# ESO-EAWS Certification

## S01: PAEXO SHOULDER by OTTOBOCK

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## Open challenges and opportunities

Work-related musculoskeletal disorders arise from a complex interaction of events that may accumulate over time. In contrast to the acute trauma model (injuries refer to those arising from a single identifiable event), the cumulative trauma model assumes injury may result from the accumulated effect of transient external loads that may, in isolation, be insufficient to exceed internal tolerances of tissues. It is when this loading accumulates by repeated exposures, or exposures of sufficiently long duration, that the internal tolerances of tissues are eventually exceeded. The cumulative trauma model therefore explains why many musculoskeletal disorders are associated with work, because individuals often repeat actions (often many thousands of times) throughout the workday or spend long periods of time (as much as eight hours or more daily) performing work activities in many occupations. Internal mechanical tolerance represents the ability of a structure to withstand loading. It is clearly multidimensional and is not considered a threshold but rather the capacity of tissues to prolong mechanical strain or fatigue. Internal tissue tolerances may themselves become lowered through repetitive or sustained loading.
External loads are produced in the physical work environment. These loads are transmitted through the biomechanics of the limbs and body to create internal loads on tissues and anatomical structures. Biomechanical factors include body position, exertions, forces, and motions. External loading also includes environmental factors whereby thermal or vibrational energy is transmitted to the body. Biomechanical loading is further affected by individual factors, such as anthropometry, strength, agility, dexterity, and other factors mediating the transmission of external loads to internal loads on anatomical structures of the body.
The literature contains numerous methodologies for measuring physical stress in manual work. Studies from different disciplines and research groups have concentrated on diverse external factors, workplaces, and jobs. Factors most often cited include forceful exertions, repetitive motions, sustained postures, strong vibration, and cold temperatures.

## Project objective

The objective of this study is to evaluate how the EAWS (Ergonomic Assessment Work-Sheet) ergonomic risk assessment index changes with the use of a passive exoskeleton supporting shoulder awkward postures (Figure 10 – Line 20b – Limits of awkward postures). **The study has been carried out with the exoskeleton Paexo Shoulder**. The output will be the release of the Paexo ESO-EAWS form according to how much the use of a passive exoskeleton unloads the demand for activation of the shoulder muscles during work-related conditions.

An exoskeleton is a wearable device supporting the human to generate the physical power required for manual tasks. Exoskeletons could be useful, when (i) other preventive measures are not feasible, usable or effective, and (ii) where the automation of tasks is not feasible when tasks constantly change (e.g. the job of movers, unloading loose loads from containers, patient handling). Exoskeletons could be classified as 'active' or 'passive'. An active exoskeleton is comprised of one or more actuators (e.g., electrical motors) that actively augment power to the human body. A passive system does not use an external power source but uses materials, springs or dampers with the ability to store energy from human movements and release it when required.

Active exoskeletons have been particularly developed for the purpose of rehabilitating injured or disabled people. Active exoskeletons with an occupation or industrial purpose are being developed, but these are mainly in a laboratory stage now.

## Paexo Shoulder Exoskeleton

Paexo Shoulder exoskeleton is the passive exoskeletons produced by Ottobock, a long-established company with 100 years of expertise in the development and production of biomechanical and orthopedic technologies. Paexo Shoulder supports people who carry out physically demanding tasks with their arms raised daily.

It relieves strain on the shoulder joints and upper arms, for example during overhead work on assembly lines and in the building trade.

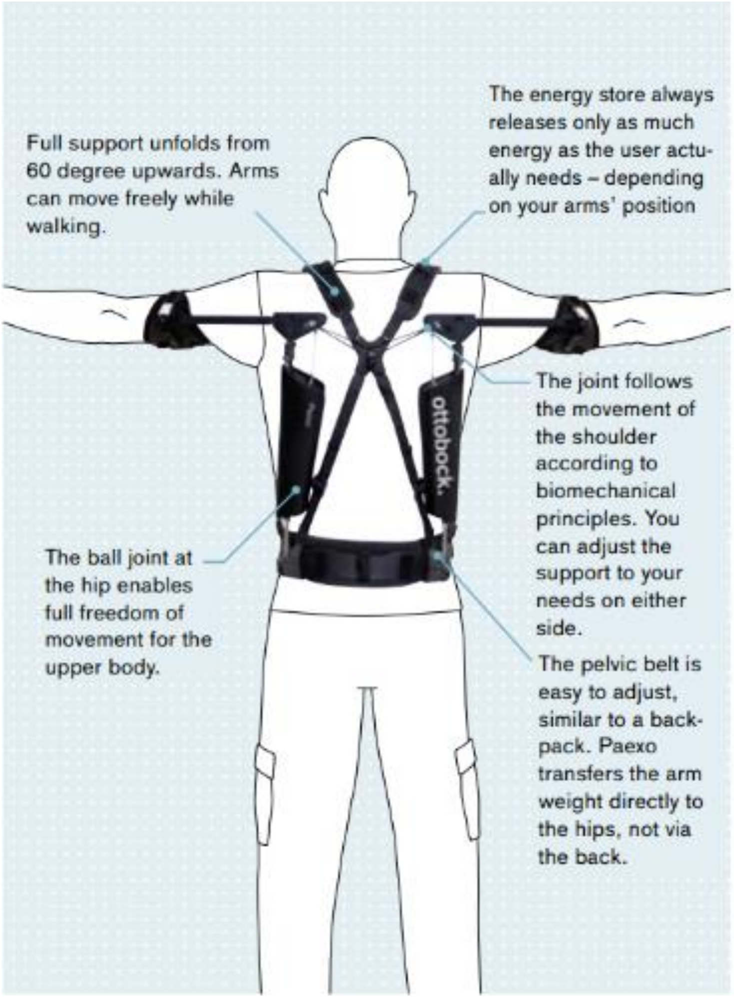



*Figure 1- Paexo Shoulder exoskeleton*

## Ergonomic Assessment Work-Sheet (EAWS)

EAWS is an ergonomic tool for a detailed biomechanical overload risk assessment, developed to provide an overall risk evaluation that includes every biomechanical risk to which an operator may be exposed during a working task.

In order to effectively address ergonomic issues in the workplace, one must develop an appreciation for the trade-offs associated with ergonomics. When one considers biomechanical rationale, one finds that it is very difficult to accommodate all parts of the body in an ideal biomechanical environment. It is often the case, that in attempting to accommodate one portion of the body, the biomechanical situation at another body site is compromised. Therefore, the key to the proper employment of occupational biomechanical principles is to be able to consider the appropriate biomechanical trade-offs with various parts of the body associated with different workplace design options.

The above brief introduction to Biomechanics is reported just to give the idea of the level of complexity we have when we aim at measuring a biomechanical load index. For this reason, in the field of occupational biomechanics, researchers adopt models, which do not have the same level of accuracy as other scientific measuring systems (e.g. Methods-Time Measurement to measure the human work). We know that all existing systems are an attempt to model the effects of forces and motions on our muscular-skeletal system and none of them currently reflect the exact actual situation. Proper use of these models and methods involves recognizing the limitations and assumptions of each technique so that they are not applied inappropriately. When properly used, these assessments can help assess the risk of work-related injury and illness.

Nonetheless, EAWS design was done based on existing and available research with the aim of finding the most appropriate and reasonable correlation against the CEN and ISO standards dealing with biomechanical load.

The EAWS structure is the following:

a) Macro-Section “Whole body”:

- Section 0: Extra Points;
- Section 1: Postures (ref. ISO 11226 and EN 1005-4);
- Section 2: Action forces (ref. ISO 11228.2 and EN 1005-3);
- Section 3: Manual material handling (ref. ISO 11228.1/2 and EN 1005-2).

b) Macro-Section “Upper limbs”

- Section 4: Upper limb load in repetitive tasks (ref. ISO 11228.3 and EN 1005-5).

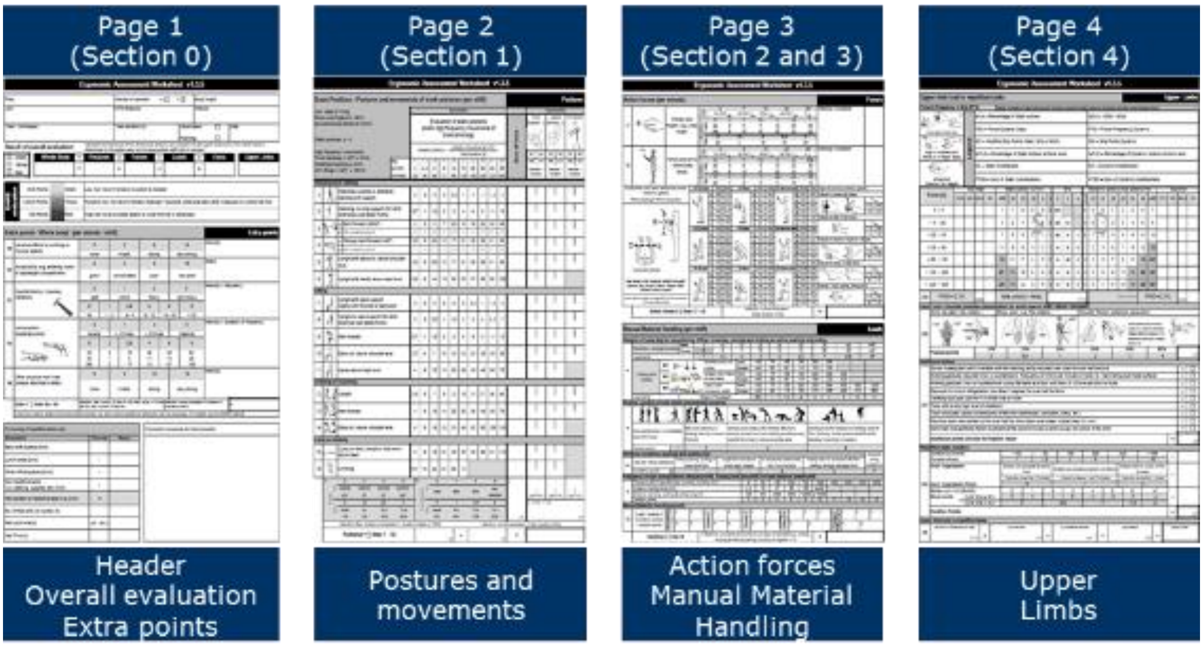
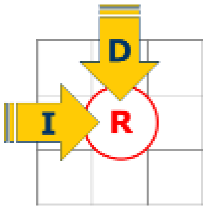



*Figure 2 - EAWS form overview*

The EAWS system calculates a load index (R), given by the product of the Intensity (I) by the Duration (D):

**R = I × D**




In Section 1, the user must select the relevant posture in the proper row (intensity) and measure the duration (column). Intersecting the column of duration with the row of intensity, the user can easily find the score.

In Sections 2, 3 and 4, the user must calculate the intensity and the duration scores of the concerned task, following specific rules, and multiply the intensity score by the duration score to find the load index.

The EAWS sheet provides one score for each Macro-Section. The overall load index of each Macro-Section is then connected to a traffic light scheme (green, yellow, red) according to the Machinery Directive 2006/42/EC (EN 614).

| | | |
|---|---|---|
| 0-25 Points | Green | Low risk: recommended; no action is needed |
| >25-50 Points | Yellow | Possible risk: not recommended; redesign if possible, otherwise take other measures to control the risk |
| >50 Points | Red | High risk: to be avoided; action to lower the risk is necessary |

*Figure 3 - EAWS traffic light result*

Whole body and upper limbs scores are evaluated on the same scale. Thus it is immediate to understand which is the most critical Macro-Section.

**Section 0: Extra Points**

Extra Points are related to additional extraordinary loads not considered in the other total body sections and therefore assigned in this special section. The standard influencing factors in Section 0 are:

- Working on moving objects;
- Difficult accessibility to the working area;
- Counter shocks, impulses, vibrations;
- Joint position (especially wrist and neck);
- Other "special" situations, like above head control work, including looking upward (neck load).

