companies to meet their ergonomic needs.

In order to further enhance the functional comparison between back exoskeletons, realistic working conditions should be incorporated in experimental designs (Kuber et al. 2022). Currently, exoskeleton evaluation studies often use controlled manual material handling tasks in experimental protocols (Baltrusch et al. 2018). Nonetheless, most manufacturing work encompasses the performance of different tasks besides lifting e.g., walking or carrying. The use of a back exoskeleton may hamper work performance and subjective user experience for one task, while proving beneficial for another task. (Kozinc et al. 2020). Acknowledging the impact of differences in support, weight and design on functional performance, including a variety of functional tests in the experimental design, could help the extrapolation of results towards a comparable outcome matrix.

Therefore, the purpose of this study was to evaluate the effect of an active and a passive back exoskeleton, and the difference between them on functional performance using the functional test battery of Baltrusch et al. (2018). We hypothesised that the active back exoskeleton improves the work performance aspect of users' functional performance more compared to the passive exoskeleton. However, subjective aspects like perceived task difficulty and general discomfort are hypothesised to be lower for the active exoskeleton due to its weight and bulkiness.

2. Material and methods

2.1. Participants

Ten healthy males and eight healthy females (age: 33 ± 13 years; height: 173.5 ± 8.8 cm; weight: 70.6 ± 12.6 kg) participated in this randomised, counterbalanced, cross-over laboratory study. Most of the participants had little (i.e., <1 h working experience with exoskeletons) or no previous experience with exoskeletons and none suffered from musculoskeletal disorders. Volunteers were excluded by the researchers when medical conditions or histories could compromise a safe completion of the experiment.

All participants received information about the study and signed a consent document prior to participation. The experimental protocol (B.U.N. 1432022000161) was approved by the Medical Ethics Commission of the Vrije Universiteit Brussel and University Hospital Brussel.

2.2. Back-support exoskeletons

In this experiment, the passive Paexo Back (Ottobock SE, Duderstadt, Germany) and active CrayX (4th generation, German Bionic Systems GMBH, Augsburg, Germany) exoskeletons were used. Both exoskeletons were chosen after careful evaluation of available options in the European market. The active CrayX was selected as one of the few active exoskeletons currently available, while the passive Paexo Back was preferred over other types based on extensive pilot testing, which yielded the best user feedback. The Paexo Back (Figure 1A) weighs approximately 4.5 kg and main components include: (i) a vest fitted with chest pads, (ii) a hip belt with adjustment wheel to regulate the level of support, and (iii) leg shells at the anterior side with straps. Adjustable bars on both sides of the exoskeleton connect the vest to the hip belt. The exoskeleton generates support by creating an extension moment between the leg shells and chest vest. Importantly, the magnitude of support throughout the movement trajectory is not constant as it is dependent of the angle between the two aforementioned end-effectors. Activating and deactivating the support is possible through the mechanical control unit, located at the hip centre. Furthermore, the control unit is able to distinguish bending from walking, causing the support to be automatically switched off when walking.

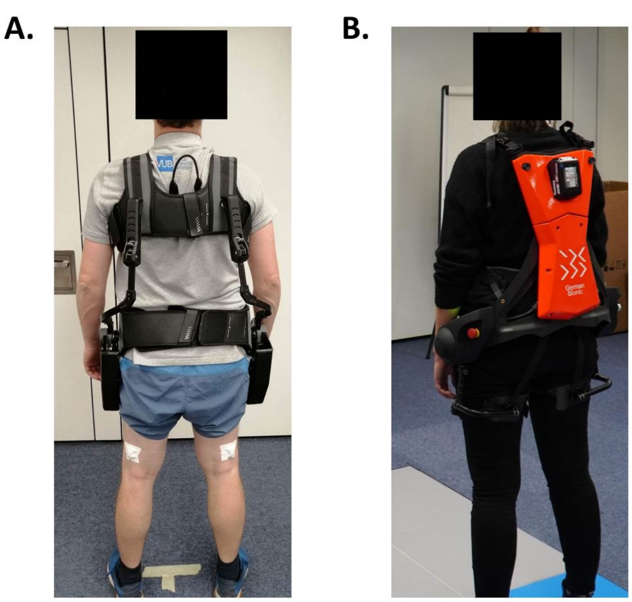

Figure 1. The back-support exoskeletons evaluated in this study were (A) the passive Paexo Back (Ottobock SE, Duderstadt, Germany) and (B) the active CrayX (German Bionic Systems GMBH, Augsburg, Germany).

The CrayX (Figure 1B) has a weight of approximately 7 kg and consists of a rigid back frame with battery holder. A chest vest connected to the back frame through straps allows for fitting the exoskeleton to the user's body. Also connected to the back frame is the hip belt, which is equipped with two electrical motors, designed to each align with the user's hip joint. A display, on/off button, and emergency stop, all located on top of the right motor, allow the user to manage the settings of the active device. Front and back leg connectors, also adjustable in size, are connected to the hip belt through anti-slip straps and to the electrical motors through bars. Contrary to the Paexo Back, an extension as well as a flexion moment can be generated to provide support to the user. Moreover, since the support is provided by the electrical motors, the magnitude is constant throughout the movement trajectory. However, the specific details of this control system are proprietary information shielded by the manufacturer, and thus, it is not possible to fully disclose its mechanism.

2.3. Experimental protocol

Prior to the experimental sessions, participants completed one familiarisation trial to get acquainted with the exoskeletons and experimental tasks (see 2.4 Test Battery). This was followed by three experimental trials, randomised in order: CrayX, Paexo Back, no exoskeleton (NoExo). On the day of the experimental trials, a concise training session, where participants were asked to walk, squat, bend and move in the exoskeleton, was performed to further minimise possible learning effects. All trials were separated by 2–3 days to ensure sufficient recovery.

2.4. Test battery

For this experiment, the test battery designed by Baltrusch et al. (2018) was used since it was reported to be sufficiently sensitive for detecting effects of an exoskeleton on performance and subjective outcomes. Moreover, Kozinc et al. (2020) investigated the reliability of this test battery and found good to excellent intra-session reliability, and moderate to excellent inter-session reliability for most of the included tasks.

The test battery consists of 12 tasks which can be grouped in three task categories: (i) material handling including lifting, load carrying, and two postural tolerance tasks, (ii) occupational side activities including walking, sit to stand, stair and ladder climbing, and (iii) range of motion including trunk rotation and bending, wide stance and squatting. In the protocol of Baltrusch et al. (2018) and Kozinc et al. (2020), support of the exoskeleton is only activated in the material handling task category. However, since this study selected the Paexo Back and CrayX based on their ability to differentiate between walking and bending, support will also be engaged during the walking task. The level of support of the Paexo Back was set at the highest level (via the adjustment wheel) and the CrayX, after consulting the supplier, was set at 90% support and 30% counter force (support for the downward movement). Support will be switched off during the other tasks.

The included tasks, grouped by task category, are outlined below (and can also be found as supplementary material).

2.4.1. Material handling

2.4.1.1. Lifting. The task variation of Kozinc et al. (2020) was chosen over the design of Baltrusch et al. (2018) because a ceiling effect was present in the latter. Participants were instructed to lift and lower a 20 kg box (L = 30 cm, W = 20 cm, H = 17 cm) as many times as possible within 2 minutes. Participants lifted the box from the origin position (H = 25 cm) to an upright position, repetitively. Participants could choose their own preferred technique. The number of lifts was taken as the outcome variable for work performance.

2.4.1.2. Load carrying. Participants walked a 10 m distance as fast as possible while carrying a 20 kg box (L = 30 cm, W = 20 cm, H = 17 cm). Walking time (lifting and lowering times of the weight were excluded) was selected as work performance outcome parameter.

2.4.1.3. Postural tolerance task – three-point kneeling position. Participants were asked to repeatedly transfer 15 bolds from one row to another row and back in a perforated metal plate while adopting a three-point kneeling position. The distance between the knee and the wrist of the supporting hand was 3 times participant's palm length. Although the task had to be performed with one hand, the working hand was allowed to be switched throughout the task as long as no support was taken with two hands. Participants were asked to perform the task until they could no longer hold the working position due to discomfort. If after 5 minutes, the participant did not indicate their will to stop, a researcher asked them to stop. Here, performance time was selected as work performance outcome parameter.

2.4.1.4. Postural tolerance task – forward bending. Participants performed task 3 as above-mentioned and a similar instruction was given. However, here, a forward bending position needed to be adopted instead of a three-point kneeling position. The height of the platform was set at knee level. Using both hands was allowed for this task as long as no support was taken to alleviate the back. Performance time was also selected as work performance outcome parameter.

2.4.2. Occupational side activities

2.4.2.1. Walking. Participants were asked to repeatedly, for a total duration of six minutes, walk between a distance of 10 metres at a self-selected speed. Distance was used as work performance outcome parameter.

2.4.2.2. Sit to stand. This task involved sitting down and standing up from a chair as fast as possible for five cycles. Participants were instructed to extend their knees once seated to ensure a controlled movement pattern and limit the exploitation of elastic energy stored in the muscle-tendon system for the standing up movement. Performance time was used as work performance outcome measurement.

2.4.2.3. Stair climbing. Participants were instructed to climb 10 steps of stairs as fast as possible. They were not allowed to use the handrails or run. The work performance outcome variable used to assess this task was the completion time.

2.4.2.4. Ladder climbing. Participants were instructed to climb up and down a ladder (up until the sixth step) as fast as possible. The work performance outcome variable used to assess this task was the completion time.

2.4.3. Range of motion

2.4.3.1. Trunk rotation. This task includes rotating the trunk five times to the right and five times to the left.

Participants were asked to perform these movements as fluently as possible. No work performance outcome measures were monitored.

2.4.3.2. Trunk bending. Participants were instructed to stand on a platform positioned 14 cm above the ground and subsequently to bend forward, reaching as low as possible. This was repeated three times. The average of the distance from the fingertips to the ground served as work performance outcome parameter for this task.

2.4.3.3. Wide stance. Instructions were given to obtain a maximum inter-feet distance by abducting the hips. When participants were not able to afterwards reobtain the starting position without losing balance, the movement was invalid. After each maximum position, the distance was measured between the midst of both heels. The average of three measurements was the work performance outcome parameter.

2.4.3.4. Squatting. This task involved squatting three consecutive times, as deep as possible. Participants were instructed to ensure that their heels made contact with the floor. No work performance measurements were taken.