<table>
<tr><th colspan="14">Extra points "Whole body" (per minute / shift)</th><th>Extra points</th></tr>
<tr><td rowspan="2">0a</td><td rowspan="2">Adverse effects by working on moving objects</td><td colspan="3">0</td><td colspan="3">3</td><td colspan="3">8</td><td colspan="3">15</td><td rowspan="2">Intensity</td></tr>
<tr><td colspan="3">none</td><td colspan="3">middle</td><td colspan="3">strong</td><td colspan="3">very strong</td></tr>
<tr><td rowspan="2">0b</td><td rowspan="2">Accessibility (e.g. entering motor or passenger compartment)</td><td colspan="3">0</td><td colspan="3">2</td><td colspan="3">5</td><td colspan="3">10</td><td rowspan="2">Status</td></tr>
<tr><td colspan="3">good</td><td colspan="3">complicated</td><td colspan="3">poor</td><td colspan="3">very poor</td></tr>
<tr><td rowspan="4">0c</td><td rowspan="4">Countershocks, impulses, vibrations<br></td><td colspan="3">0</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">5</td><td rowspan="4">Intensity × frequency</td></tr>
<tr><td colspan="3">light</td><td colspan="3">visible</td><td colspan="3">heavy</td><td colspan="3">very heavy</td></tr>
<tr><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">2,5</td><td colspan="2">4</td><td colspan="2">6</td><td colspan="2">8</td></tr>
<tr><td colspan="2">[n]</td><td colspan="2">1 - 2</td><td colspan="2">4 - 5</td><td colspan="2">8 - 10</td><td colspan="2">18 - 20</td><td colspan="2">> 20</td></tr>
<tr><td rowspan="4">0d</td><td rowspan="4">Joint position (especially wrist)<br></td><td colspan="3">0</td><td colspan="3">1</td><td colspan="3">3</td><td colspan="3">5</td><td rowspan="4">Intensity × duration or frequency</td></tr>
<tr><td colspan="3">neutral</td><td colspan="3">~ 1/3 max</td><td colspan="3">~ 2/3 max</td><td colspan="3">maximal</td></tr>
<tr><td colspan="2">0</td><td colspan="2">2</td><td colspan="2">2,5</td><td colspan="2">4</td><td colspan="2">6</td><td colspan="2">8</td></tr>
<tr><td colspan="2">[s]<br>[n]<br>[%]</td><td colspan="2">3<br>1<br>5</td><td colspan="2">10<br>8<br>17</td><td colspan="2">20<br>11<br>33</td><td colspan="2">40<br>16<br>67</td><td colspan="2">60<br>20<br>100</td></tr>
<tr><td rowspan="2">0e</td><td rowspan="2">Other physical work load (please describe in detail)</td><td colspan="3">0</td><td colspan="3">5</td><td colspan="3">10</td><td colspan="3">15</td><td rowspan="2">Intensity</td></tr>
<tr><td colspan="3">none</td><td colspan="3">middle</td><td colspan="3">strong</td><td colspan="3">very strong</td></tr>
<tr><td></td><td>Extra = ∑ lines 0a – 0e</td><td colspan="6">Attention: Max. score = 40 (line 0c, 0d); Max. score = 15 (line 0a, 0e); Max. score = 10 (line 0b)</td><td colspan="6">Attention: correct evaluation, if duration of evaluation ≠ 60 s</td><td>=</td></tr>
<tr><td></td><td colspan="14">Lines 0a-b mainly relate to the Automotive Industry, for other sectors additional elements may be necessary. For details see the EAWS manual.</td></tr>
</table>

*Figure 4 - EAWS Section 0: Extra points whole body*

**Section 1: Body Postures**

On the left side of the page (Figure 5), load points for symmetric body postures can be assigned. If there are any asymmetric static posture due to trunk rotation, lateral trunk bending or arm extension (far reach), the right side of the page has to be used (Figure 6).

| Basic Positions | No. | | Posture | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Standing (and walking)** | | | | | | | | | | |
| Standing | 1 | | Standing & walking in alteration, standing with support | 0 | 0 | 0 | 0 | 0,5 | 1 | 1 | 1 | 1,5 | 2 |
| | 2 | | Standing, no body support (for other restrictions see Extra Points) | 0,7 | 1 | 1,5 | 2 | 3 | 4 | 6 | 8 | 11 | 13 |
| | 3 | a | Bent forward (20-60°) | 2 | 3 | 5 | 7 | 9,5 | 12 | 18 | 23 | 32 | 40 |
| | | b | with suitable support | 1,3 | 2 | 3,5 | 5 | 6,5 | 8 | 12 | 15 | 20 | 25 |
| | 4 | a | Strongly bent forward (>60°) | 3,3 | 5 | 8,5 | 12 | 17 | 21 | 30 | 38 | 51 | 63 |
| | | b | with suitable support | 2 | 3 | 5 | 7 | 9,5 | 12 | 18 | 23 | 31 | 38 |
| | 5 | | Upright with elbow at / above shoulder level | 3,3 | 5 | 8,5 | 12 | 17 | 21 | 30 | 38 | 51 | 63 |
| | 6 | | Upright with hands above head level | 5,3 | 8 | 14 | 19 | 26 | 33 | 47 | 60 | 80 | 100 |
| | | | **Sitting** | | | | | | | | | | |
| Sitting | 7 | | Upright with back support slightly bent forward or backward | 0 | 0 | 0 | 0 | 0 | 0 | 0,5 | 1 | 1,5 | 2 |
| | 8 | | Upright no back support (for other restriction see Extra Points) | 0 | 0 | 0,5 | 1 | 1,5 | 2 | 3 | 4 | 5,5 | 7 |
| | 9 | | Bent forward | 0,7 | 1 | 1,5 | 2 | 3 | 4 | 6 | 8 | 11 | 13 |
| | 10 | | Elbow at / above shoulder level | 2,7 | 4 | 7 | 10 | 13 | 16 | 23 | 30 | 40 | 50 |
| | 11 | | Hands above head level | 4 | 6 | 10 | 14 | 20 | 25 | 35 | 45 | 60 | 75 |
| | | | **Kneeling or crouching** | | | | | | | | | | |
| Kneeling | 12 | | Upright | 3,3 | 5 | 7 | 9 | 12 | 15 | 21 | 27 | 36 | 45 |
| | 13 | | Bent forward | 4 | 6 | 10 | 14 | 20 | 25 | 35 | 45 | 60 | 75 |
| | 14 | | Elbow at / above shoulder level | 6 | 9 | 16 | 23 | 33 | 43 | 62 | 80 | 108 | 135 |
| | | | **Lying or climbing** | | | | | | | | | | |
| Lying or Climbing | 15 | | (Lying on back, breast or side) arms above head | 6 | 9 | 15 | 21 | 29 | 37 | 53 | 68 | 91 | 113 |
| | 16 | | Climbing | 6,7 | 10 | 22 | 33 | 50 | 66 | | | | |

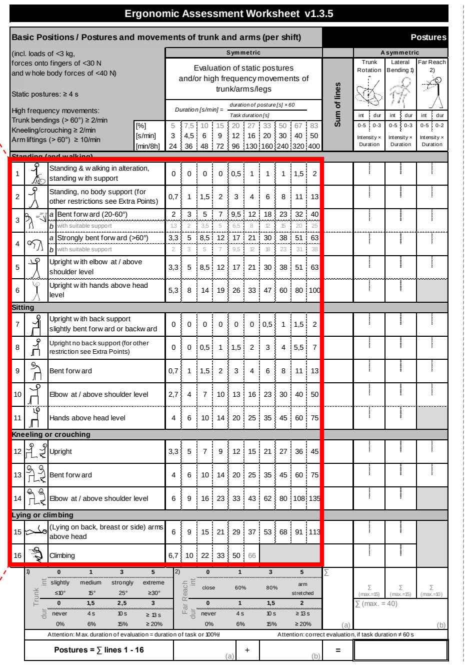



*Figure 5 - EAWS Section 1: symmetric body postures*

On this page, static postures (which are defined in EAWS as postures maintained for at least 4 consecutive seconds) and high frequency movements are evaluated, including loads weighing less than 3 kg, action forces onto fingers less than 30N, and whole body forces less than 40 N.

In the EAWS form, Section 2, the columns indicate the duration (in % of the cycle, s/min or % of shift) of a specific posture. The rows show a graphic visualization of different posture types (intensity).

The asymmetric body postures:

- trunk rotation (use duration table 1);
- lateral trunk bending (use duration table 1);
- arm extension (far reach) (use duration table 2),

are evaluated on the right side of the page. At the bottom of the left side of the page, there is a table to assign the "intensity" and the "duration" points.

Trunk Rotation and Lateral Bending table (use duration table 1);

Far Reach table (use duration table 2, see Figure 6 - EAWS Section 1: asymmetric body postures).

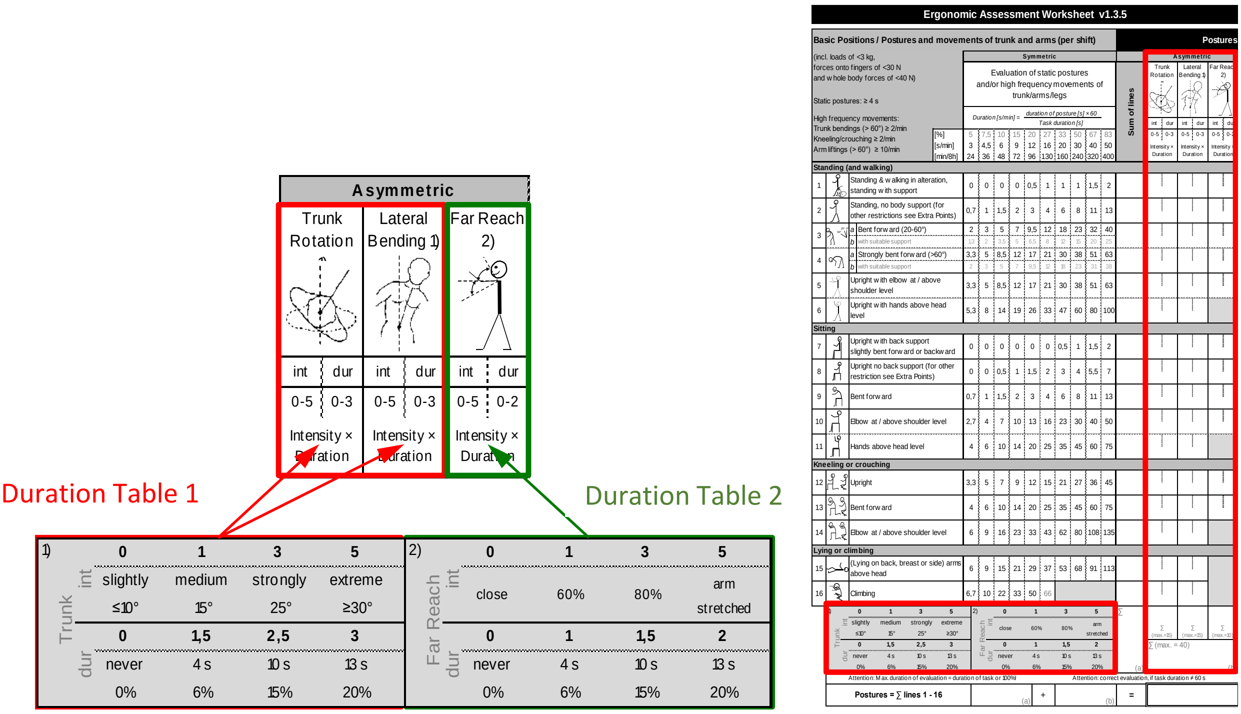



*Figure 6 - EAWS Section 1: asymmetric body postures*

**Section 2 – Action Forces**

In Section 2 (Figure 7), Action Forces are evaluated:

Row 17: Forces onto/with fingers if greater than or equal to 30 N;

Row 18: Action forces onto arms and whole-body forces if greater than or equal to 40 N (excluding manual material handling evaluated in Section 3).

In the lower part of this section, data are abstracted from the "Force Atlas" and represented in figures and values. These values are the result of detailed German academic research about force limits at different anthropometric percentiles for each body and hand postures. In the Force Atlas, the statistical distribution of the maximum forces, depending on the postures of hand, arms and body, is established for significant percentiles. The force values assigned in section 2 of EAWS are the ones for the 15th and 40th percentile neutral gender (in the standard EAWS form neutral gender is set equal to feminine gender). 15th percentile data are used for planning, 40th percentile data for direct observational analyses.

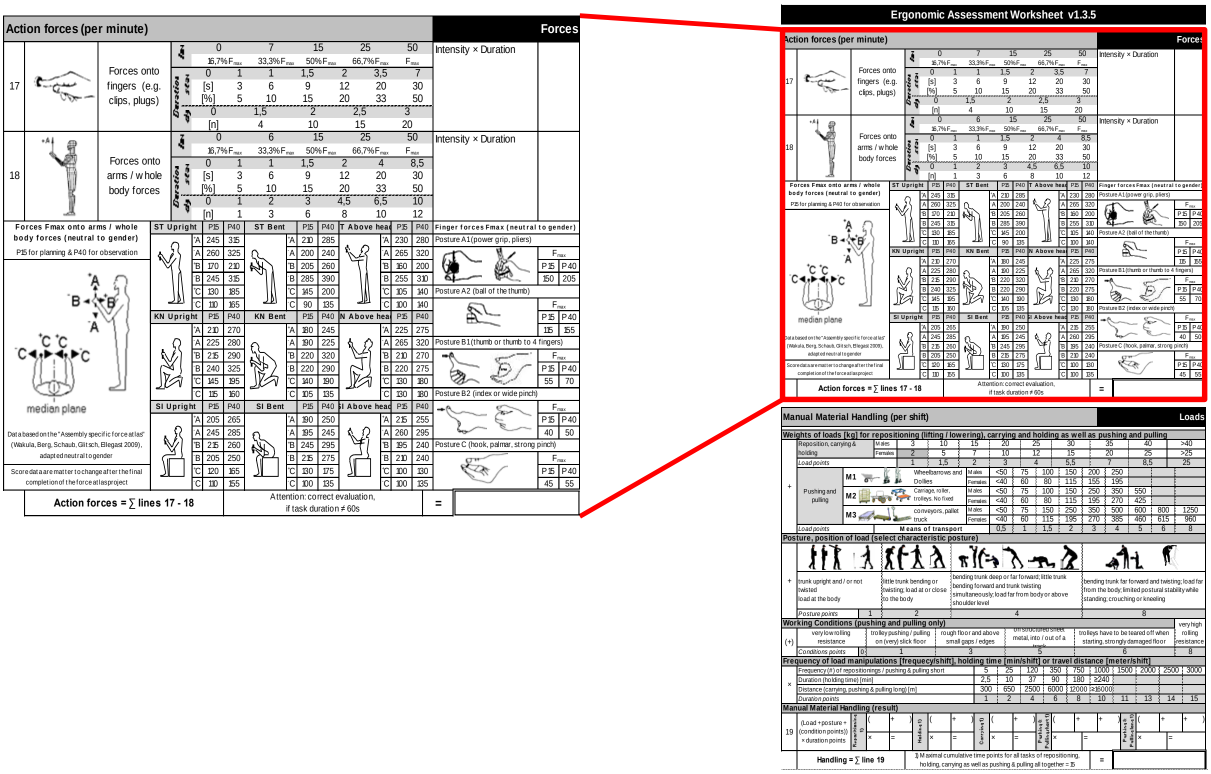



*Figure 7 - EAWS Section 2, Body Forces*

## Section 3: Manual Material Handling of Loads

In section 3 (Figure 8), the efforts due to manual material handling (greater than or equal to 3 kg) subdivided into repositioning, holding, carrying, pushing & pulling (short and long) are evaluated.

In the case of automotive assembly, it is recommended to enlarge these limits to 20 m or 15 s for easier application. This leads to:

- Repositioning (R): get and place a load within the workplace (approximately equivalent to a maximum displacement of 20 m):
- Holding (H): hold a load longer than 15 s, no carrying;
- Carrying (C): get, carry and place for a distance longer than 20 m;
- Pushing & Pulling (P&P): transporting a load with a means of transport;
    - Short, if distance ≤ 20 m
    - Long, if distance > 20 m

Influencing factors:

- Weights of loads;
- Posture;
- Working conditions;
- Frequency / Duration / Distance per shift.

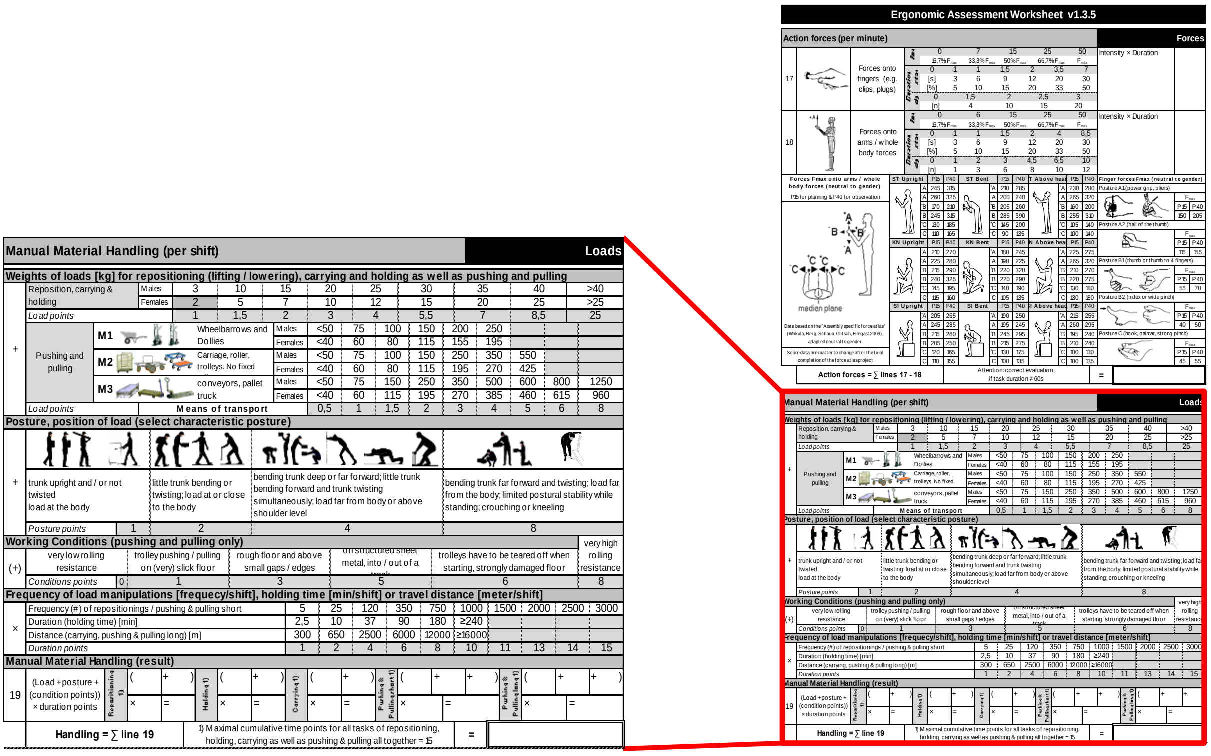



*Figure 8 - EAWS Section 3: manual material handling of loads*

## Section 4: Repetitive Motions of the Upper Limbs

Section 4 of EAWS has been designed to meet the requirements defined in the general framework of the ISO 11228-3 standard and has been calibrated against the OCRA Index. However, the approach of section 4 EAWS differs from the OCRA Index, above all in the choice to use the concept of real action (e.g. Get & Place an object) compared to the one of technical action (Grasp an object), a choice dictated by the intention of the EAWS authors to adopt a design logic, less tied to the ways of act of the individual performer of the work cycle. The following are other significant differences between EAWS section 4 and OCRA Index:

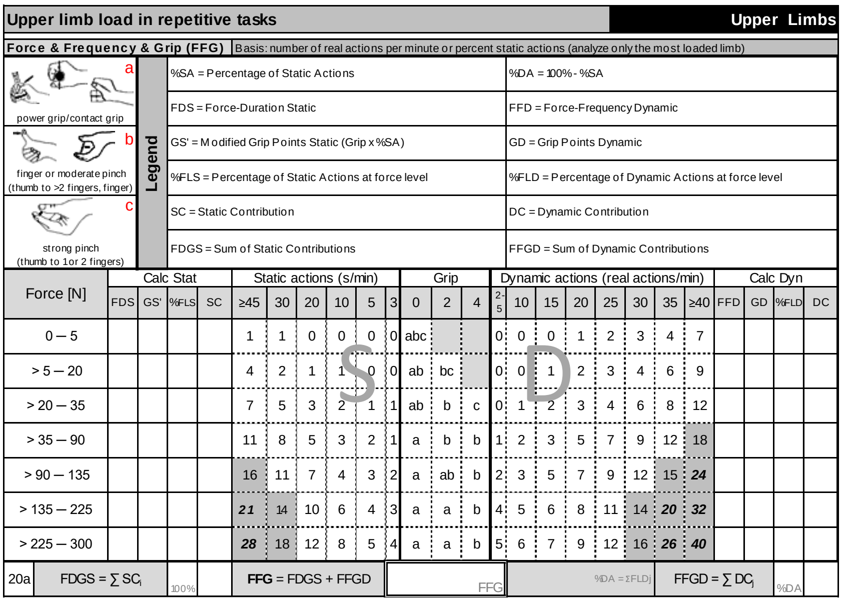
The type of Grip in section 4 is evaluated for each real action jointly with the level of force and the frequency / duration of the action itself;

The pinch-type Grip without force does not generate additional load points compared to those assigned to the real action;

In EAWS there is no step effect between different intervals of intensity or duration level of the influencing factors. The value curves are the result of linear interpolations between known benchmark points.

In the upper part of the page, the following information is analysed (Figure 9):

- Frequency of dynamic real actions / duration of real static actions;
- Force or load level of each real action;
- Type of grip of each real action.



**Upper limb load in repetitive tasks** — **Upper Limbs**

**Force & Frequency & Grip (FFG)** Basis: number of real actions per minute or percent static actions (analyze only the most loaded limb)

| | Legend | |
|---|---|---|
| a: power grip/contact grip | %SA = Percentage of Static Actions | %DA = 100% - %SA |
| | FDS = Force-Duration Static | FFD = Force-Frequency Dynamic |
| b: finger or moderate pinch (thumb to >2 fingers, finger) | GS' = Modified Grip Points Static (Grip x %SA) | GD = Grip Points Dynamic |
| | %FLS = Percentage of Static Actions at force level | %FLD = Percentage of Dynamic Actions at force level |
| c: strong pinch (thumb to 1or 2 fingers) | SC = Static Contribution | DC = Dynamic Contribution |
| | FDGS = Sum of Static Contributions | FFGD = Sum of Dynamic Contributions |

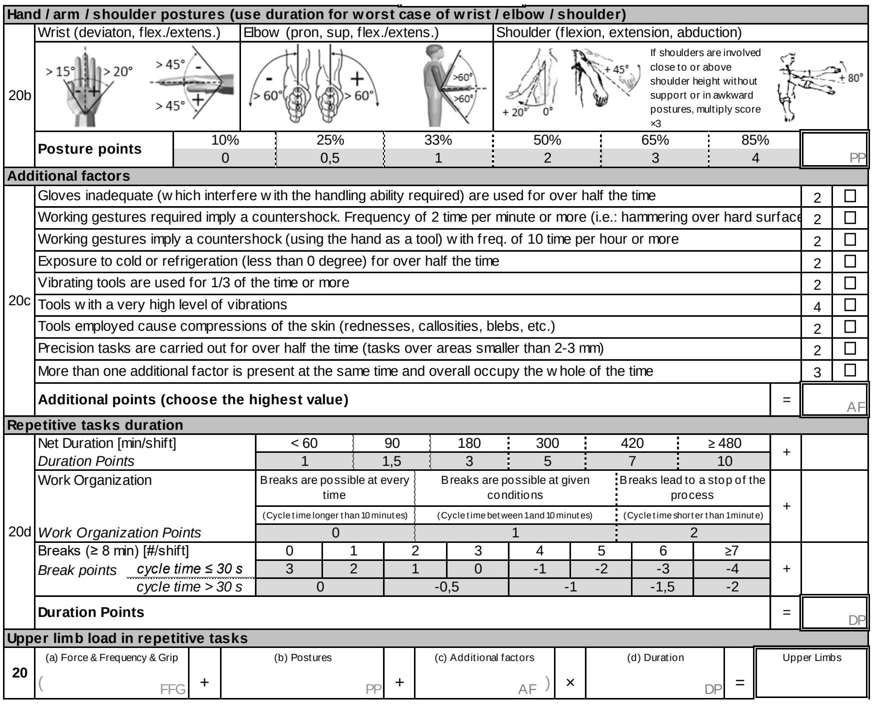
| Force [N] | Calc Stat FDS | GS' | %FLS | SC | Static actions (s/min) ≥45 | 30 | 20 | 10 | 5 | 3 | Grip 0 | 2 | 4 | Dynamic actions (real actions/min) 2-5 | 10 | 15 | 20 | 25 | 30 | 35 | ≥40 | Calc Dyn FFD | GD | %FLD | DC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 – 5 | | | | | 1 | 1 | 0 | 0 | 0 | 0 | abc | | | 0 | 0 | 0 | 1 | 2 | 3 | 4 | 7 | | | | |
| > 5 – 20 | | | | | 4 | 2 | 1 | 1 | 0 | 0 | ab | bc | | 0 | 0 | 1 | 2 | 3 | 4 | 6 | 9 | | | | |
| > 20 – 35 | | | | | 7 | 5 | 3 | 2 | 1 | 1 | ab | b | c | 0 | 1 | 2 | 3 | 4 | 6 | 8 | 12 | | | | |
| > 35 – 90 | | | | | 11 | 8 | 5 | 3 | 2 | 1 | a | b | b | 1 | 2 | 3 | 5 | 7 | 9 | 12 | 18 | | | | |
| > 90 – 135 | | | | | 16 | 11 | 7 | 4 | 3 | 2 | a | ab | b | 2 | 3 | 5 | 7 | 9 | 12 | 15 | ***24*** | | | | |
| > 135 – 225 | | | | | ***21*** | 14 | 10 | 6 | 4 | 3 | a | a | b | 4 | 5 | 6 | 8 | 11 | 14 | ***20*** | ***32*** | | | | |
| > 225 – 300 | | | | | ***28*** | 18 | 12 | 8 | 5 | 4 | a | a | b | 5 | 6 | 7 | 9 | 12 | 16 | ***26*** | ***40*** | | | | |

| 20a | FDGS = ∑ $SC_i$ | 100% | | **FFG** = FDGS + FFGD | FFG | %DA = ΣFLDj | FFGD = ∑ $DC_j$ | %DA | |
|---|---|---|---|---|---|---|---|---|---|

*Figure 9 - EAWS Section 4: force-frequency-grip score*

The following items are evaluated in the lower part of the page (Figure 10):

- Posture of hands, arms and shoulders;
- Special points, and;
- Duration of repetitive tasks;
- Work Organization;
- Number of breaks;
- Shift duration.