2.5. Instrumentation and measurements

Work performance measurements as well as subjective measurements were used to assess participants' functional performance during the different experimental conditions. Work performance outcomes included distance, performance time or repetition count, depending on the task. Subjective parameters included perceived task difficulty and general discomfort, assessed through two questionnaires, which were filled out after each task. Both questionnaires included a visual analogue scale on which participants could indicate, with a vertical line, their level of experienced discomfort or task difficulty. The chosen method offers a more nuanced differentiation of participants' opinions compared to numerical rating scales, reducing variation in individual interpretation (Kersten, Küçükdeveci, and Tennant 2012). Additionally, it is a widely utilised approach for evaluating subjective measures (Pesenti et al. 2021). The level of comfort in the task performed was assessed using the question 'Please indicate the comfort of the device in the task you just performed", while the difficulty of the task was evaluated using the question "How difficult was the task you just performed?'. Both visual analogue scales were labelled at one end with 'no discomfort' or 'no difficulties' and at the other end with 'severe discomfort' or 'severe difficulties'. A table (see Appendix Table 1) was included in the paper, presenting all the obtained data related to work performance measurements and subjective parameters.

2.6. Statistics

A Shapiro-Wilk test and Q-Q plots were used to check normality of the three main parameters i.e., work performance, general discomfort and perceived task difficulty. Differences between the three experimental conditions with regard to work performance and perceived task difficulty were analysed through a Friedman test where both outcome variables were analysed separately for each task. When significant, a pairwise comparison was performed between the conditions, using the Wilcoxon signed-rank test with a Bonferroni correction for multiple testing. General discomfort was only surveyed during the two exoskeleton conditions and the difference in VAS-scores was analysed through a Wilcoxon signed-rank test. To investigate the relation between the three main outcome variables as well as the relation between participants' anthropometric characteristics (i.e., Body Mass Index, BMI) and the outcome variables, a Spearman rank order correlation was conducted. For all statistical analyses, an alpha-error of 5% was considered as a valid cut-off for significance testing. R 4.0.3 (R Core Team 2021) software was used to perform all data analyses and visualisation. All data are presented as means ± standard error.

3. Results

3.1. Work performance

Figure 2 presents the percentage of change in work performance when executing the test battery with both exoskeletons. Work performance values were normalised to the NoExo-condition to enhance comparison. Tasks included in the manual handling category were generally not influenced by either exoskeleton. However, work performance during load carrying was affected by the CrayX exoskeleton: performance time significantly increased compared to NoExo (NoExo $= 5.4 \pm 0.7$ s; CrayX $= 6.1 \pm 0.9$ s; $p < .01$), and the Paexo Back condition (Paexo $= 5.6 \pm 0.9$ s; $p < .001$). No significant difference between the Paexo Back and NoExo was found regarding load carrying time.

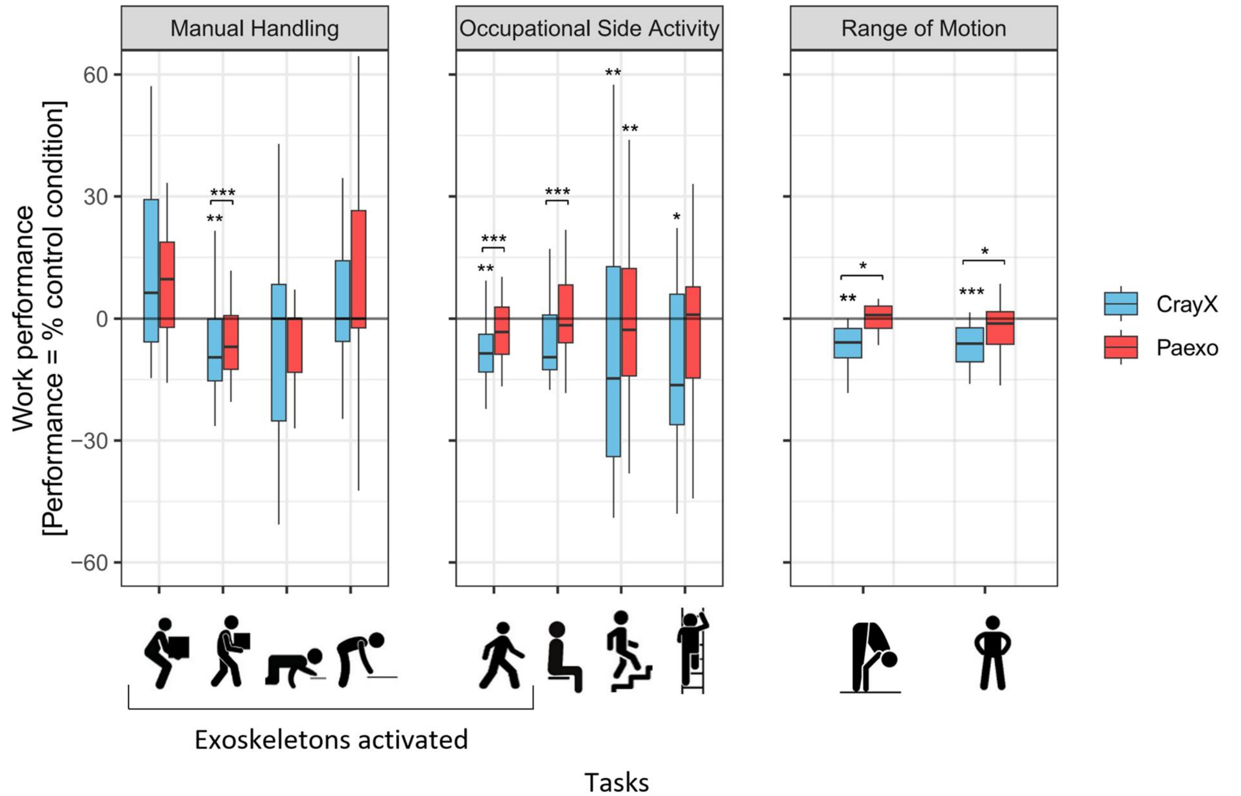

Figure 2. Change in objective work performance between the CrayX, Paexo Back and NoExo. Values were normalised to the NoExo condition to enhance comparison. Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$). Asterisks (*) on top of the bars indicate significant differences compared to NoExo. The CrayX exoskeleton hampered performance compared to the Paexo Back and NoExo. During most of the tasks, the Paexo Back was not associated with a change in work performance, compared to NoExo. Illustrated tasks in order are: lifting, load carrying, three-point kneeling, forward bending, walking, sit to stand, stair climbing, ladder climbing, trunk bending, wide stance. Trunk rotation and squatting were not included in the figure as no work performance measurements were obtained.

Similar to material handling category, the Paexo Back did not contribute to a significant change in work performance during the occupational side activities, with the exception of the stair climbing task where the exoskeleton significantly impaired performance time compared to NoExo (NoExo = 6.8 ± 1.6 s; Paexo = 7.7 ± 1.6 s; $p < .001$). In contrast to the Paexo Back exoskeleton, the CrayX significantly decreased work performance during the majority of the tasks included in the occupational side activity category, compared to NoExo (walking: NoExo = 558.6 ± 75.9 m, CrayX = 505.6 m ± 59.4 m, $p = .004$; stair climbing: NoExo = 6.8 s ± 1.6 s, CrayX = 8.3 ± 2.0 s, $p = .001$; ladder climbing: NoExo = 5.8 s ± 2.2 s, CrayX = 6.2 s ± 1.0 s, $p = .02$). However, during the sit-to-stand task, no significant difference between CrayX and NoExo was found. Furthermore, no significant difference in work performance between the CrayX and Paexo Back condition was observed for the stair task and ladder climbing task. For the six-minute walk test and the sit-to-stand task, the CrayX attributed to a significantly lower work performance compared to the Paexo Back (six-minute walking: Paexo = 537.7 ± 55.6 m, CrayX = 505.6 m ± 59.4 m, $p = .008$; sit-to-stand: Paexo = 9.1 ± 1.7 s, CrayX = 9.9 ± 1.8 s, $p = .03$).

During tasks included in the range of motion category, both trunk bending and wide stance were significantly more limited in the CrayX condition compared to the Paexo Back condition (trunk bending: CrayX = 7.7 ± 10.2 cm, Paexo = 2.5 ± 9.3 cm, $p = .02$; wide stance: CrayX = 116.7 ± 13.2 cm, Paexo = 121.4 ± 13.1 cm, $p < .001$). Moreover, the range of motion was significantly lower when wearing the CrayX compared to NoExo (trunk bending: NoExo = 1.6 ± 9.5 cm, $p = .001$; wide stance: NoExo = 125.1 ± 14.9 cm, $p = .01$) while no significant difference in range of motion between the Paexo Back and NoExo was observed.