**Hand / arm / shoulder postures (use duration for worst case of wrist / elbow / shoulder)**

| | Wrist (deviaton, flex./extens.) | Elbow (pron, sup, flex./extens.) | Shoulder (flexion, extension, abduction) |
|---|---|---|---|
| 20b | > 15° > 20° > 45° > 45° | > 60° > 60° >60° >60° | + 20° 0° + 45° If shoulders are involved close to or above shoulder height without support or in awkward postures, multiply score ×3 + 80° |

| Posture points | 10% | 25% | 33% | 50% | 65% | 85% | |
|---|---|---|---|---|---|---|---|
| | 0 | 0,5 | 1 | 2 | 3 | 4 | PP |

**Additional factors**

| 20c | | | |
|---|---|---|---|
| | Gloves inadequate (w hich interfere w ith the handling ability required) are used for over half the time | 2 | ☐ |
| | Working gestures required imply a countershock. Frequency of 2 time per minute or more (i.e.: hammering over hard surface | 2 | ☐ |
| | Working gestures imply a countershock (using the hand as a tool) w ith freq. of 10 time per hour or more | 2 | ☐ |
| | Exposure to cold or refrigeration (less than 0 degree) for over half the time | 2 | ☐ |
| | Vibrating tools are used for 1/3 of the time or more | 2 | ☐ |
| | Tools w ith a very high level of vibrations | 4 | ☐ |
| | Tools employed cause compressions of the skin (rednesses, callosities, blebs, etc.) | 2 | ☐ |
| | Precision tasks are carried out for over half the time (tasks over areas smaller than 2-3 mm) | 2 | ☐ |
| | More than one additional factor is present at the same time and overall occupy the w hole of the time | 3 | ☐ |
| | **Additional points (choose the highest value)** | = | AF |

**Repetitive tasks duration**

| 20d | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Net Duration [min/shift] | < 60 | 90 | 180 | 300 | 420 | ≥ 480 | | | + |
| | *Duration Points* | 1 | 1,5 | 3 | 5 | 7 | 10 | | | |
| | Work Organization | Breaks are possible at every time (Cycle time longer than 10 minutes) | Breaks are possible at given conditions (Cycle time between 1 and 10 minutes) | Breaks lead to a stop of the process (Cycle time shorter than 1 minute) | | | | | | + |
| | *Work Organization Points* | 0 | 1 | 2 | | | | | | |
| | Breaks (≥ 8 min) [#/shift] | 0 | 1 | 2 | 3 | 4 | 5 | 6 | ≥7 | + |
| | *Break points* *cycle time ≤ 30 s* | 3 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | |
| | *cycle time > 30 s* | 0 | | -0,5 | | -1 | | -1,5 | -2 | |
| | **Duration Points** | | | | | | | | | = DP |

**Upper limb load in repetitive tasks**

| 20 | (a) Force & Frequency & Grip ( FFG | + | (b) Postures PP | + | (c) Additional factors AF ) | × | (d) Duration DP | = | Upper Limbs |
|---|---|---|---|---|---|---|---|---|---|

*Figure 10 - EAWS Section 4: postures, additional factors and work organization*

# Method

## Participants

Thirteen subjects (25-40 years) volunteered to participate in this study (range values; height: 168-183 cm, weight: 52 - 75 kg). All subjects reported to be in good health at the occasion of experiments and none of them reported any musculoskeletal issues that could preclude their participation in the study. The experimental procedures were conducted in accordance with the *Declaration of Helsinki.*

## Experimental conditions

Two sessions of EAWS were considered: *Postures and movements* and *Upper limb*. Subjects were instructed to perform 12 different tasks, mimicking the postures indicated in the Ergonomic Assessment Work-Sheet (EAWS).
Four postures were tested, each defined according to a reference position. The reference position was defined equally for all subjects and tasks as the *standard anatomical position* (Figure 11A). The specific postures studied were:

(1) shoulder abducted at 90°, elbow flexed at 90°, elbow pronated at 90° (Figure 11B);
(2) shoulder flexed at 90°, elbow flexed at 90°, elbow pronated at 90° (Figure 11C);
(3) shoulder flexed at 90°, elbow pronated at 90° (Figure 11D);
(4) shoulder abducted at 90°, elbow pronated at 90° (Figure 11E).

The 0° reference for each of the joints listed in the four postures was defined according to the joint angle measured in the reference position. Here, *shoulder* refers to the glenohumeral joint and *elbow* refers to humeroulnar and proximal radioulnar joints.

A total of 24 tasks per subject were applied. Eight of these tasks were static, whereby subjects had to hold 4 given postures for two durations, 6 s and 20 s. The remaining four tasks were dynamic, with subjects moving from rest to the same 4 postures tested in the static tasks and back to rest continuously during 50 s. Static and dynamic tasks were applied twice, once without and once with the Paexo Shoulder exoskeleton (Ottobock, Duderstadt, Germany; Figure 12). The number of static tasks applied amounted to 16 (4 postures (Figure 12) x 2 durations (6 s and 20 s) x 2 conditions (with vs without Paexo)). Starting from the reference posture, subjects were instructed to reach and hold the given posture for a given duration and then rest for an equal duration three times. The eight dynamic trials comprised 4 postures and 2 conditions, with and without Paexo. In dynamic tasks there were no rest periods, both when reaching the given and the reference postures. For each condition, the 12 tasks were randomized, with a rest period between trials of the same duration of the preceding trial.

According to the instructions provided during the training with Paexo, users should chose the level of support according to how comfortable they felt for a given task. Specifically, we asked subjects to strive for the level of support sufficiently high for them not to feel loading their muscle while sustaining the four requested postures. Given the anthropometric variation between subjects, the number of expenders used and the level of support were variable.
It should be noted though subjects were asked to chose their preferred level of support while bearing in mind both the static and dynamic tasks. No change in the level of support was considered between these two conditions. They likely selected the level of support providing the most appropriate compromise between sustaining the arms during static tasks and not offering to much resistance during the dynamic tasks.

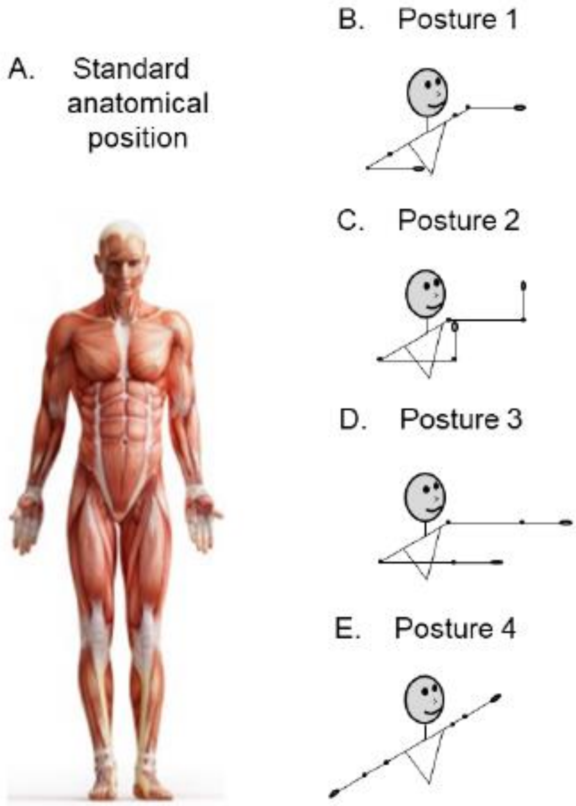



*Figure 11 - Schematic representation of the postures which were studied in the present study.*

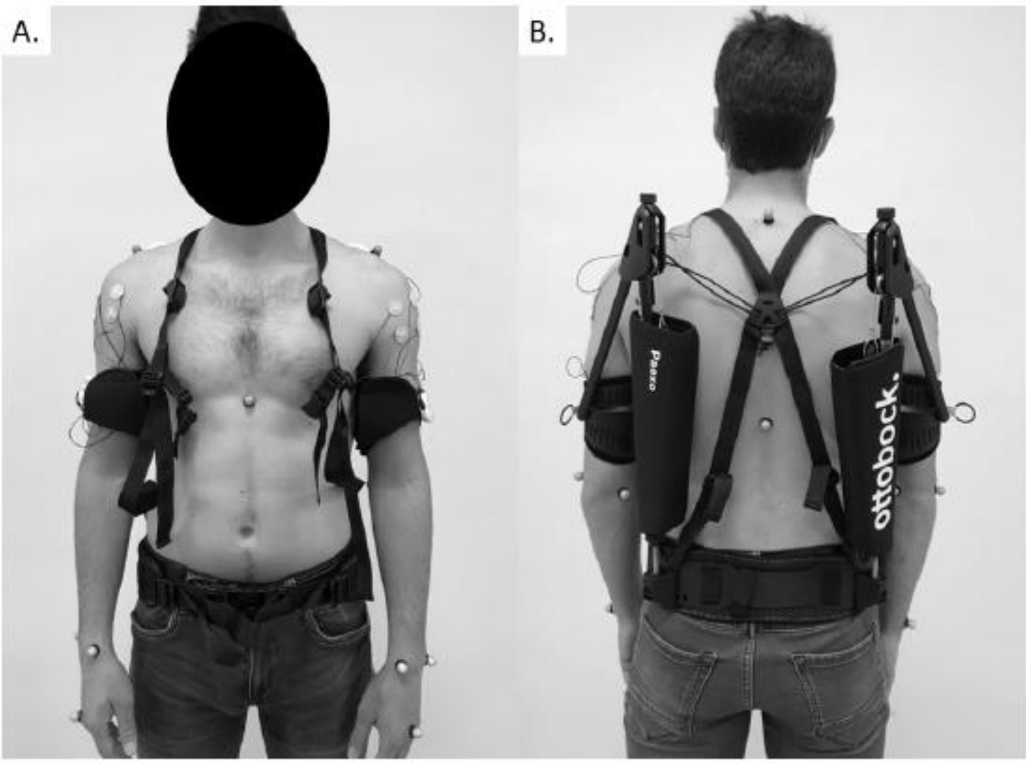



*Figure 12 - Anterior (A) and posterior (B) view of subject while wearing Paexo Shoulder*

## Surface Electromyography

A pair of circular, surface electrodes (24 mm diameter with roughly 30 mm center-to-center distance, Spes Medica, Battipaglia, Italy) was used to collect surface electromyograms (EMGs) bilaterally from the following, upper limb muscles:

- anterior deltoid
- medial deltoid
- posterior deltoid
- biceps brachii (long head)
- triceps brachii (lateral head)
- the upper portion of trapezius muscle

Selection was based on the documented, biomechanical function of each of these muscles.
The selected muscles are either prime movers or stabilizers of the shoulder [1–3]. After carefully shaving and cleaning the skin with abrasive paste, surface electrodes were positioned on the skin surface over the muscle of interest (Figure 13). Bipolar EMGs were recorded with a wireless system (200 V/V gain; 10–500 Hz bandwidth amplifier; DuePro system, OTBioelettronica and LISiN, Politecnico di Torino, Turin, Italy). EMGs were digitized at 2048 Hz with a 16 bits A/D converter.

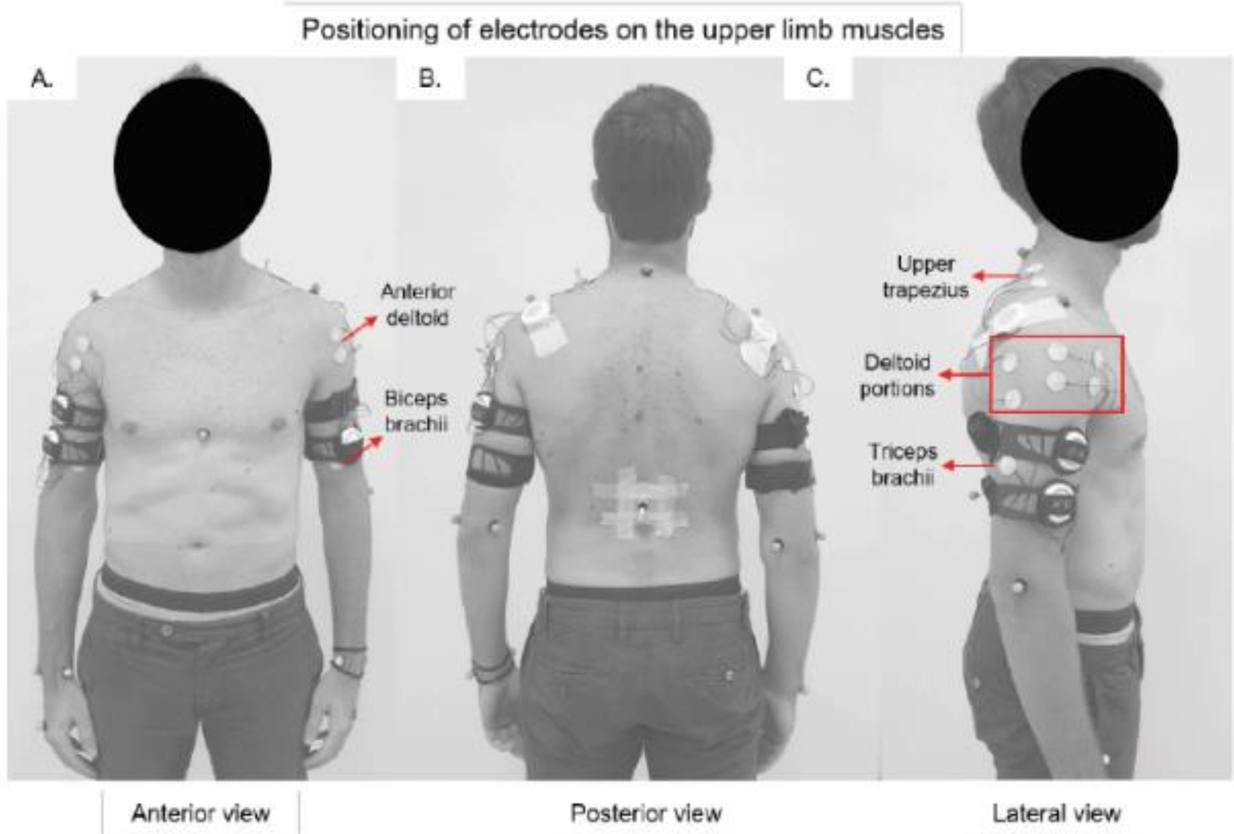



*Figure 13 - Positioning of a pair of electrodes on the six upper limb muscles tested during the experimental conditions with and without exoskeleton; anterior view (A), posterior view (B) and lateral view (C).*

## Motion analysis

Kinematics data were obtained after labelling a set of 15 reflective markers, which coordinates were captured by a 12 camera VICON system (100 Hz, Vero v2.2, Nexus 2.9 software, Oxford, UK). Markers were positioned in the upper limbs according to the protocol proposed by Hebert et al [4]. More specifically, markers were placed bilaterally on the subject's skin overlying specific landmarks. Seven segments were created from the markers' coordinates: trunk, left arm, right arm, left forearm, right forearm, left hand, and right hand. Three markers defined a segment: one proximal marker, one distal marker and a third, non-colinear marker. From these three markers we defined the center of the joints linking pairs of segments and therefore the local reference system for each segment (Table 1, column 1).

The protocol proposed by Hebert et al [4] was chosen according to the following criteria, based on the review by Valevicius et al [7]:

- relatively small number of markers (*N*=15);
- markers are positioned in anatomical and non-clustered locations;
- the joints of interest are modelled: shoulder and elbow;
- all the degrees of freedom of interest are included in the kinematic model;
- the kinematic model provides a static calibration method, eliminating the need for manual labelling;
- *Cardan-Euler Angles* is the method used to obtain angular kinematics;
- the reliability or validity of the kinematic model was evaluated for this protocol.

*Table 1 - Kinematic data collection protocol*

| Markers | Moving segment | Reference segment | Designated joint movement | Reference segment | Displacement to joint center (offset) | | | Local coordinate system |
|---|---|---|---|---|---|---|---|---|
| | | | | | Lateral | Anterior | Superior | |
| C7–T10–Sternum–**L** ACR–**R** ACR | Thorax | Global (laboratory) | Trunk | | 0 | 0 | 0 | Global reference frame |
| **L** ACR – **L** MEPI – **L** LEPI | **L** arm | Thorax | **L** shoulder | **L** ACR – **R** ACR | 0 | 0 | -17% | Z axis – the line connecting the ACR and the midpoint of MEPI and LEPI.<br>Y axis – the line perpendicular to the plane formed by ACR, MEPI and LEPI, pointing forward.<br>X axis - the line connecting the left and the right ACR, pointing to the right. |
| **R** ACR – **R** MEPI – **R** LEPI | **R** arm | Thorax | **R** shoulder | **R** ACR – **L** ACR | 0 | 0 | -17% | |
| **L** MEPI – **L** ULN – **L** RAD – **L** LEPI | **L** forearm | **L** arm | **L** elbow | **L** MEPI – **L** LEPI | Midpoint | 6% | 13% | Z axis – the line connecting the ACR and the midpoint of MEPI and LEPI.<br>Y axis – the line perpendicular to the plane formed by ACR, MEPI and LEPI, pointing forward.<br>X axis - the line connecting the MEPI and LEPI, pointing to the right. |
| **R** MEPI – **R** ULN – **R** RAD – **R** LEPI | **R** forearm | **R** arm | **R** elbow | **R** MEPI – **R** LEPI | Midpoint | 6% | 13% | |
| **L** ULN – **L** HAND – **L** RAD | **L** hand | **L** forearm | **L** wrist | **L** ULN – **L** RAD | Midpoint | 0 | 0 | Z axis – the line connecting the midpoint of MEPI and LEPI and the midpoint of ULN and RAD.<br>Y axis – the line perpendicular to the plane formed by MEPI and LEPI and ULN and RAD, pointing forward.<br>X axis - the line connecting the ULN and RAD, pointing to the right. |
| **R** ULN – **R** HAND – **R** RAD | **R** hand | **R** forearm | **R** wrist | **R** ULN – **R** RAD | Midpoint | 0 | 0 | |

Acronyms: left (**L**); right (**R**); spinous process, 7th cervical vertebra (**C7**); spinous process, 10th thoracic vertebra (**T10**); acromion (**ACR**); medial epicondyle (**MEPI**); lateral epicondyle (**LEPI**); ulnar styloid (**ULN**); radial styloid (**RAD**); 3rd metacarpal phalanx (**HAND**). **Global reference frame**: Z axis pointed superior, Y axis pointed anterior, X axis pointed right to the participant. Offsets are expressed as a percentage of reference segment length.

## Assessment of muscle activity

Prior to processing EMGs, phases of interest were identified from joint angle data. During static trials, analysis was focused on periods when the subject was sustaining the requested posture; hereafter defined as *holding phase*. During dynamic trials, concentric and eccentric phases were identified for each of the movement cycles recorded. Phases were identified separately for each trial. For the eight static trials, more specifically, *holding phases* were identified from the local minima and maxima of the first derivative of the shoulder angle in the sagittal or frontal plane, depending on the posture. The first and last second of the *holding phase* were not considered to segment the surface EMGs, thereby eliminating any transient resulting from individuals' adaptation to the just, adopted posture (rest or requested posture; Figure 14A). From a close inspection of Figure 14A, it is possible to observe in the first and last second of the *holding phases* a variable EMG activity of upper trapezius resulting from the transition phase between the start position and required posture, and vice versa. For the dynamic tasks, the concentric and eccentric phases were defined based on percentiles of the distribution of shoulder joint angle. More specifically, the concentric phase was defined for shoulder angle from the 10th and 90th percentiles, wherein shoulder angular velocity was positive whereas the eccentric phase was defined within the same percentile range though for negative velocity values (see red and blue lines over the shoulder angle in Figure 14B). Depending on the posture requested in each trial (Figure 11), different anatomical planes were considered for segmenting movement phases. For postures 1 and 4 we identified movement phases based on shoulder angle in the frontal plane, while shoulder flexion-extension was considered for segmenting the movement in postures 2 and 3. The 10th and 90th percentiles were respectively used to attenuate the contribution of movement artefacts, resulting from changes in movement direction, to the surface EMG. After the identification of cycles from variations in the shoulder angle within each experimental condition, bipolar surface EMGs collected from all muscles were visually inspected. Whenever any signal presented contact problems, likely due to unstable electrode-amplifier connection or artefacts resulting from wearing Paexo, the corresponding signal was disregarded (see general considerations below). After controlling for signal quality, bipolar EMGs were band-pass filtered with a fourth order Butterworth bidirectional filter (15 – 350 Hz cut-off) and the level of muscle excitation was estimated from the Root Mean Square (RMS) amplitude of surface EMG. For the static tasks, RMS values were computed over epochs corresponding to the *holding phases* (providing a total of 3 RMS values per muscle) while, for the dynamic tasks, the RMS amplitude was calculated separately for all concentric and eccentric phases (providing a minimum of 15 RMS values per phase for each muscle).

For each condition and muscle, we specifically:

i) computed the average RMS value over repetitions, both for dynamic and static tasks and separately between conditions;

ii) averaged the RMS amplitude across the concentric and eccentric phases, providing a global indication of the level of muscle excitation for the dynamic trials. The decision of averaging both phases was motivated by the necessity of having a global excitation value representative of the whole task, according to EAWS.

iii) compute the average, RMS amplitude when subject wore Paexo relative to average RMS values obtained while subjects were not wearing Paexo. This index was considered to assess how much Paexo reduces the level of excitation in each muscles during the static and dynamic trials.

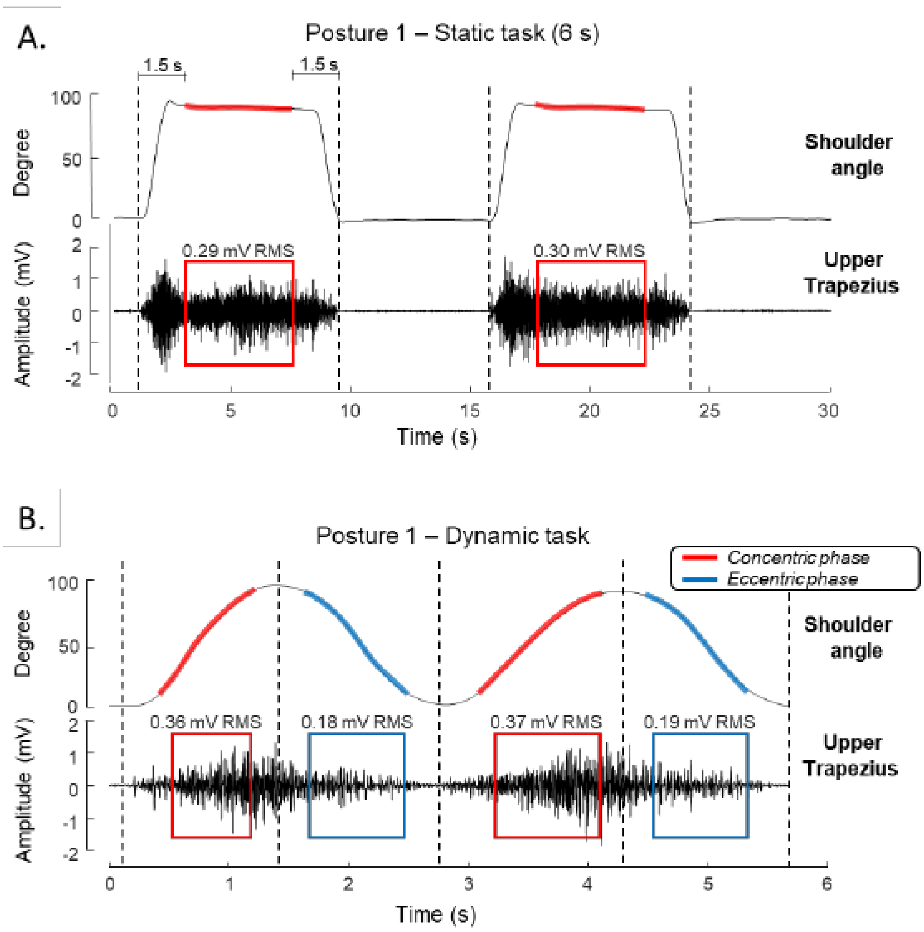



*Figure 14: (A) Shoulder angle in the frontal plane and bipolar EMG sampled from the upper portion of trapezius (left side) during Posture 1. Vertical and dashed lines indicate the instants corresponding to the start and the end of sustained phase. Red line over the shoulder angle indicates the epoch considered to select the portion of surface EMG related to the holding phase (red square). (B) Angle data and bipolar EMG collected respectively from the same joint and muscle during two cycles while subject repeated 15 consecutive times for Posture 1. Vertical and dashed lines indicate the instants corresponding to the local minima and maxima of angle data. Red and blue lines over the shoulder angle indicate respectively the segment considered to identify the surface EMG epochs corresponding to the concentric and eccentric phases of movement (red and blue squares).*

## Statistical analysis

Inferential statistics was applied to test for differences in the range of shoulder motion and in the relative variation in EMG amplitude between static trials of different durations (6s and 20s were studied here). These results would possibly indicate whether the attenuation effect of Paexo on the EMG amplitude was associated with the duration of static task. If this was the case, different laws would possibly be necessary to update EAWS for different task durations. Parametric statistics was applied after verifying the data distribution was Gaussian (Kolmogorov-Smirnov, $p > 0.05$ in all cases). A two-way analysis of variance (ANOVA) for repeated measures was used to evaluate the effect of duration of static trials (2 levels: 6s and 20s) on the relative variation in EMG amplitude, with posture as between factor (4 levels). This same arrangement was applied to test for differences in range of motion between conditions. Whenever any main effect was observed, post-hoc analysis was evaluated with the Bonferroni correction. The level of statistical significance was set at 5%.