3.2. Perceived task difficulty

Figure 3 displays the perceived task difficulty (%) as reported after the performance of each functional task

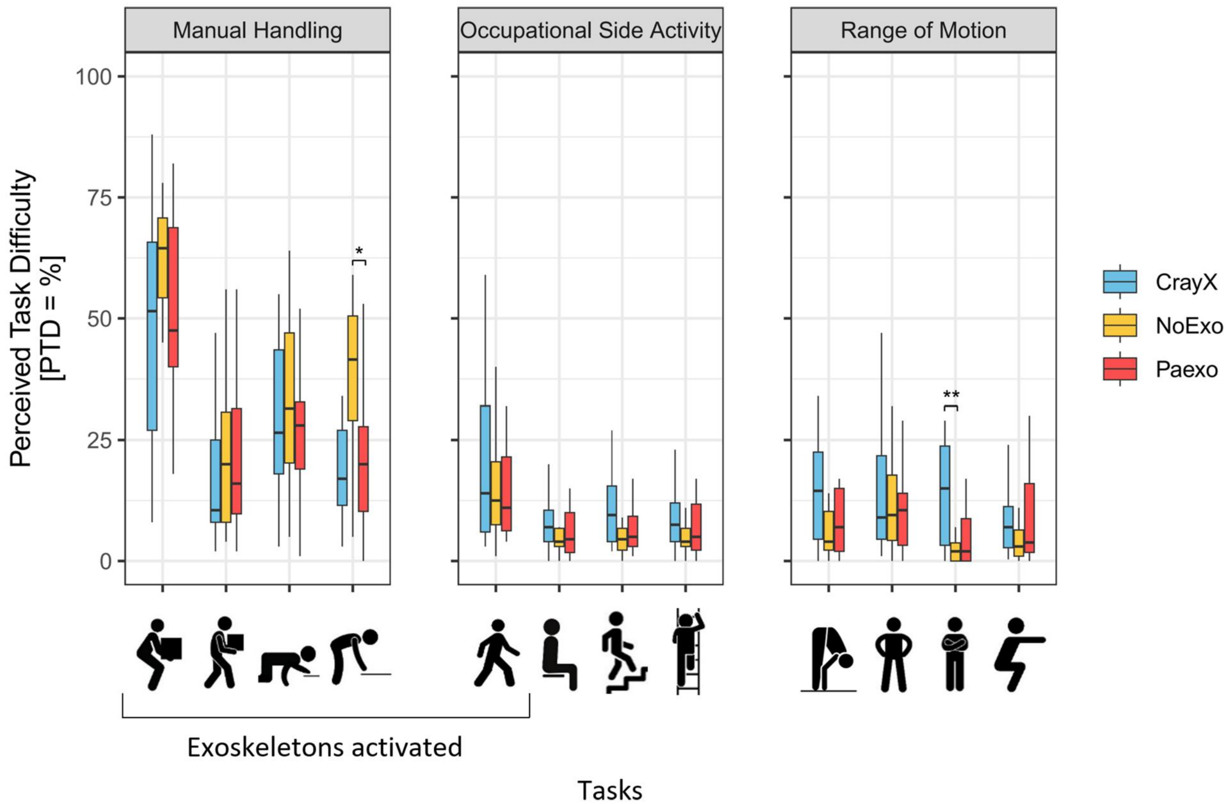

Figure 3. Difference in perceived task difficulty between the CrayX, Paexo Back and NoExo condition. Significance codes: ** ($p <$ .01); * ($p <$ .05). Compared to NoExo, perceived task difficulty significantly decreased when working with the Paexo Back during the static forward bending task. The CrayX significantly increased difficulty levels compared to NoExo during the rotation task. Illustrated tasks in order are: lifting, load carrying, three-point kneeling, forward bending, walking, sit to stand, stair climbing, ladder climbing, trunk bending, wide stance, trunk rotation, and squatting.

during the three different conditions (NoExo, Paexo Back, CrayX). During tasks included in the material handling category, the Paexo Back significantly decreased perceived task difficulty compared to NoExo (NoExo = 37.7 ± 15.4%; Paexo = 21.8 ± 15.4%; p = .03). In the other tasks of this category, no significant difference between the three conditions was found. During tasks included in the occupational side activity category, no significant differences between the three experimental conditions were found. During tasks included in the range of motion category, the CrayX significantly increased perceived task difficulty of the rotation task compared to NoExo (NoExo = 2.8 ± 3.7%; CrayX = 18.6 ± 20.5%; $p <$ .01). No significant difference between the other conditions was found in the other tasks.

3.3. General discomfort

Figure 4 displays the general discomfort (%) as reported after the performance of each functional task during the two exoskeleton conditions. During tasks included in the material handling category, no significant differences in general discomfort between the two exoskeleton conditions are present. During tasks included in the occupational side activity category, the CrayX exoskeleton attributed to a significantly higher discomfort score in the stair climbing task than the Paexo Back (CrayX = 28.9 ± 20.3%; Paexo = 14.3 ± 12.0%; p = .02). No significant differences between conditions in the other tasks in this category were found. During wide stance, the CrayX obtained a significantly higher general discomfort score than the Paexo Back (CrayX = 37.1 ± 21.3%; Paexo = 16.9 ± 16.9%; $p <$ .001). No other significant differences were found in tasks included in the range of motion category.

Overall, highest discomfort scores for both the exoskeletons were obtained during the performance of the strenuous tasks. Discomfort wearing the Paexo Back peaked during the lifting task (45.6 ± 15.9%), while the CrayX was perceived the most uncomfortable during the three-point kneeling task (43.9 ± 18.5%). Lowest discomfort scores were perceived during the ladder climbing task for both exoskeleton conditions (CrayX = 20.1 ± 17.3%, Paexo = 13.3 ± 12.1%).

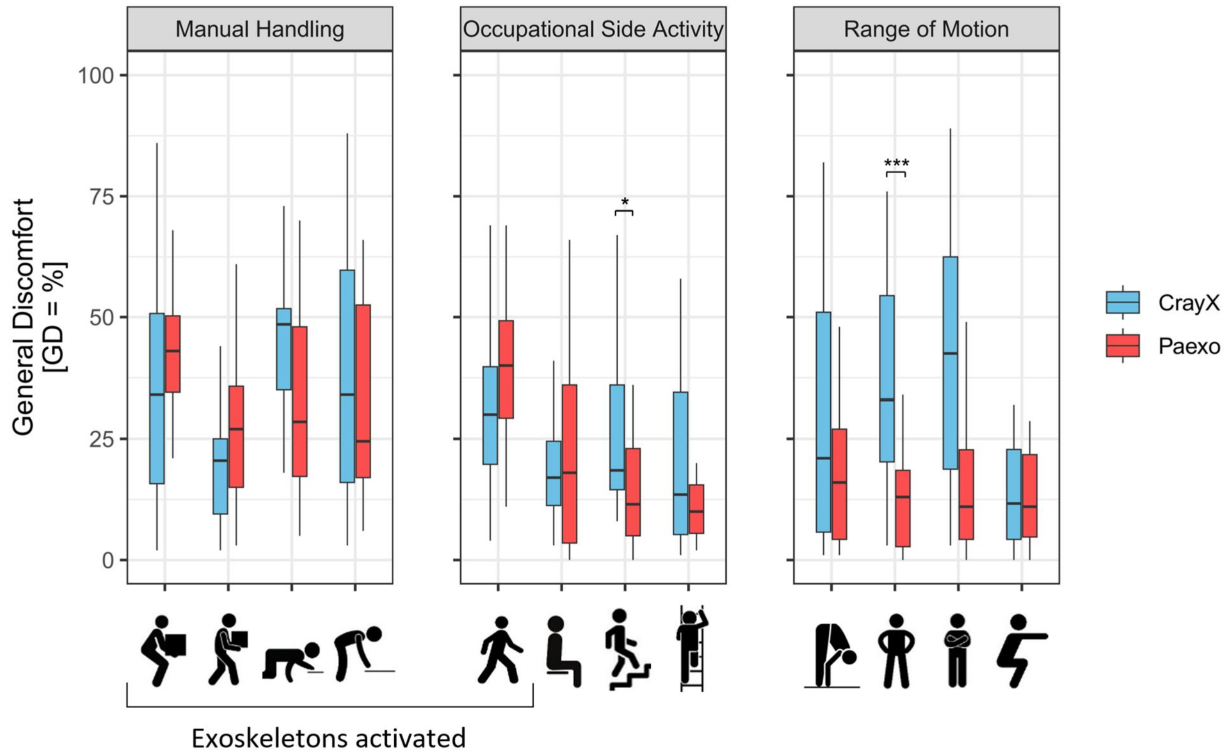

Figure 4. Difference in general discomfort between the CrayX and Paexo Back. Significance codes: *** ($p < .001$); * ($p < .05$). A significant difference between the two exoskeleton conditions was found during stair climbing and wide stance. Here, the CrayX consistently obtained the highest discomfort score. Illustrated tasks in order are: lifting, load carrying, three-point kneeling, forward bending, walking, sit to stand, stair climbing, ladder climbing, trunk bending, wide stance, trunk rotation, and squatting.

3.4. Relation work performance – perceived task difficulty – general discomfort

For all three task categories, Spearman's rank correlations were computed to assess the relationship between perceived task difficulty and general discomfort per exoskeleton. There was a positive correlation between the two conditions in all task categories and for both exoskeletons (material handling – Paexo Back: $r(16) = .49$, $p < .001$; material handling – CrayX: $r(16) = .42$, $p < .001$; occupational side activity – Paexo Back: $r(16) = .59$, $p < .001$; occupational side activity – CrayX: $r(16) = .59$, $p < .001$; range of motion – Paexo Back: $r(16) = .57$, $p < .001$; range of motion – CrayX: $r(16) = .49$, $p < .001$).

Furthermore, the relationship between general discomfort and work performance was investigated per task category and exoskeleton. A significant negative correlation between the two variables was found in the occupational side activity category as well as for the range of motion category, only in the Paexo-trials (occupational side activity – Paexo Back: $r(16) = .26$, $p = .03$; range of motion – Paexo Back: $r(16) = .26$, $p = .03$).

Lastly, in the occupation side activity and range of motion category, a significant positive correlation between BMI and general discomfort was found in the CrayX trials (occupational side activity – CrayX: $r(16) = .41$, $p < .001$; range of motion – CrayX: $r(16) = .36$, $p = .002$). Regarding the Paexo Back, this positive relation was solely present in the occupational side activity category ($r(16) = .27$, $p = .03$).

4. Discussion

The goal of this study was to evaluate the effect of an active and passive back exoskeleton, and the difference between them on users' functional performance i.e., work performance, perceived task difficulty and general discomfort, by means of a functional test battery. In this regard, the active CrayX and passive Paexo Back were selected. In summary, work performance was significantly more hindered by the CrayX compared to the Paexo Back and NoExo in half of the tasks, while the Paexo Back was often not associated with a change in work performance compared to NoExo. However, perceived task difficulty was not significantly different between the two exoskeletons and seldomly differed from NoExo. Furthermore, small differences in general discomfort between the active and passive back exoskeleton were reported throughout the performance of the test battery. Depending on the task category and exoskeleton condition, significant correlations between general discomfort, perceived task difficulty and work performance were found.

4.1. Manual handling category

In the material handling category, both exoskeletons did not affect work performance, apart from the load carrying performance, which will later be discussed in more detail. As outlined by Pesenti et al. (2021), exoskeletons are primarily designed to reduce the effort required for a task, as opposed to enhancing performance. However, perceived task difficulty was not significantly affected by the active CrayX, although a tendency to alleviate perceived task difficulty compared to NoExo can be observed. It is possible that the short duration of tasks as well as the relatively short familiarisation period limited the effects of the device. Furthermore, we can consider the significant relation between comfort and perceived task difficulty. Relatively high discomfort could have triggered participants to adjust their movements in order to avoid uncomfortable contact with the device, which would add to the task difficulty and therefore cancel out the beneficial support of the CrayX. However, since no causal relation is yet established, above-mentioned speculations should be further investigated in order to understand the limiting factors of the exoskeleton hereby improving the added value to the user.