# Results

## General considerations

The 13 subjects tested successfully completed all static and dynamic trials. None reported any discomfort while wearing Paexo during both static and dynamics trials. Artefacts were observed occasionally, in roughly 15% of the trials recorded. These occurrences were mainly related to the contact between Paexo and electrodes, in particular for the trapezius and posterior deltoid muscles during dynamic contractions and exclusively for the left side. Only EMGs from the contralateral muscles were therefore considered for computing the index of effort reduction for these instances. Notwithstanding the rare occurrences of packet loss, all EMGs retained were of high quality as were all kinematic data.

## Qualitative considerations from a representative example

Although statistical analysis was only applied to test for a duration effect of static trials on the relative variation in EMG amplitude, results from all subjects tested were inspected closely. Data from a representative subject are shown in Figures 15 and 16, for an individual, static repetition (Figure 15) and for a single, dynamic cycle (Figure 16).

## Static trial

The participant successfully maintained the *holding phase* for the requested posture with and without the exoskeleton. Variations in shoulder abduction angle were remarkably smaller than 5° within the 20 s period of posture maintenance, regardless of whether the subject was wearing Paexo or not. The steady maintenance of shoulder position is further evidenced by the roughly constant degree of activity observed in the raw EMGs collected for the three main muscles crossing the shoulder joint. The activity of the deltoid muscles decreased by roughly 30% when this specific participant maintained Posture 4 with assistance from Paexo.

## Dynamic trial

As for the static trial, similar considerations on the consistency of kinematic data and on the amplitude of EMGs across conditions apply for the dynamic trials. The range of shoulder motion while a representative participant repeatedly abducted his left and right shoulders differed by less than 5° when wearing and not wearing Paexo. Variations in the average duration of cycles between the two conditions were less than 0.2 s across the four postures.

Regarding the degree of muscle excitation, the effect of Paexo appears to be contraction and muscle dependent. While there was a general decrease in excitation with Paexo, reduced excitation was more clearly evident for the concentric than eccentric phase. This is particularly true for the triceps brachii and upper trapezius muscles in *Postures 3* and *4*, for which Paexo demanded greater effort in the eccentric phase. This specific, loading effect was not representative for the other muscles and postures. Of concern here is the assuaging effect of Paexo on the shoulder muscles muscle often vulnerable to overuse injuries, three of which are illustrated in Figure 16 for a single subject.

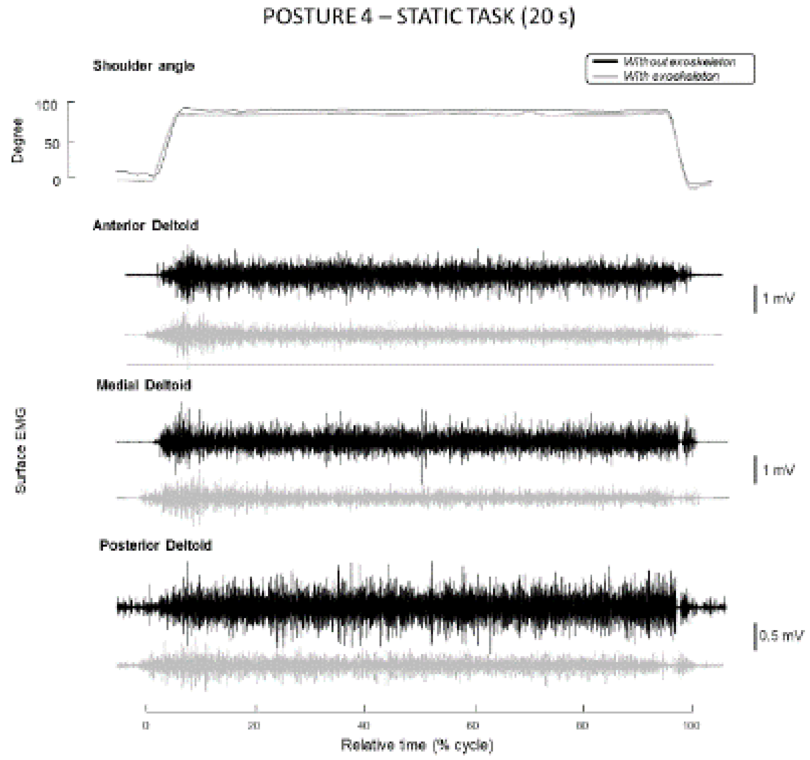



*Figure 15: (A) Shoulder angle in the frontal plane and bipolar EMGs sampled from the three portions of the deltoid muscle (left side). Signals are shown for a representative subject while maintaining Posture 4 for 20 seconds with (grey) and without (black) Paexo.*

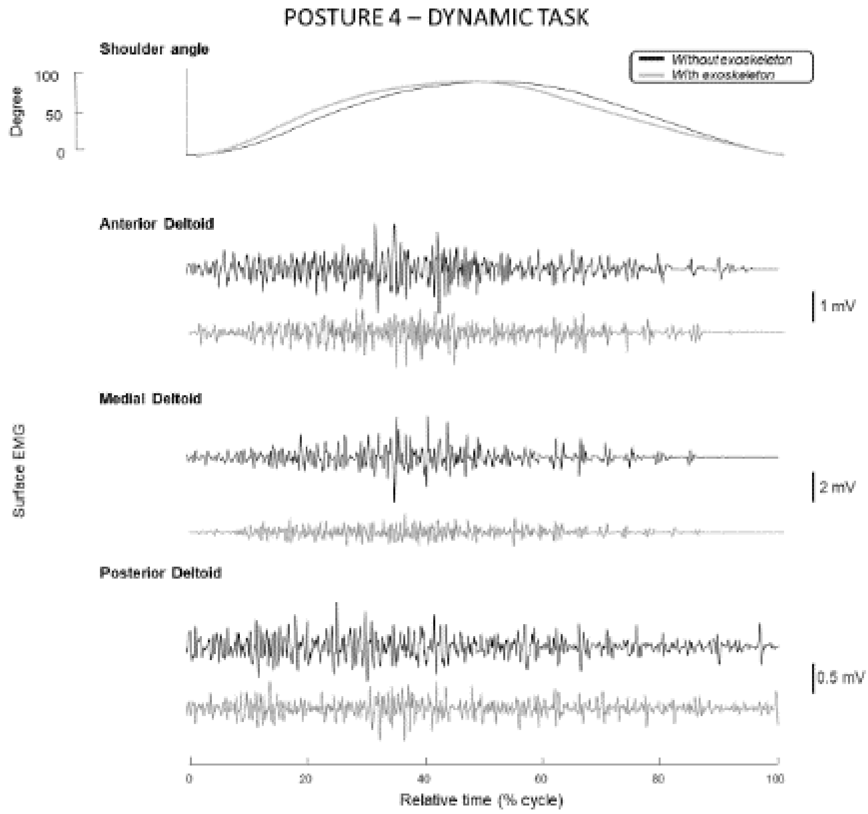



*Figure 16: (A) Shoulder angle in the frontal plane and bipolar EMGs sampled from the three portions of deltoid muscle (left side), acquired during a single cycle while subject repeated 15 consecutive times the Posture 4 with (grey) and without (black) Paexo.*

## Considerations from group data

### *Static trial*

Visual inspection of group data suggests the amplitude of EMGs generally decreased when participants wore Paexo during the static condition, regardless of duration and posture (Figure 17). ANOVA did not reveal a significant main effect for Duration on the EMG amplitude ($F<2.51$, $p>0.11$ for all cases). In general, however, no significant differences in the relative variation in EMG amplitude were observed between trials of different durations for all muscles, indicating the percent decrease in EMG amplitude is likely to manifest equally in tasks of different durations.

ANOVA also demonstrated no interaction between Duration and Posture for all the muscles under investigation ($F<0.74$, $p>0.52$).

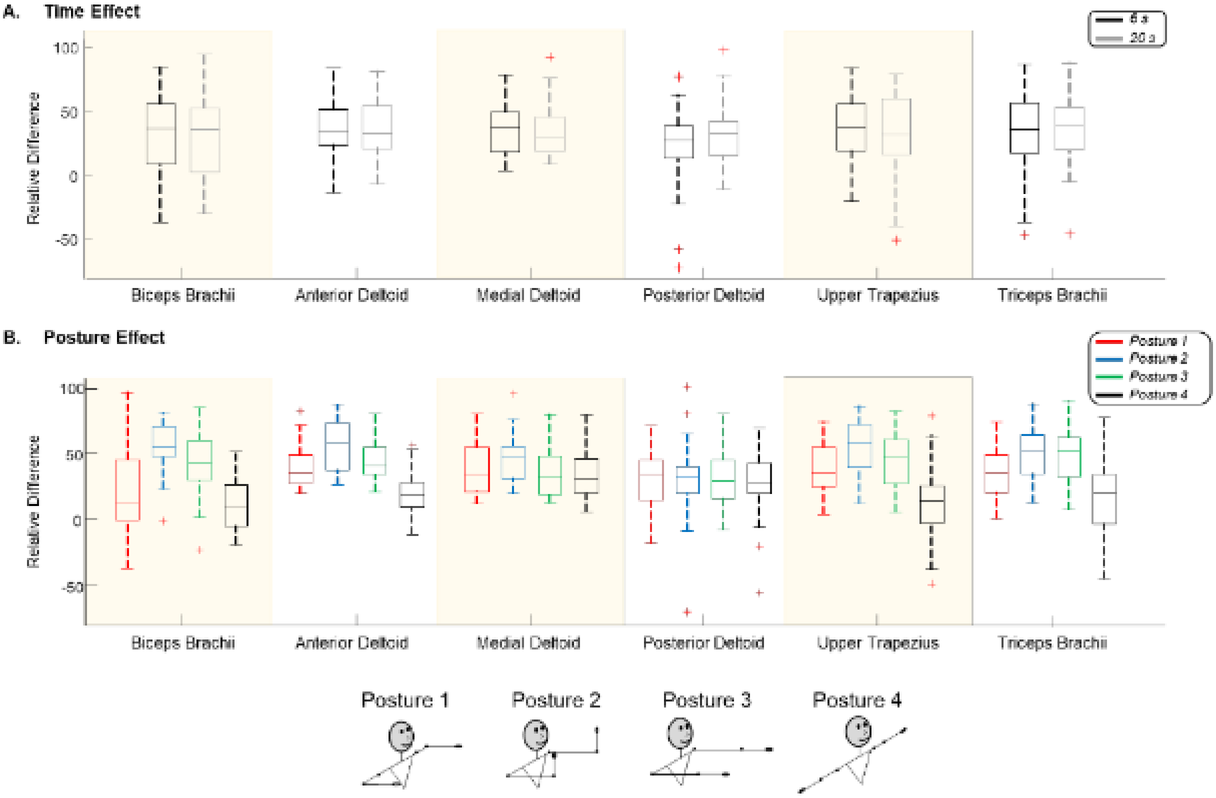



*Figure 17: Median and interquartile intervals of the percent reductions in the EMG amplitude for all muscles evaluated during the static condition. Positive values indicate percent decrease in EMG amplitude with the use of Paexo. Boxplots in (A) show the relative variation in EMG amplitude, pooled across postures, for each muscle and for static trials lasting 6s (black) and 20s (grey). Boxplots in (B) show group data for the relative variation in EMG amplitude, pooled across static trials of different durations, for each posture and muscle. Red crosses denote outlier value.*

### *Dynamic trial*

Visual inspection of group data suggests the amplitude of EMGs generally decreased when participants wore Paexo, in both concentric and eccentric phases (Figure 18). During eccentric contractions, however, in particular for postures 2 and 3, wearing Paexo resulted in a percent increase in EMG amplitude for triceps brachii and upper trapezius (Figure 18). The higher EMG amplitude for these muscles with than without Paexo could be presumably due to the resistance provided by the exoskeleton to shoulder extension for returning to the reference anatomical position. These results indicate the global, attenuation effect of Paexo on muscle excitation was phase dependent for specific muscles and postures during the dynamic condition.