The Paexo Back exoskeleton positively influenced perceived task difficulty during the static forward bending task, compared to NoExo, in contrast to the CrayX. A similar positive effect on perceived task difficulty was observed in the study of Baltrusch et al. (2018). However, perceived task difficulty levels of the dynamic tasks were not affected by the Paexo Back. The phenomenon of passive back support exoskeletons being more beneficial during static tasks rather than dynamic tasks has been suggested by other studies and can be attributed to the support mechanism (Poliero et al. 2022; Toxiri et al. 2019). Since the static forward bending task resisted trunk bending, thereby supporting the back extensor muscles, the task could be performed with less effort compared to NoExo. However, during dynamic tasks i.e., lifting and lowering a box, participants had to overcome the resistance that the exoskeleton provided during the lowering movement, thereby increasing their muscular efforts as compared to NoExo. This would limit the net-gain of the device since users only benefitted from the support for half of the movement i.e., lifting. Therefore, when implementing the Paexo Back in shop floors, the characteristics of the task that are predominantly present should be considered as static tasks seem more favourable. However, for the other included tasks, no differences in perceived task difficulty were observed, and conform the results of the CrayX, relatively high discomfort scores were reported. Previously mentioned significant relation between comfort and perceived task difficulty was also present for the Paexo Back during the first task category, possibly due to a similar reason as for the CrayX.

4.2. Walking performance

The Paexo Back did not affect load carrying time and walking distance. Furthermore, perceived task difficulty of these walking tasks was not influenced by the passive exoskeleton. Given that the Laevo V2.5 passive back exoskeleton (Laevo, B.V., Delft, Netherlands) was subjected to the same experimental protocol with similar outcome variables (Baltrusch et al. 2018), a comparison of the results is deemed appropriate. Results of the Paexo Back are in high contrast to the results of the Laevo exoskeleton. Although the support of the latter was deactivated to minimise resistance, the Laevo still significantly decreased walking performance while also increasing the perceived task difficulty of the walking task (Baltrusch et al. 2018). The Laevo exoskeleton's inability to distinguish between walking and trunk/hip-bending may explain its inferior performance compared to the Paexo Back. This suggests that a differentiation mechanism can improve exoskeleton compatibility with industrial work environments where walking is common.

Contrary to the Paexo Back, the CrayX was associated with a significant increase in carrying time and a significant decrease in walking distance. However, perceived task difficulty remained unaffected. We hypothese that the bulkiness of the device and/or the device's mass distribution could have hindered the users' walking pattern, e.g., arm swing was often hindered by the electrical motors located at the hip joint, leading to a slower work performance (Rodriguez-Cianca et al. 2019; Stirling et al. 2020). Although hypothesised to be small due to the unaffected perceived task difficulty, some level of resistance to the walking movement could also have led to a decreased walking performance.

4.3. Occupational side activities and range of motion category

The CrayX significantly decreased work performance of all tasks included in the occupational side activities and range of motion category compared to NoExo, with exception of the sit to stand task. In contrast, the Paexo Back only significantly impaired work performance during stair climbing compared to baseline. There was a general elevation of the perceived task difficulty scores for both exoskeletons compared to NoExo, and general discomfort scores ranked between 14% and 22% for the Paexo Back, and between 15% and 30% for the CrayX condition. We assume that the more rigid design of the CrayX, with most of the rigid structures located at the back and hips, hindered the hip and trunk range of motion to such extend that the instructed task could not be performed as usual (conform results obtained in NoExo condition). Furthermore, it is possible that the constraints imposed by the CrayX may have contributed to an (non-significant) increase in perceived task difficulty, as participants had to exert more effort in terms of overcoming the restrictions on their movements to achieve the proposed task goals.

In contrast, the more flexible design of the passive Paexo Back could have minimised hindrance in range of motion, hereby limiting its negative impact on work performance in the last two task categories (Näf et al. 2018). However, we also experienced difficulties in fitting the Paexo Back correctly in numerous participants, as reported by other researchers when fitting other passive back exoskeletons (Baltrusch et al. 2018; Huysamen et al. 2018). This often led to movements of the hip belt or even an upward shift of the entire device, which prevented the exoskeleton from functioning efficiently. As such we suggest that a balance between flexibility and rigidity should be considered in future designs in order to limit shifts of belts or straps (Langlois et al. 2018; Stirling et al. 2020) while maximising the range of motion of the user. Furthermore, designers should consider the positive relation between comfort and BMI, obtained for both exoskeletons during different tasks. Although the size of both exoskeletons was adjustable, it is possible that the one-fits-all design does not suffice for the variability in anthropometric characteristics of the users (Stirling et al. 2020).

4.4. Implications for ergonomists and exoskeleton developers

The distinct impact on functional performance between the active CrayX and passive Paexo Back exoskeleton highlights the necessity for careful consideration by ergonomists when selecting a specific exoskeleton. While the CrayX holds potential to benefit users during work performance, the findings of this study suggest that certain considerations should first be addressed to ensure its effectiveness and by extension, added value to the work environment. In this regard, hindrance to the range of motion of the user should be drastically limited. Contrary to the CrayX, depending on the frequency of having to perform static tasks, the passive Paexo Back has demonstrated its ability to provide an advantage to the user in certain static tasks. However, increasing its potential across a broader range of tasks seems warranted in order to maximise its utility. These results should emphasise the importance of functional performance of exoskeletons to companies and exoskeleton developers since challenges regarding hindering work performance or comfort of the user could hamper the successful implementation of exoskeletons in the shop floors.

4.5. Limitations and future research

The results of this study revealed a high degree of variability, as indicated by the large standard deviations. This suggests that individuals exhibit different responses to exoskeletons. However, the sample size in this investigation was not adequate to permit a detailed exploration of potential underlying factors that may account for these individual differences. Furthermore, a limited amount of objective performance outcome parameters was used in this experimental design. To enhance the understanding of the individual human-exoskeleton interaction, objective physiological measurements e.g., electromyography or energy expenditure, and biomechanical measurements, e.g. joint angles could be a helpful addition. Moreover, although active exoskeleton devices tend to weigh more than passive devices, the weight difference between the active and passive exoskeleton could potentially limit the generalisability of the observed correlations to other exoskeletons. Lastly, Kozinc et al. (2020) reported systematic effects of decreased task difficulty and discomfort for this test battery. Although the performance of the test battery was never repeated with the same exoskeleton, and the exoskeleton conditions as well as the order of tasks were randomised to counteract systematic effects, one should be aware that results refer to acute effects and may change if participants use the exoskeletons for a longer period of time.

5. Conclusion

The present study demonstrates a significant difference between the active CrayX and passive Paexo Back exoskeleton. The CrayX often hindered work performance and retained from affecting the perceived task difficulty, forming a strong impetus for designers to optimise the device's capabilities in order to increase the added value for as well as the acceptance of the user. In contrast, the Paexo Back did not contribute to changes in work performance and positively impacted perceived task difficulty during the performance of a static task. However, in order to enhance its functionality, benefits for the user should be pursued over a broader range of tasks. Importantly, both exoskeletons obtained relatively high general discomfort scores. This, in context of the significant relation between general discomfort and perceived task difficulty, highlights the need to exoskeleton developers to enhance the design in such way that comfort can be guaranteed during a versatile range of tasks.

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Appendix Table 1. Work Performance, Perceived Task Difficulty (P T), and General Discomfort (GD) ratings.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
1	Female	27.0538	NoExo	Lifting	25		74
1	Female	27.0538	Paexo	Lifting	30	51	73
1	Female	27.0538	CrayX	Lifting	32	15	74
1	Female	27.0538	NoExo	Load carrying	4.55		69
1	Female	27.0538	Paexo	Load carrying	5.45	52	36
1	Female	27.0538	CrayX	Load carrying	6.58	79	53
1	Female	27.0538	NoExo	Forward bending	300		59
1	Female	27.0538	Paexo	Forward bending	300	55	0
1	Female	27.0538	CrayX	Forward bending	300	16	11
1	Female	27.0538	NoExo	3-point kneeling	300		38
1	Female	27.0538	Paexo	3-point kneeling	300	29	1
1	Female	27.0538	CrayX	3-point kneeling	148	73	26
1	Female	27.0538	NoExo	Walking	540		19
1	Female	27.0538	Paexo	Walking	520	40	32
1	Female	27.0538	CrayX	Walking	490	69	40
1	Female	27.0538	NoExo	Sit to stand	11.11		16
1	Female	27.0538	Paexo	Sit to stand	12.61	24	10
1	Female	27.0538	CrayX	Sit to stand	11	38	13
1	Female	27.0538	NoExo	Stair climbing	8.3		9
1	Female	27.0538	Paexo	Stair climbing	9.13	18	16
1	Female	27.0538	CrayX	Stair climbing	11.77	67	10
1	Female	27.0538	NoExo	Ladder climbing	5.49		5
1	Female	27.0538	Paexo	Ladder climbing	6.26	18	15
1	Female	27.0538	CrayX	Ladder climbing	7	47	16
1	Female	27.0538	NoExo	Trunk bending	−2.5		1
1	Female	27.0538	Paexo	Trunk bending	12	13	1
1	Female	27.0538	CrayX	Trunk bending	−1	82	82
1	Female	27.0538	NoExo	Wide stance	99.7		7
1	Female	27.0538	Paexo	Wide stance	98.7	2	5
1	Female	27.0538	CrayX	Wide stance	95.2	33	9
1	Female	27.0538	NoExo	Trunk rotation			6
1	Female	27.0538	Paexo	Trunk rotation		48	17
1	Female	27.0538	CrayX	Trunk rotation		89	74
1	Female	27.0538	NoExo	Squatting			47
1	Female	27.0538	Paexo	Squatting		21	24
1	Female	27.0538	CrayX	Squatting		32	24
2	Male	24.22145	NoExo	Lifting	27		66
2	Male	24.22145	Paexo	Lifting	31	38	28
2	Male	24.22145	CrayX	Lifting	35	44	14
2	Male	24.22145	NoExo	Load carrying	5.3		4
2	Male	24.22145	Paexo	Load carrying	5.77	12	12
2	Male	24.22145	CrayX	Load carrying	6.7	25	10
2	Male	24.22145	NoExo	Forward bending	300		31
2	Male	24.22145	Paexo	Forward bending	173	22	3
2	Male	24.22145	CrayX	Forward bending	226	88	79
2	Male	24.22145	NoExo	3-point kneeling	300		7
2	Male	24.22145	Paexo	3-point kneeling	300	16	16
2	Male	24.22145	CrayX	3-point kneeling	300	35	18
2	Male	24.22145	NoExo	Walking	485		9
2	Male	24.22145	Paexo	Walking	500	16	4
2	Male	24.22145	CrayX	Walking	530	50	59
2	Male	24.22145	NoExo	Sit to stand	7.4		4
2	Male	24.22145	Paexo	Sit to stand	7.08	0	0
2	Male	24.22145	CrayX	Sit to stand	7.24	20	0
2	Male	24.22145	NoExo	Stair climbing	11.4		0
2	Male	24.22145	Paexo	Stair climbing	9.98	9	6
2	Male	24.22145	CrayX	Stair climbing	9.47	18	4
2	Male	24.22145	NoExo	Ladder climbing	6.1		0
2	Male	24.22145	Paexo	Ladder climbing	4.91	14	11
2	Male	24.22145	CrayX	Ladder climbing	5.18	24	10
2	Male	24.22145	NoExo	Trunk bending	−6		12
2	Male	24.22145	Paexo	Trunk bending	−3	12	12
2	Male	24.22145	CrayX	Trunk bending	3.5	18	0
2	Male	24.22145	NoExo	Wide stance	117.0		11
2	Male	24.22145	Paexo	Wide stance	117.0	12	7
2	Male	24.22145	CrayX	Wide stance	115.2	22	2
2	Male	24.22145	NoExo	Trunk rotation			0
2	Male	24.22145	Paexo	Trunk rotation		5	0
2	Male	24.22145	CrayX	Trunk rotation		16	0
2	Male	24.22145	NoExo	Squatting			0
2	Male	24.22145	Paexo	Squatting		0	0

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
2	Male	24.22145	CrayX	Squatting		21	3
3	Male	20.17301	NoExo	Lifting	35		72
3	Male	20.17301	Paexo	Lifting	34	34	71
3	Male	20.17301	CrayX	Lifting	31	18	23
3	Male	20.17301	NoExo	Load carrying	5.65		21
3	Male	20.17301	Paexo	Load carrying	5.61	29	40
3	Male	20.17301	CrayX	Load carrying	6.04	5	3
3	Male	20.17301	NoExo	Forward bending	205		44
3	Male	20.17301	Paexo	Forward bending	300	16	4
3	Male	20.17301	CrayX	Forward bending	224	13	17
3	Male	20.17301	NoExo	3-point kneeling	269		54
3	Male	20.17301	Paexo	3-point kneeling	288	25	19
3	Male	20.17301	CrayX	3-point kneeling	168	24	11
3	Male	20.17301	NoExo	Walking	510		18
3	Male	20.17301	Paexo	Walking	480	33	8
3	Male	20.17301	CrayX	Walking	440	28	15
3	Male	20.17301	NoExo	Sit to stand	8.22		6
3	Male	20.17301	Paexo	Sit to stand	7.71	17	4
3	Male	20.17301	CrayX	Sit to stand	9.3	16	11
3	Male	20.17301	NoExo	Stair climbing	6.62		6
3	Male	20.17301	Paexo	Stair climbing	6.81	5	7
3	Male	20.17301	CrayX	Stair climbing	8.94	14	7
3	Male	20.17301	NoExo	Ladder climbing	5.64		2
3	Male	20.17301	Paexo	Ladder climbing	6.48	3	5
3	Male	20.17301	CrayX	Ladder climbing	6.1	3	0
3	Male	20.17301	NoExo	Trunk bending	6.5		2
3	Male	20.17301	Paexo	Trunk bending	6.5	5	0
3	Male	20.17301	CrayX	Trunk bending	20.5	53	7
3	Male	20.17301	NoExo	Wide stance	108.3		32
3	Male	20.17301	Paexo	Wide stance	117.5	12	32
3	Male	20.17301	CrayX	Wide stance	97.7	23	6
3	Male	20.17301	NoExo	Trunk rotation			0
3	Male	20.17301	Paexo	Trunk rotation		0	0
3	Male	20.17301	CrayX	Trunk rotation		3	0
3	Male	20.17301	NoExo	Squatting			5
3	Male	20.17301	Paexo	Squatting		3	2
3	Male	20.17301	CrayX	Squatting		15	11
4	Male	22.92097	NoExo	Lifting	41		7
4	Male	22.92097	Paexo	Lifting	36	41	18
4	Male	22.92097	CrayX	Lifting	35	39	23
4	Male	22.92097	NoExo	Load carrying	5.32		11
4	Male	22.92097	Paexo	Load carrying	5.63	24	12
4	Male	22.92097	CrayX	Load carrying	5.37	25	23
4	Male	22.92097	NoExo	Forward bending	300		13
4	Male	22.92097	Paexo	Forward bending	300	44	28
4	Male	22.92097	CrayX	Forward bending	300	35	17
4	Male	22.92097	NoExo	3-point kneeling	243		19
4	Male	22.92097	Paexo	3-point kneeling	240	32	28
4	Male	22.92097	CrayX	3-point kneeling	219	54	24
4	Male	22.92097	NoExo	Walking	680		11
4	Male	22.92097	Paexo	Walking	620	28	11
4	Male	22.92097	CrayX	Walking	630	29	24
4	Male	22.92097	NoExo	Sit to stand	8.65		4
4	Male	22.92097	Paexo	Sit to stand	9.19	24	1
4	Male	22.92097	CrayX	Sit to stand	9.77	15	7
4	Male	22.92097	NoExo	Stair climbing	5.54		4
4	Male	22.92097	Paexo	Stair climbing	7.65	10	6
4	Male	22.92097	CrayX	Stair climbing	6.82	19	20
4	Male	22.92097	NoExo	Ladder climbing	4.66		3
4	Male	22.92097	Paexo	Ladder climbing	5.35	12	10
4	Male	22.92097	CrayX	Ladder climbing	5.85	19	12
4	Male	22.92097	NoExo	Trunk bending	−16.5		14
4	Male	22.92097	Paexo	Trunk bending	−9.5	27	17
4	Male	22.92097	CrayX	Trunk bending	−6.5	24	15
4	Male	22.92097	NoExo	Wide stance	146.7		8
4	Male	22.92097	Paexo	Wide stance	131.5	19	11
4	Male	22.92097	CrayX	Wide stance	129.0	36	14
4	Male	22.92097	NoExo	Trunk rotation			4
4	Male	22.92097	Paexo	Trunk rotation		11	8
4	Male	22.92097	CrayX	Trunk rotation		17	7
4	Male	22.92097	NoExo	Squatting			7

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
4	Male	22.92097	Paexo	Squatting		13	10
4	Male	22.92097	CrayX	Squatting		15	9
5	Male	24.4898	NoExo	Lifting	36		55
5	Male	24.4898	Paexo	Lifting	43	34	34
5	Male	24.4898	CrayX	Lifting	35	33	39
5	Male	24.4898	NoExo	Load carrying	5.45		27
5	Male	24.4898	Paexo	Load carrying	5.06	3	2
5	Male	24.4898	CrayX	Load carrying	5.44	5	6
5	Male	24.4898	NoExo	Forward bending	199		46
5	Male	24.4898	Paexo	Forward bending	254.15	10	9
5	Male	24.4898	CrayX	Forward bending	264	33	19
5	Male	24.4898	NoExo	3-point kneeling	214		49
5	Male	24.4898	Paexo	3-point kneeling	122	12	12
5	Male	24.4898	CrayX	3-point kneeling	257	48	34
5	Male	24.4898	NoExo	Walking	600		14
5	Male	24.4898	Paexo	Walking	590	21	4
5	Male	24.4898	CrayX	Walking	550	6	10
5	Male	24.4898	NoExo	Sit to stand	10.42		20
5	Male	24.4898	Paexo	Sit to stand	8.15	2	1
5	Male	24.4898	CrayX	Sit to stand	8.64	12	3
5	Male	24.4898	NoExo	Stair climbing	6.34		5
5	Male	24.4898	Paexo	Stair climbing	5.55	7	3
5	Male	24.4898	CrayX	Stair climbing	6.48	8	2
5	Male	24.4898	NoExo	Ladder climbing	5.26		10
5	Male	24.4898	Paexo	Ladder climbing	4.91	8	3
5	Male	24.4898	CrayX	Ladder climbing	5.47	5	2
5	Male	24.4898	NoExo	Trunk bending	−0.2		11
5	Male	24.4898	Paexo	Trunk bending	3	19	3
5	Male	24.4898	CrayX	Trunk bending	7	2	2
5	Male	24.4898	NoExo	Wide stance	116.7		13
5	Male	24.4898	Paexo	Wide stance	111.0	6	2
5	Male	24.4898	CrayX	Wide stance	109.0	53	3
5	Male	24.4898	NoExo	Trunk rotation			1
5	Male	24.4898	Paexo	Trunk rotation		4	1
5	Male	24.4898	CrayX	Trunk rotation		8	2
5	Male	24.4898	NoExo	Squatting			3
5	Male	24.4898	Paexo	Squatting		15	2
5	Male	24.4898	CrayX	Squatting		3	3
6	Female	22.9854	NoExo	Lifting	18		62
6	Female	22.9854	Paexo	Lifting	24	32	48
6	Female	22.9854	CrayX	Lifting	27	53	69
6	Female	22.9854	NoExo	Load carrying	5.23		33
6	Female	22.9854	Paexo	Load carrying	6.22	36	16
6	Female	22.9854	CrayX	Load carrying	6.32	42	8
6	Female	22.9854	NoExo	Forward bending	300		41
6	Female	22.9854	Paexo	Forward bending	300	25	15
6	Female	22.9854	CrayX	Forward bending	297	56	9
6	Female	22.9854	NoExo	3-point kneeling	250		61
6	Female	22.9854	Paexo	3-point kneeling	248	48	35
6	Female	22.9854	CrayX	3-point kneeling	185	51	49
6	Female	22.9854	NoExo	Walking	480		45
6	Female	22.9854	Paexo	Walking	490	50	20
6	Female	22.9854	CrayX	Walking	480	19	5
6	Female	22.9854	NoExo	Sit to stand	9.18		4
6	Female	22.9854	Paexo	Sit to stand	9.63	5	4
6	Female	22.9854	CrayX	Sit to stand	10.03	20	8
6	Female	22.9854	NoExo	Stair climbing	8.21		5
6	Female	22.9854	Paexo	Stair climbing	8.87	23	10
6	Female	22.9854	CrayX	Stair climbing	11.17	17	4
6	Female	22.9854	NoExo	Ladder climbing	6.43		3
6	Female	22.9854	Paexo	Ladder climbing	6.34	8	3
6	Female	22.9854	CrayX	Ladder climbing	8.3	36	12
6	Female	22.9854	NoExo	Trunk bending	−3.5		3
6	Female	22.9854	Paexo	Trunk bending	−3	2	2
6	Female	22.9854	CrayX	Trunk bending	15.5	52	14
6	Female	22.9854	NoExo	Wide stance	120.8		19
6	Female	22.9854	Paexo	Wide stance	110.3	2	29
6	Female	22.9854	CrayX	Wide stance	116.5	16	7
6	Female	22.9854	NoExo	Trunk rotation			7
6	Female	22.9854	Paexo	Trunk rotation		8	0
6	Female	22.9854	CrayX	Trunk rotation		42	27