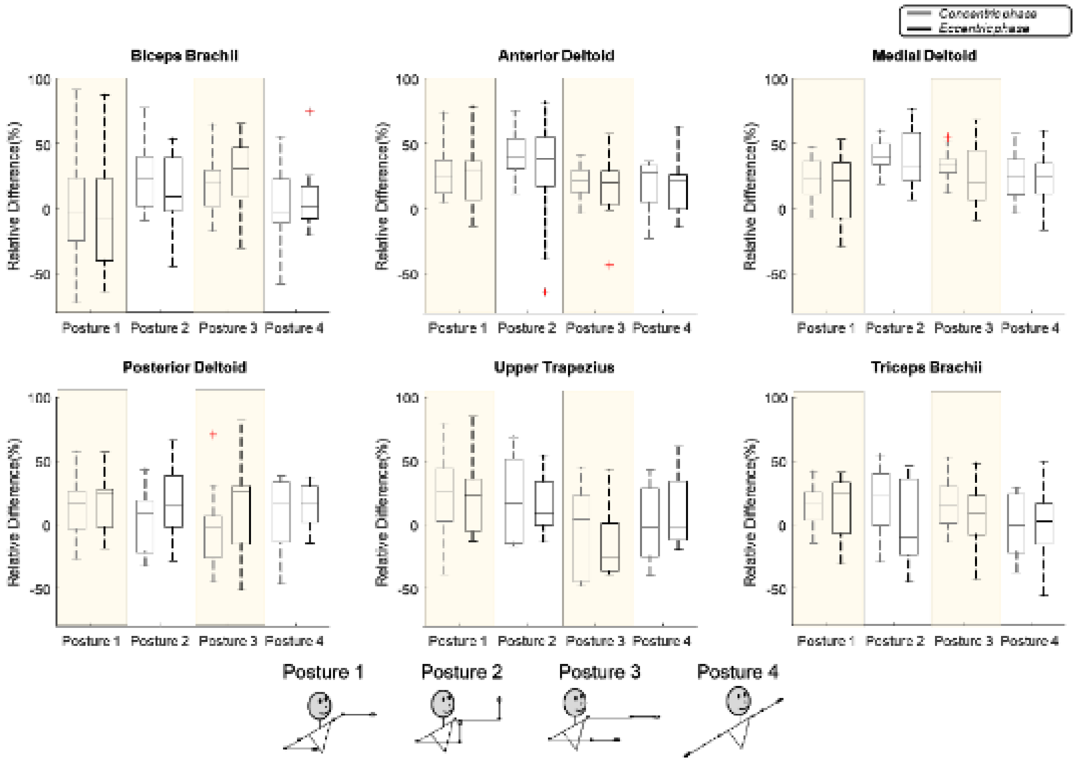



*Figure 18: Boxplots showing percent reductions in EMG amplitude during the concentric (grey boxes) and eccentric (black boxes) phases of dynamic trials. Positive values indicate percent decreases in EMG amplitude with Paexo. Red crosses denote outlier value.*

## Range of motion

Considering subjects started from the anatomical reference position, range of motion values closer to 90° would imply maximal, gravity torque over the shoulder joint. Statistical analysis indicated that range of shoulder motion was significantly lower with than without Paexo, with differences in range of motion between conditions amounting to less than 6° across subjects. Given the shoulder was on average at 90° of flexion or extension, this 6° difference would correspond to less than 1% decrease in gravity moment over the shoulder. This figure is somewhat small and therefore is unlikely to affect the overall percent reduction in muscle effort reported in the next section.

## Conclusive remarks

In this section we summarize the relative, effort reduction when subjects performed static and dynamic trials while wearing Paexo. Relative, effort reduction is presented separately for each of the four postures and for the static and dynamic trials. Specific muscles were selected for defining the percent reduction in the effort level. The choice of muscles was motivated by their mechanical action over the body segments for the different postures evaluated. The percent reduction in muscle excitation was computed by averaging the relative reduction in EMG amplitude across specific muscles. For the dynamic conditions, the average relative reduction was computed considering both concentric and eccentric phases.

*Table 2 - Muscles considered for static conditions and percentage reduction of muscle effort – **Static***

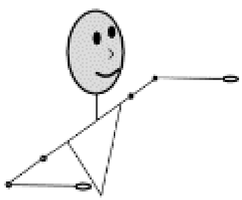
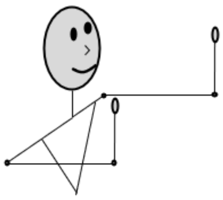
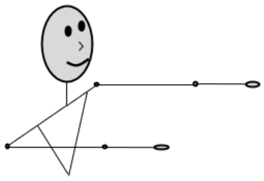
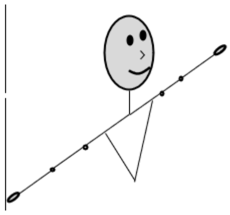
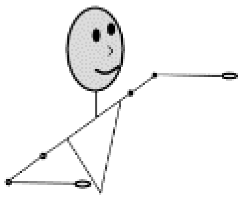
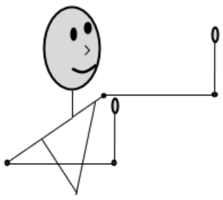
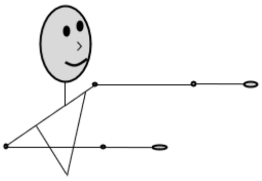
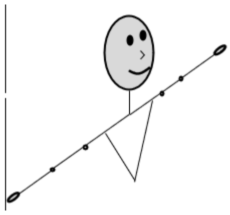
| **Posture** | | | |
|---|---|---|---|
|  |  |  |  |
| **Muscle considered** | | | |
| Trapezius<br>Medial deltoid | Trapezius<br>Anterior deltoid<br>Biceps brachii | Trapezius<br>Anterior deltoid<br>Biceps brachii | Trapezius<br>Medial deltoid<br>Anterior deltoid<br>Posterior deltoid |
| **Relative, effort reduction** | | | |
| **36%** | **51%** | **40%** | **21%** |

*Table 3 - Muscles considered for dynamic conditions and percentage reduction of muscle effort – **Dynamic***

| **Posture** | | | |
|---|---|---|---|
|  |  |  |  |
| **Muscles considered** | | | |
| Trapezius<br>Medial deltoid<br>Posterior deltoid | Trapezius<br>Anterior deltoid<br>Posterior deltoid<br>Biceps Brachii | Trapezius<br>Anterior deltoid<br>Posterior deltoid<br>Biceps Brachii | Trapezius<br>Medial deltoid<br>Anterior deltoid<br>Posterior deltoid |
| **Relative, effort reduction** | | | |
| **22%** | **22%** | **11%** | **17%** |

# Impact on EAWS

## Section 0

**Impact of wearing an exoskeleton during work tasks on Extra Points**

The use of an exoskeleton generates a trade-off, where the positive effect of reducing the bio-mechanical load is mitigated by an increase of load or discomfort due to a reduced capacity of movement and an increased weight to support.

To consider the negative effect of wearing an exoskeleton, the following criteria have been adopted to provide a standard value of extra points (use line 0e) to be considered in the Whole Body index calculation.

Line 0e = + 1 point to score the discomfort of wearing the exoskeleton – Base Value

Line 0e = + 1 point for each further requirement not met

**Requirements**

- TORQUE SUPPLY FUNCTION
  - zero torque at flexion angle 0°;
  - max torque at flexion angle 90°;
  - continuity during torque supply;
  - torque tuning
- PASSIVE KINEMATIC CHAIN
  - shoulder motion freedom;
  - absence of encumbrance on the upper side of the shoulder (relatively to the type of workstation where the exoskeleton is used);
- PHYSICAL HUMAN ROBOT INTERFACE
  - sizes and regulations to fit the device on specific users available;
  - breathable material;
  - no overheating;
  - contact area to distribute reaction forces without causing high force points;
- SAFETY AND USABILITY
  - Weight < 3kg = 0 points | Weight < 4,5 kg = 1 point | Weight < 6 kg = 2 points | Weight >= 6 kg = 5 point
  - no or very limited encumbrance outside the operator's body;
  - no entanglement prone protruding parts

*Note about "weight": The weight is the only requirement assessed on different degrees of intensity. All other requirements follow an on-off criteria.*

**Paexo Shoulder exoskeleton scoring on Section 0**

The Extra points for wearing **Paexo Shoulder exoskeleton** in Section 0 is assessed as follows

- TORQUE SUPPLY FUNCTION
  - zero torque at flexion angle 0°;
  - max torque at flexion angle 90°;

  - continuity during torque supply;
  - torque tuning

  Full support unfolds from 60 degree upwards.

- PASSIVE KINEMATIC CHAIN
  - shoulder motion freedom;
  - absence of encumbrance on the upper side of the shoulder (relatively to the type of workstation where the exoskeleton is used);
- PHYSICAL HUMAN ROBOT INTERFAC
  - sizes and regulations to fit the device on specific users available;
  - breathable material;
  - no overheating;
  - contact area to distribute reaction forces without causing high force points;
- SAFETY AND USABILITY
  - Weight < 3kg = **0 points**
  - no or very limited encumbrance outside the operator's body;
  - no entanglement prone protruding parts

**Total extra points for Paexo Shoulder exoskeleton = 1 point (Base Value)**

## Section 1

**Symmetric body postures involving shoulder**

In Section 1 EAWS deals with static body postures and the lines influenced by the use of the **Paexo Shoulder exoskeleton** are lines 5 and 6 (standing), 10 and 11 (sitting) and line 14 (crouching or kneeling).

Based on a massive sample of motion and time studies carried out by the Fondazione Ergo, we know that a representative distribution of frequencies of shoulder awkward posture in a typical manual industrial task is the following:

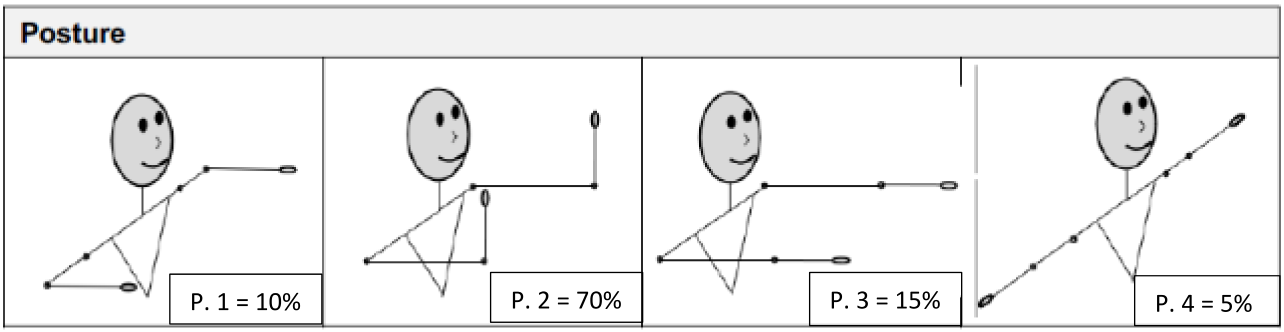



*Figure 19 - Analyzed shoulder postures*

Using the frequency values shown in Figure 19, the weighted average of the percentage reduction of muscular effort in static postures is 46,4%. Conservatively, the proposed EAWS reference score reduction is 40%.

The percentages of reduction of EAWS scores, calculated through the processing of laboratory values, were attenuated according to a prudential principle adopted in all development phases of the EAWS system. The intensity of the attenuation is proportional to the value of the reduction of the scores. All the reduction values of the EAWS scores generated by the correct use of the certified exoskeleton and published in this report have been approved by the Scientific Committee of the EAWS International Platform.

The reference percentage score reduction (RSR%) has been applied to Section 1 of the EAWS system only to Lines 10 and 11 (Sitting), in which the biomechanical load is completely driven by the awkward posture of the shoulder (sitting with proper back support does not generate significant biomechanical load).

Line 10b scores = Line 10a scores x (1 – 40%)

To calculate the percentage score reduction (SR%) for the other lines (5b, 6b and 14b), the following formula has been applied:

With reference to Figure 20 - Lines affected using the :

Line 5b scores = Line 5a scores – (Line 10a scores – Line 10b scores)

Line 6b scores = Line 6a scores – (Line 11a scores – Line 11b scores)

Line 14b scores = Line 14a scores – (Line 11a scores – Line 11b scores)

Where the difference (Line 11a scores – Line 11b scores) represents the reduction of score imputable to the effect of the exoskeleton on the shoulder.

**SECTION 1**

**STANDING**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | a | Elbow at/above shoulder level | 3,3 | 5 | 8,5 | 12 | 17 | 21 | 30 | 38 | 51 | 63 |
| | b | With certiied exoskeleton | 2,2 | 3,4 | 5,7 | 8,0 | 11,8 | 14,6 | 20,8 | 26,0 | 35,0 | 43,0 |
| | | **RS% w/certified exoskeleton (ref. Line 10)** | **33%** | **32%** | **33%** | **33%** | **31%** | **30%** | **31%** | **32%** | **31%** | **32%** |
| 6 | a | Hands above head level | 5,3 | 8 | 14 | 19 | 26 | 33 | 47 | 60 | 80 | 100 |
| | b | With certiied exoskeleton | 3,7 | 5,6 | 10 | 13,4 | 18 | 23 | 33 | 42 | 56 | 70 |
| | | **RS% w/certified exoskeleton (ref. Line 11)** | **30%** | **30%** | **29%** | **29%** | **31%** | **30%** | **30%** | **30%** | **30%** | **30%** |

SITTING

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | a | Elbow at/above shoulder level | 2,7 | 4 | 7 | 10 | 13 | 16 | 23 | 30 | 40 | 50 |
| | b | With certiied exoskeleton | 1,6 | 2,4 | 4,2 | 6,0 | 7,8 | 9,6 | 13,8 | 18,0 | 24,0 | 30,0 |
| | | **RS% w/certified exoskeleton** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** |
| 11 | a | Hands above head level | 4 | 6 | 10 | 14 | 20 | 25 | 35 | 45 | 60 | 75 |
| | b | With certiied exoskeleton | 2,4 | 3,6 | 6 | 8,4 | 12 | 15 | 21 | 27 | 36 | 45 |
| | | **RS% w/certified exoskeleton** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** | **40%** |

CROUCHING

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | a | Elbow at/above shoulder level | 6 | 9 | 16 | 23 | 33 | 43 | 62 | 80 | 108 | 135 |
| | b | With certiied exoskeleton | 4,9 | 7,4 | 13,2 | 19,0 | 27,8 | 36,6 | 52,8 | 68,0 | 92,0 | 115,0 |
| | | **RS% w/certified exoskeleton (ref. Line 10)** | **18%** | **18%** | **18%** | **17%** | **16%** | **15%** | **15%** | **15%** | **15%** | **15%** |

*Figure 20 - Lines affected using the Paexo Shoulder*

**Asymmetric body postures involving shoulder**

The asymmetric body posture involving the shoulder is the “far reach” (see Figure 6 - EAWS Section 1: asymmetric body postures at page 10). In our study, that situation is represented by posture 3 in the following figure.