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
6	Female	22.9854	NoExo	Squatting			35
6	Female	22.9854	Paexo	Squatting		8	22
6	Female	22.9854	CrayX	Squatting		23	26
7	Male	22.02432	NoExo	Lifting	30		66
7	Male	22.02432	Paexo	Lifting	34	21	38
7	Male	22.02432	CrayX	Lifting	32	9	8
7	Male	22.02432	NoExo	Load carrying	4.62		16
7	Male	22.02432	Paexo	Load carrying	4.7	9	6
7	Male	22.02432	CrayX	Load carrying	5.84	7	11
7	Male	22.02432	NoExo	Forward bending	139		49
7	Male	22.02432	Paexo	Forward bending	300	11	21
7	Male	22.02432	CrayX	Forward bending	279	15	4
7	Male	22.02432	NoExo	3-point kneeling	300		32
7	Male	22.02432	Paexo	3-point kneeling	156	6	29
7	Male	22.02432	CrayX	3-point kneeling	189	18	18
7	Male	22.02432	NoExo	Walking	640		9
7	Male	22.02432	Paexo	Walking	620	11	10
7	Male	22.02432	CrayX	Walking	540	40	6
7	Male	22.02432	NoExo	Sit to stand	8.59		7
7	Male	22.02432	Paexo	Sit to stand	9.02	44	4
7	Male	22.02432	CrayX	Sit to stand	9.57	6	4
7	Male	22.02432	NoExo	Stair climbing	5.39		4
7	Male	22.02432	Paexo	Stair climbing	5.39	5	2
7	Male	22.02432	CrayX	Stair climbing	6.25	10	12
7	Male	22.02432	NoExo	Ladder climbing	3.9		4
7	Male	22.02432	Paexo	Ladder climbing	4.26	13	12
7	Male	22.02432	CrayX	Ladder climbing	4.94	4	6
7	Male	22.02432	NoExo	Trunk bending	4		6
7	Male	22.02432	Paexo	Trunk bending	3	3	4
7	Male	22.02432	CrayX	Trunk bending	6	8	21
7	Male	22.02432	NoExo	Wide stance	131.6		18
7	Male	22.02432	Paexo	Wide stance	136.3	14	4
7	Male	22.02432	CrayX	Wide stance	133.7	20	12
7	Male	22.02432	NoExo	Trunk rotation			2
7	Male	22.02432	Paexo	Trunk rotation		3	1
7	Male	22.02432	CrayX	Trunk rotation		18	20
7	Male	22.02432	NoExo	Squatting			4
7	Male	22.02432	Paexo	Squatting		8	4
7	Male	22.02432	CrayX	Squatting		6	4
8	Female	24.3152	NoExo	Lifting	26		77
8	Female	24.3152	Paexo	Lifting	24	30	42
8	Female	24.3152	CrayX	Lifting	23	2	59
8	Female	24.3152	NoExo	Load carrying	5.97		19
8	Female	24.3152	Paexo	Load carrying	6.51	28	19
8	Female	24.3152	CrayX	Load carrying	6.7	6	5
8	Female	24.3152	NoExo	Forward bending	300		42
8	Female	24.3152	Paexo	Forward bending	300	22	20
8	Female	24.3152	CrayX	Forward bending	263	44	13
8	Female	24.3152	NoExo	3-point kneeling	300		24
8	Female	24.3152	Paexo	3-point kneeling	300	24	28
8	Female	24.3152	CrayX	3-point kneeling	232	38	27
8	Female	24.3152	NoExo	Walking	560		22
8	Female	24.3152	Paexo	Walking	490	46	4
8	Female	24.3152	CrayX	Walking	480	5	5
8	Female	24.3152	NoExo	Sit to stand	9.33		3
8	Female	24.3152	Paexo	Sit to stand	7.83	3	1
8	Female	24.3152	CrayX	Sit to stand	8.63	3	4
8	Female	24.3152	NoExo	Stair climbing	6.38		2
8	Female	24.3152	Paexo	Stair climbing	7.93	23	4
8	Female	24.3152	CrayX	Stair climbing	8.35	11	9
8	Female	24.3152	NoExo	Ladder climbing	5.11		6
8	Female	24.3152	Paexo	Ladder climbing	5.38	5	2
8	Female	24.3152	CrayX	Ladder climbing	6.21	6	4
8	Female	24.3152	NoExo	Trunk bending	−3.5		1
8	Female	24.3152	Paexo	Trunk bending	−4	4	1
8	Female	24.3152	CrayX	Trunk bending	−3	1	3
8	Female	24.3152	NoExo	Wide stance	113.8		0
8	Female	24.3152	Paexo	Wide stance	98.0	5	3
8	Female	24.3152	CrayX	Wide stance	101.3	19	1
8	Female	24.3152	NoExo	Trunk rotation			0
8	Female	24.3152	Paexo	Trunk rotation		24	2

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
8	Female	24.3152	CrayX	Trunk rotation		58	2
8	Female	24.3152	NoExo	Squatting			0
8	Female	24.3152	Paexo	Squatting		5	3
8	Female	24.3152	CrayX	Squatting		0	3
9	Female	21.4876	NoExo	Lifting	30		45
9	Female	21.4876	Paexo	Lifting	35	36	40
9	Female	21.4876	CrayX	Lifting	39	15	15
9	Female	21.4876	NoExo	Load carrying	5.16		23
9	Female	21.4876	Paexo	Load carrying	5.12	20	16
9	Female	21.4876	CrayX	Load carrying	5.95	44	21
9	Female	21.4876	NoExo	Forward bending	247		29
9	Female	21.4876	Paexo	Forward bending	240	20	18
9	Female	21.4876	CrayX	Forward bending	300	16	13
9	Female	21.4876	NoExo	3-point kneeling	300		6
9	Female	21.4876	Paexo	3-point kneeling	300	21	19
9	Female	21.4876	CrayX	3-point kneeling	300	22	20
9	Female	21.4876	NoExo	Walking	610		5
9	Female	21.4876	Paexo	Walking	600	43	22
9	Female	21.4876	CrayX	Walking	590	24	14
9	Female	21.4876	NoExo	Sit to stand	10.02		17
9	Female	21.4876	Paexo	Sit to stand	9.13	36	15
9	Female	21.4876	CrayX	Sit to stand	9.06	25	17
9	Female	21.4876	NoExo	Stair climbing	7.61		15
9	Female	21.4876	Paexo	Stair climbing	8.85	31	17
9	Female	21.4876	CrayX	Stair climbing	11.34	33	14
9	Female	21.4876	NoExo	Ladder climbing	5.48		6
9	Female	21.4876	Paexo	Ladder climbing	5.45	16	17
9	Female	21.4876	CrayX	Ladder climbing	6.92	33	14
9	Female	21.4876	NoExo	Trunk bending	−7		2
9	Female	21.4876	Paexo	Trunk bending	−10	22	15
9	Female	21.4876	CrayX	Trunk bending	−4	18	20
9	Female	21.4876	NoExo	Wide stance	110.8		6
9	Female	21.4876	Paexo	Wide stance	115.8	16	14
9	Female	21.4876	CrayX	Wide stance	109.3	18	15
9	Female	21.4876	NoExo	Trunk rotation			1
9	Female	21.4876	Paexo	Trunk rotation		12	4
9	Female	21.4876	CrayX	Trunk rotation		21	12
9	Female	21.4876	NoExo	Squatting			7
9	Female	21.4876	Paexo	Squatting		10	10
9	Female	21.4876	CrayX	Squatting		14	11
10	Male	27.99474	NoExo	Lifting	33		64
10	Male	27.99474	Paexo	Lifting	37	39	81
10	Male	27.99474	CrayX	Lifting	40	56	47
10	Male	27.99474	NoExo	Load carrying	4.7		17
10	Male	27.99474	Paexo	Load carrying	5.34	15	56
10	Male	27.99474	CrayX	Load carrying	5.25	17	9
10	Male	27.99474	NoExo	Forward bending	93		28
10	Male	27.99474	Paexo	Forward bending	153	66	26
10	Male	27.99474	CrayX	Forward bending	102	67	33
10	Male	27.99474	NoExo	3-point kneeling	101		41
10	Male	27.99474	Paexo	3-point kneeling	102	48	34
10	Male	27.99474	CrayX	3-point kneeling	161	35	44
10	Male	27.99474	NoExo	Walking	540		7
10	Male	27.99474	Paexo	Walking	470	64	11
10	Male	27.99474	CrayX	Walking	420	39	14
10	Male	27.99474	NoExo	Sit to stand	7.32		2
10	Male	27.99474	Paexo	Sit to stand	7.45	19	58
10	Male	27.99474	CrayX	Sit to stand	7.47	41	20
10	Male	27.99474	NoExo	Stair climbing	4.92		1
10	Male	27.99474	Paexo	Stair climbing	5.53	34	5
10	Male	27.99474	CrayX	Stair climbing	6.57	50	27
10	Male	27.99474	NoExo	Ladder climbing	4.39		1
10	Male	27.99474	Paexo	Ladder climbing	5.28	20	2
10	Male	27.99474	CrayX	Ladder climbing	5.22	58	23
10	Male	27.99474	NoExo	Trunk bending	−1		3
10	Male	27.99474	Paexo	Trunk bending	−4	11	4
10	Male	27.99474	CrayX	Trunk bending	11	55	2
10	Male	27.99474	NoExo	Wide stance	143.7		2
10	Male	27.99474	Paexo	Wide stance	140.8	34	12
10	Male	27.99474	CrayX	Wide stance	128.0	66	28
10	Male	27.99474	NoExo	Trunk rotation			15

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
10	Male	27.99474	Paexo	Trunk rotation		61	22
10	Male	27.99474	CrayX	Trunk rotation		46	7
10	Male	27.99474	NoExo	Squatting			1
10	Male	27.99474	Paexo	Squatting		62	30
10	Male	27.99474	CrayX	Squatting		7	3
11	Female	19.98282	NoExo	Lifting	14		67
11	Female	19.98282	Paexo	Lifting	18	48	82
11	Female	19.98282	CrayX	Lifting	22	29	68
11	Female	19.98282	NoExo	Load carrying	5.23		23
11	Female	19.98282	Paexo	Load carrying	5.65	12	33
11	Female	19.98282	CrayX	Load carrying	6.03	21	39
11	Female	19.98282	NoExo	Forward bending	167		29
11	Female	19.98282	Paexo	Forward bending	166	24	38
11	Female	19.98282	CrayX	Forward bending	150	27	24
11	Female	19.98282	NoExo	3-point kneeling	170		24
11	Female	19.98282	Paexo	3-point kneeling	173	28	35
11	Female	19.98282	CrayX	3-point kneeling	243	51	32
11	Female	19.98282	NoExo	Walking	570		14
11	Female	19.98282	Paexo	Walking	520	22	26
11	Female	19.98282	CrayX	Walking	520	39	40
11	Female	19.98282	NoExo	Sit to stand	10.3		4
11	Female	19.98282	Paexo	Sit to stand	10.45	1	1
11	Female	19.98282	CrayX	Sit to stand	11.25	18	5
11	Female	19.98282	NoExo	Stair climbing	6.83		8
11	Female	19.98282	Paexo	Stair climbing	7.01	1	1
11	Female	19.98282	CrayX	Stair climbing	7.75	33	5
11	Female	19.98282	NoExo	Ladder climbing	5.58		7
11	Female	19.98282	Paexo	Ladder climbing	5.17	2	2
11	Female	19.98282	CrayX	Ladder climbing	6.35	1	1
11	Female	19.98282	NoExo	Trunk bending	9		57
11	Female	19.98282	Paexo	Trunk bending	6	1	17
11	Female	19.98282	CrayX	Trunk bending	17	3	34
11	Female	19.98282	NoExo	Wide stance	128.5		16
11	Female	19.98282	Paexo	Wide stance	132.2	1	14
11	Female	19.98282	CrayX	Wide stance	130.3	33	24
11	Female	19.98282	NoExo	Trunk rotation			3
11	Female	19.98282	Paexo	Trunk rotation		1	2
11	Female	19.98282	CrayX	Trunk rotation		22	7
11	Female	19.98282	NoExo	Squatting			3
11	Female	19.98282	Paexo	Squatting		1	0
11	Female	19.98282	CrayX	Squatting		4	1
12	Male	25.66115	NoExo	Lifting	42		65
12	Male	25.66115	Paexo	Lifting	45	47	47
12	Male	25.66115	CrayX	Lifting	43	58	70
12	Male	25.66115	NoExo	Load carrying	5.19		7
12	Male	25.66115	Paexo	Load carrying	5.97	26	6
12	Male	25.66115	CrayX	Load carrying	5.85	20	8
12	Male	25.66115	NoExo	Forward bending	300		36
12	Male	25.66115	Paexo	Forward bending	300	14	8
12	Male	25.66115	CrayX	Forward bending	300	76	14
12	Male	25.66115	NoExo	3-point kneeling	300		41
12	Male	25.66115	Paexo	3-point kneeling	300	14	20
12	Male	25.66115	CrayX	3-point kneeling	300	77	11
12	Male	25.66115	NoExo	Walking	490		3
12	Male	25.66115	Paexo	Walking	540	40	4
12	Male	25.66115	CrayX	Walking	510	18	4
12	Male	25.66115	NoExo	Sit to stand	9.82		5
12	Male	25.66115	Paexo	Sit to stand	9.65	66	9
12	Male	25.66115	CrayX	Sit to stand	10.9	23	5
12	Male	25.66115	NoExo	Stair climbing	6.07		6
12	Male	25.66115	Paexo	Stair climbing	6.96	13	4
12	Male	25.66115	CrayX	Stair climbing	8.14	67	16
12	Male	25.66115	NoExo	Ladder climbing	4.7		3
12	Male	25.66115	Paexo	Ladder climbing	5.81	34	5
12	Male	25.66115	CrayX	Ladder climbing	5.65	35	6
12	Male	25.66115	NoExo	Trunk bending	14		4
12	Male	25.66115	Paexo	Trunk bending	13.5	27	11
12	Male	25.66115	CrayX	Trunk bending	20	61	52
12	Male	25.66115	NoExo	Wide stance	138.0		5
12	Male	25.66115	Paexo	Wide stance	136.2	47	12
12	Male	25.66115	CrayX	Wide stance	135.3	50	9

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
12	Male	25.66115	NoExo	Trunk rotation			2
12	Male	25.66115	Paexo	Trunk rotation		14	4
12	Male	25.66115	CrayX	Trunk rotation		73	18
12	Male	25.66115	NoExo	Squatting			3
12	Male	25.66115	Paexo	Squatting		12	5
12	Male	25.66115	CrayX	Squatting		30	8
13	Male	20.81165	NoExo	Lifting	42		59
13	Male	20.81165	Paexo	Lifting	44	45	42
13	Male	20.81165	CrayX	Lifting	36	26	56
13	Male	20.81165	NoExo	Load carrying	5.51		35
13	Male	20.81165	Paexo	Load carrying	5.11	35	17
13	Male	20.81165	CrayX	Load carrying	5.43	43	25
13	Male	20.81165	NoExo	Forward bending	226		16
13	Male	20.81165	Paexo	Forward bending	209	45	27
13	Male	20.81165	CrayX	Forward bending	260	52	19
13	Male	20.81165	NoExo	3-point kneeling	300		60
13	Male	20.81165	Paexo	3-point kneeling	219	66	28
13	Male	20.81165	CrayX	3-point kneeling	161	50	45
13	Male	20.81165	NoExo	Walking	550		21
13	Male	20.81165	Paexo	Walking	570	35	6
13	Male	20.81165	CrayX	Walking	510	4	6
13	Male	20.81165	NoExo	Sit to stand	8.9		5
13	Male	20.81165	Paexo	Sit to stand	7.78	36	5
13	Male	20.81165	CrayX	Sit to stand	8.84	4	0
13	Male	20.81165	NoExo	Stair climbing	5.23		20
13	Male	20.81165	Paexo	Stair climbing	6.03	14	10
13	Male	20.81165	CrayX	Stair climbing	5.68	16	4
13	Male	20.81165	NoExo	Ladder climbing	5.34		9
13	Male	20.81165	Paexo	Ladder climbing	4.92	10	4
13	Male	20.81165	CrayX	Ladder climbing	5.65	9	3
13	Male	20.81165	NoExo	Trunk bending	27		65
13	Male	20.81165	Paexo	Trunk bending	29	46	60
13	Male	20.81165	CrayX	Trunk bending	28.8	3	31
13	Male	20.81165	NoExo	Wide stance	127.3		19
13	Male	20.81165	Paexo	Wide stance	124.5	49	17
13	Male	20.81165	CrayX	Wide stance	110.7	21	9
13	Male	20.81165	NoExo	Trunk rotation			2
13	Male	20.81165	Paexo	Trunk rotation		49	9
13	Male	20.81165	CrayX	Trunk rotation		66	29
13	Male	20.81165	NoExo	Squatting			1
13	Male	20.81165	Paexo	Squatting		29	26
13	Male	20.81165	CrayX	Squatting		1	0
14	Male	25.08286	NoExo	Lifting	34		25
14	Male	25.08286	Paexo	Lifting	30	68	58
14	Male	25.08286	CrayX	Lifting	36	35	42
14	Male	25.08286	NoExo	Load carrying	5.86		5
14	Male	25.08286	Paexo	Load carrying	4.66	51	9
14	Male	25.08286	CrayX	Load carrying	5.43	20	2
14	Male	25.08286	NoExo	Forward bending	300		5
14	Male	25.08286	Paexo	Forward bending	274	63	20
14	Male	25.08286	CrayX	Forward bending	139	3	3
14	Male	25.08286	NoExo	3-point kneeling	270		5
14	Male	25.08286	Paexo	3-point kneeling	162	48	29
14	Male	25.08286	CrayX	3-point kneeling	300	62	3
14	Male	25.08286	NoExo	Walking	720		1
14	Male	25.08286	Paexo	Walking	600	54	16
14	Male	25.08286	CrayX	Walking	490	65	3
14	Male	25.08286	NoExo	Sit to stand	9.16		2
14	Male	25.08286	Paexo	Sit to stand	7.6	38	10
14	Male	25.08286	CrayX	Sit to stand	10.05	46	9
14	Male	25.08286	NoExo	Stair climbing	5.58		3
14	Male	25.08286	Paexo	Stair climbing	6.23	36	3
14	Male	25.08286	CrayX	Stair climbing	7.17	37	2
14	Male	25.08286	NoExo	Ladder climbing	4.41		0
14	Male	25.08286	Paexo	Ladder climbing	4.97	10	0
14	Male	25.08286	CrayX	Ladder climbing	5.39	39	8
14	Male	25.08286	NoExo	Trunk bending	−3		0
14	Male	25.08286	Paexo	Trunk bending	−5	44	2
14	Male	25.08286	CrayX	Trunk bending	−3	48	6
14	Male	25.08286	NoExo	Wide stance	134.3		3
14	Male	25.08286	Paexo	Wide stance	134.7	17	0

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
14	Male	25.08286	CrayX	Wide stance	130.0	55	4
14	Male	25.08286	NoExo	Trunk rotation			0
14	Male	25.08286	Paexo	Trunk rotation		0	0
14	Male	25.08286	CrayX	Trunk rotation		73	23
14	Male	25.08286	NoExo	Squatting			1
14	Male	25.08286	Paexo	Squatting		0	0
14	Male	25.08286	CrayX	Squatting		54	55
15	Female	23.33412	NoExo	Lifting	24		77
15	Female	23.33412	Paexo	Lifting	31	79	73
15	Female	23.33412	CrayX	Lifting	32	2	59
15	Female	23.33412	NoExo	Load carrying	5.2		56
15	Female	23.33412	Paexo	Load carrying	5.81	61	55
15	Female	23.33412	CrayX	Load carrying	6.32	2	47
15	Female	23.33412	NoExo	Forward bending	210		51
15	Female	23.33412	Paexo	Forward bending	300	57	14
15	Female	23.33412	CrayX	Forward bending	195	7	28
15	Female	23.33412	NoExo	3-point kneeling	210		64
15	Female	23.33412	Paexo	3-point kneeling	180	56	52
15	Female	23.33412	CrayX	3-point kneeling	300	6	17
15	Female	23.33412	NoExo	Walking	530		10
15	Female	23.33412	Paexo	Walking	560	69	18
15	Female	23.33412	CrayX	Walking	470	22	11
15	Female	23.33412	NoExo	Sit to stand	10.65		32
15	Female	23.33412	Paexo	Sit to stand	12.6	59	46
15	Female	23.33412	CrayX	Sit to stand	11.75	54	33
15	Female	23.33412	NoExo	Stair climbing	6.33		7
15	Female	23.33412	Paexo	Stair climbing	9.81	26	12
15	Female	23.33412	CrayX	Stair climbing	9.97	16	21
15	Female	23.33412	NoExo	Ladder climbing	14.12		11
15	Female	23.33412	Paexo	Ladder climbing	7.87	51	35
15	Female	23.33412	CrayX	Ladder climbing	7.34	15	56
15	Female	23.33412	NoExo	Trunk bending	8.5		4
15	Female	23.33412	Paexo	Trunk bending	5.5	48	15
15	Female	23.33412	CrayX	Trunk bending	16.5	44	7
15	Female	23.33412	NoExo	Wide stance	118.0		19
15	Female	23.33412	Paexo	Wide stance	110.0	17	10
15	Female	23.33412	CrayX	Wide stance	106.7	68	30
15	Female	23.33412	NoExo	Trunk rotation			3
15	Female	23.33412	Paexo	Trunk rotation		10	11
15	Female	23.33412	CrayX	Trunk rotation		64	24
15	Female	23.33412	NoExo	Squatting			4
15	Female	23.33412	Paexo	Squatting		48	4
15	Female	23.33412	CrayX	Squatting		5	6
16	Male	22.94409	NoExo	Lifting	38		54
16	Male	22.94409	Paexo	Lifting	32	78	59
16	Male	22.94409	CrayX	Lifting	36	56	59
16	Male	22.94409	NoExo	Load carrying	5.64		5
16	Male	22.94409	Paexo	Load carrying	5.14	43	14
16	Male	22.94409	CrayX	Load carrying	5.38	23	25
16	Male	22.94409	NoExo	Forward bending	300		52
16	Male	22.94409	Paexo	Forward bending	300	62	53
16	Male	22.94409	CrayX	Forward bending	300	64	52
16	Male	22.94409	NoExo	3-point kneeling	300		7
16	Male	22.94409	Paexo	3-point kneeling	300	70	49
16	Male	22.94409	CrayX	3-point kneeling	300	52	46
16	Male	22.94409	NoExo	Walking	570		24
16	Male	22.94409	Paexo	Walking	520	37	7
16	Male	22.94409	CrayX	Walking	510	50	36
16	Male	22.94409	NoExo	Sit to stand	8.05		3
16	Male	22.94409	Paexo	Sit to stand	8.23	11	6
16	Male	22.94409	CrayX	Sit to stand	9.46	11	3
16	Male	22.94409	NoExo	Stair climbing	7.35		4
16	Male	22.94409	Paexo	Stair climbing	8.09	0	5
16	Male	22.94409	CrayX	Stair climbing	8.37	28	4
16	Male	22.94409	NoExo	Ladder climbing	6.5		4
16	Male	22.94409	Paexo	Ladder climbing	8.65	7	0
16	Male	22.94409	CrayX	Ladder climbing	7.1	11	4
16	Male	22.94409	NoExo	Trunk bending	3.5		4
16	Male	22.94409	Paexo	Trunk bending	6	21	10
16	Male	22.94409	CrayX	Trunk bending	3.5	34	23
16	Male	22.94409	NoExo	Wide stance	157.6		4

(*continued*)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
16	Male	22.94409	Paexo	Wide stance	131.7	0	0
16	Male	22.94409	CrayX	Wide stance	132.3	56	35
16	Male	22.94409	NoExo	Trunk rotation			0
16	Male	22.94409	Paexo	Trunk rotation		22	0
16	Male	22.94409	CrayX	Trunk rotation		30	0
16	Male	22.94409	NoExo	Squatting			0
16	Male	22.94409	Paexo	Squatting		22	0
16	Male	22.94409	CrayX	Squatting		9	2
17	Female	21.10727	NoExo	Lifting	24		78
17	Female	21.10727	Paexo	Lifting	24	55	62
17	Female	21.10727	CrayX	Lifting	27	35	43
17	Female	21.10727	NoExo	Load carrying	8.11		32
17	Female	21.10727	Paexo	Load carrying	8.64	28	27
17	Female	21.10727	CrayX	Load carrying	9.01	22	32
17	Female	21.10727	NoExo	Forward bending	173		56
17	Female	21.10727	Paexo	Forward bending	159	6	40
17	Female	21.10727	CrayX	Forward bending	193	61	34
17	Female	21.10727	NoExo	3-point kneeling	140		31
17	Female	21.10727	Paexo	3-point kneeling	126	57	26
17	Female	21.10727	CrayX	3-point kneeling	126	46	42
17	Female	21.10727	NoExo	Walking	400		40
17	Female	21.10727	Paexo	Walking	430	64	31
17	Female	21.10727	CrayX	Walking	380	31	26
17	Female	21.10727	NoExo	Sit to stand	9.87		0
17	Female	21.10727	Paexo	Sit to stand	10.99	0	4
17	Female	21.10727	CrayX	Sit to stand	15.31	13	9
17	Female	21.10727	NoExo	Stair climbing	8.99		0
17	Female	21.10727	Paexo	Stair climbing	10.25	0	3
17	Female	21.10727	CrayX	Stair climbing	10.23	12	14
17	Female	21.10727	NoExo	Ladder climbing	6.56		16
17	Female	21.10727	Paexo	Ladder climbing	7.49	4	15
17	Female	21.10727	CrayX	Ladder climbing	7.7	4	7
17	Female	21.10727	NoExo	Trunk bending	−5		8
17	Female	21.10727	Paexo	Trunk bending	−1	27	17
17	Female	21.10727	CrayX	Trunk bending	−1.5	5	4
17	Female	21.10727	NoExo	Wide stance	123.3		17
17	Female	21.10727	Paexo	Wide stance	126.0	50	41
17	Female	21.10727	CrayX	Wide stance	116.3	76	47
17	Female	21.10727	NoExo	Trunk rotation			0
17	Female	21.10727	Paexo	Trunk rotation		11	0
17	Female	21.10727	CrayX	Trunk rotation		43	21
17	Female	21.10727	NoExo	Squatting			11
17	Female	21.10727	Paexo	Squatting		24	18
17	Female	21.10727	CrayX	Squatting		0	15
18	Female	23.82813	NoExo	Lifting	34		22
18	Female	23.82813	Paexo	Lifting	34	45	40
18	Female	23.82813	CrayX	Lifting	32	86	88
18	Female	23.82813	NoExo	Load carrying	5.32		4
18	Female	23.82813	Paexo	Load carrying	5.12	15	8
18	Female	23.82813	CrayX	Load carrying	5.7	17	9
18	Female	23.82813	NoExo	Forward bending	223		51
18	Female	23.82813	Paexo	Forward bending	274	29	49
18	Female	23.82813	CrayX	Forward bending	300	18	6
18	Female	23.82813	NoExo	3-point kneeling	300		27
18	Female	23.82813	Paexo	3-point kneeling	300	5	4
18	Female	23.82813	CrayX	3-point kneeling	300	49	55
18	Female	23.82813	NoExo	Walking	580		4
18	Female	23.82813	Paexo	Walking	560	47	27
18	Female	23.82813	CrayX	Walking	560	37	34
18	Female	23.82813	NoExo	Sit to stand	6.81		3
18	Female	23.82813	Paexo	Sit to stand	8.03	9	11
18	Female	23.82813	CrayX	Sit to stand	9.88	6	7
18	Female	23.82813	NoExo	Stair climbing	5.26		2
18	Female	23.82813	Paexo	Stair climbing	7.57	2	3
18	Female	23.82813	CrayX	Stair climbing	5.76	64	57
18	Female	23.82813	NoExo	Ladder climbing	4.52		3
18	Female	23.82813	Paexo	Ladder climbing	4.59	5	6
18	Female	23.82813	CrayX	Ladder climbing	5.21	12	11
18	Female	23.82813	NoExo	Trunk bending	4.5		3
18	Female	23.82813	Paexo	Trunk bending	0.5	1	1
18	Female	23.82813	CrayX	Trunk bending	8	13	21

(continued)

Appendix Table 1. Continued.

Subject	Sex	BMI	Condition	Task	Work performance	GD	PTD
18	Female	23.82813	NoExo	Wide stance	114.0		3
18	Female	23.82813	Paexo	Wide stance	112.8	1	1
18	Female	23.82813	CrayX	Wide stance	104.5	3	4
18	Female	23.82813	NoExo	Trunk rotation			4
18	Female	23.82813	Paexo	Trunk rotation		23	80
18	Female	23.82813	CrayX	Trunk rotation		46	61
18	Female	23.82813	NoExo	Squatting			2
18	Female	23.82813	Paexo	Squatting		5	2
18	Female	23.82813	CrayX	Squatting		30	9

BMI: body mass index; GD: general discomfort; PTD: perceived task difficulty.