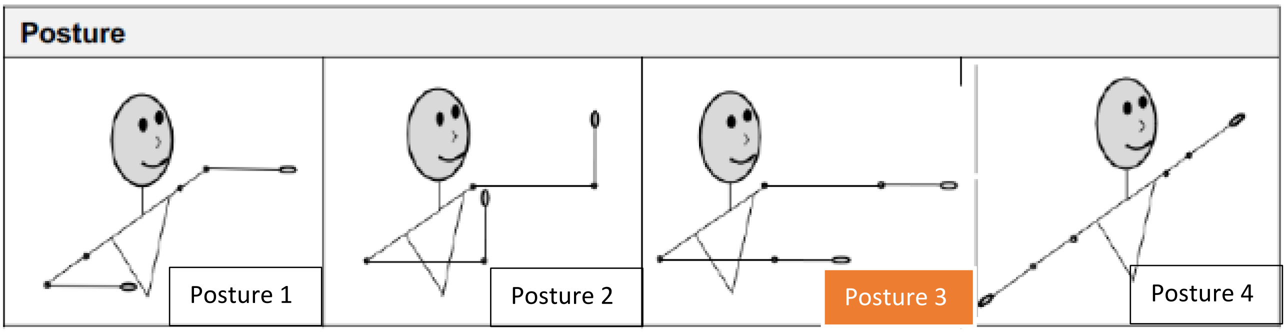



*Figure 21- Analyzed shoulder postures, asymmetric (far reach)*

In Table 2 - Muscles considered for static conditions and percentage reduction of muscle effort – **Static** at page 25, the percentage reduction for that posture is 40%, therefore we set the reference EAWS score reduction at 35% and applied that reduction to the score values of far reach intensity scale (see Figure 22 - Far reach intensity scale).

FAR REACH

| | | | | |
|---|---|---|---|---|
| a | Far Reach intensity | 1 | 3 | 5 |
| b | With certiied exoskeleton | 0,7 | 2,0 | 3,3 |
| | **RS% w/certified exosk. (Far-Reach Intensity scale)** | **35%** | **35%** | **35%** |

*Figure 22 - Far reach intensity scale*

## Section 4

Section 4 deals with the repetitive movements of the upper limbs, which tend to have a dynamic behavior rather than a static one. To set the percentage score reduction (SR%), we refer to Table 3 - Muscles considered for dynamic conditions and percentage reduction of muscle effort – **Dynamic** at page 26.

In Figure  we show the calculation of the RS% as the weighted average of the RS% of each posture studied. The weights have been set based on our extensive work analysis experience.

| Posture | 1 | 2 | 3 | 4 | WAVG |
|---|---|---|---|---|---|
| RS% | 22,0% | 22,0% | 11,0% | 17,0% | **20,1%** |
| weight | 10,0% | 70,0% | 15,0% | 5,0% | 100,0% |

*Figure 23 - SR% dynamic actions*

Based on the weighted average result, we set the RS% for the dynamic shoulder postures at 20%.

Line 20b in Section 4 is redesigned as it appears in Figure :

**SECTION 4**

| | | | 10% | 25% | 33% | 50% | 65% | 85% |
|---|---|---|---|---|---|---|---|---|
| 20b | | **Posture points (Duration)** | 10% | 25% | 33% | 50% | 65% | 85% |
| | a | Intensity | 0 | 0,5 | 1 | 2 | 3 | 4 |
| | b | Intensity w / certified exoskeleton (only for shoulders) | 0,0 | 1,2 | 2,4 | 4,8 | 7,2 | 9,6 |

*Figure 24 - Section 4, Intensity Posture Scores*

## Project specification

Although the number of studies has grown over the last years there are still several open questions related to the benefits and risks of using exoskeletons. It is necessary to start thinking about how to integrate exoskeletons in the form of EAWS assessment. The ESO-EAWS project by Fondazione Ergo in cooperation with the Polytechnic of Torino and the University of Bologna is a first step towards an integration of exoskeletons into the EAWS system.

The integration of exoskeletons in the EAWS sheets is actually focused on workplace design and not related to risk prevention. When using an exoskeleton validated for the lowering of biomechanical load the EAWS points for the corresponding postures decrease, indicating a less prejudicial working condition. The consequences of wearing an exoskeleton on musculoskeletal complaints and disorders have to be studied over a longer period of time and with data from field studies conducted in the industry.

The reduction of EAWS score is an indication of an improvement of working conditions. With reference to this study, such an improvement is limited to specific situations in which shoulder awkward postures are relevant in intensity and duration. The study also provided an evaluation of the counter-effects due to:

- torque supply function
- passive kinematic chain
- physical human-robot interface
- safety and usability.

These counter-effects generates extra-points in section 0 of the Eso-EAWS form, which balance out the reduction of scores of Section 1 (Body Postures) if the shoulder awkward postures do not generate a minimum level of biomechanical load. The conclusions of the study will limit the adoption of the exoskeleton only to the specific situations where they become relevant.

The study design used in the ESO-EAWS project, alongside the results obtained, is very much in line with many of the research studies carried out by Ottobock in the last few years.

This refers to the number and nature of test persons (Number: 10-20 in many cases; Gender: male in nearly all cases; Age: category 20-30 in many cases). By using electromyography as a proxy of active muscle loading, the ESO-EAWS project corroborates existing studies with Paexo.

The focus on limited tasks to fulfil with an exoskeleton is also typical for the majority of these existing studies.

Due to the specific and well-defined focus we did not compare our results with those reported in other studies with Paexo. To rescale the points associated with specific postures in the EAWS system, a general indication of the degree of reduction of muscular effort when wearing Paexo during maintenance of these specific postures was warranted. This could be achieved only through the monitoring of the amplitude of surface electromyograms collected from a set of upper limb muscles, mostly likely elicited when maintaining the specific postures object of evaluation in the EAWS scale. For this reason, an ad-hoc protocol was conducted, which results corroborate the general biomechanical relief offered by Paexo as assessed in terms of joint compression forces and physiological parameters (heart rate, oxygen consumption).

More details about other studies of Ottobock are available at the following link:

- EU project Andy - https://www.tandfonline.com/doi/full/10.1080/10255842.2020.1714977
- "Objective and Subjective Effects of a Passive Exoskeleton on Overhead Work": https://hal.archives-ouvertes.fr/hal-02301922/document
- Biomechanical and Metabolic Effectiveness of an Industrial Exoskeleton for Overhead Work https://www.mdpi.com/1660-4601/16/23/4792/htm
- Principle study about the effect of an industrial exoskeleton on overhead work: https://paexo.com/wp-content/uploads/2019/11/OT-Study-Paexo-Shoulder-EN.pdf.

# Final recommendations

With reference to the considerations mentioned in the (2019) European Agency for Safety and Health at Work's publication **"The impact of using exoskeletons on occupational safety and health"**:

*"The most important concern is that caution should be exercised when using technology so close to the human body. Technical and organizational measures should be taken into account when designing workplaces, before employees are equipped with exoskeletons. In general, using exoskeletons to improve the ergonomic design of workplaces should always be the last resort."*

*"It should be mentioned that the use of exoskeletons to improve the ergonomic design in stationary workplaces cannot be recommended, but there are also a vast number of non-stationary or mobile workplaces in which ergonomic measures are not possible. In this context, exoskeletons may offer a promising approach to reduce WRMSDs in future."*

we point out some recommendations regarding the use of S01 (passive upper limb) exoskeletons.

The use of an exoskeleton should be limited in a **proper application field,** which is defined by the following characteristics:

- Method re-design, which remains the main strategy to improve productivity and reduce biomechanical load, is not possible nor justifiable.
- The benefit of using S01 exoskeletons is relevant when the duration of shoulder awkward postures represents at least 1/3 of the cycle time.
- Maximum benefit of using S01 exoskeletons is achievable with static postures.
- Handling light components/tools (weight < 3 kg)
- Worker is standing in a sufficiently wide space (free workplace radius > 1 m and components/tools are not bulky)

## Certification of the exoskeleton Paexo Shoulder

The results of the study confirm the biomechanical load reduction effect, measured by the EAWS system, generated by awkward shoulder postures in both static and dynamic situations.

The application of the reduced scores shown on the modified EAWS form (called Paexo ESO-EAWS) is conditioned using an exoskeleton certified by the Fondazione Ergo. The certification procedure is the procedure that was designed and applied in this study.

**Paexo Shoulder, used to conduct the study, is therefore certified by the Fondazione Ergo as an effective tool to reduce the EAWS score of Section 1 and Section 4, where awkward shoulder postures are involved. This certification must be renewed whenever Paexo Shoulder undergoes changes.**

# Paexo ESO-EAWS form – Section 1

**Basic Positions / Postures and movements of trunk and arms (per shift)** — **Postures**

(incl. loads of <3 kg,
forces onto fingers of <30 N
and w hole body forces of <40 N)

Static postures: ≥ 4 s

High frequency movements:
Trunk bendings (> 60°) ≥ 2/min
Kneeling/crouching ≥ 2/min
Arm liftings (> 60°) ≥ 10/min

Symmetric: Evaluation of static postures and/or high frequency movements of trunk/arms/legs

Duration [s/min] = $\frac{\text{duration of posture [s]} \times 60}{\text{Task duration [s]}}$

Asymmetric: Trunk Rotation; Lateral Bending 1); Far Reach 2) — int / dur: 0-5 / 0-3 (Trunk Rotation); 0-5 / 0-3 (Lateral Bending); 0-5 / 0-2 (Far Reach); Intensity × Duration

| | | | | | | | | | | | | Sum of lines | Trunk Rotation (Intensity × Duration) | Lateral Bending 1) (Intensity × Duration) | Far Reach 2) (Intensity × Duration) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [%] | | 5 | 7,5 | 10 | 15 | 20 | 27 | 33 | 50 | 67 | 83 | | | |
| | [s/min] | | 3 | 4,5 | 6 | 9 | 12 | 16 | 20 | 30 | 40 | 50 | | | |
| | [min/8h] | | 24 | 36 | 48 | 72 | 96 | 130 | 160 | 240 | 320 | 400 | | | |
| **Standing (and walking)** | | | | | | | | | | | | | | | |
| 1 | Standing & w alking in alteration, standing w ith support | | 0 | 0 | 0 | 0 | 0,5 | 1 | 1 | 1 | 1,5 | 2 | | | | |
| 2 | Standing, no body support (for other restrictions see Extra Points) | | 0,7 | 1 | 1,5 | 2 | 3 | 4 | 6 | 8 | 11 | 13 | | | | |
| 3 | a | Bent forw ard (20-60°) | 2 | 3 | 5 | 7 | 9,5 | 12 | 18 | 23 | 32 | 40 | | | | |
| | b | with suitable support | 1,3 | 2 | 3,5 | 5 | 6,5 | 8 | 12 | 15 | 20 | 25 | | | | |
| 4 | a | Strongly bent forw ard (>60°) | 3,3 | 5 | 8,5 | 12 | 17 | 21 | 30 | 38 | 51 | 63 | | | | |
| | b | with suitable support | 2 | 3 | 5 | 7 | 9,5 | 12 | 18 | 23 | 31 | 38 | | | | |
| 5 | a | Elbow at/above shoulder level | 3,3 | 5 | 8,5 | 12 | 17 | 21 | 30 | 38 | 51 | 63 | | | | |
| | b | With certif. exoskeleton | 2,2 | 3,4 | 5,7 | 8,0 | 11,8 | 14,6 | 20,8 | 26,0 | 35,0 | 43,0 | | | | |
| 6 | a | Hands above head level | 5,3 | 8 | 14 | 19 | 26 | 33 | 47 | 60 | 80 | 100 | | | | |
| | b | With certif. exoskeleton | 3,7 | 5,6 | 10,0 | 13,4 | 18,0 | 23,0 | 33,0 | 42,0 | 56,0 | 70,0 | | | | |
| **Sitting** | | | | | | | | | | | | | | | |
| 7 | Upright w ith back support slightly bent forw ard or backw ard | | 0 | 0 | 0 | 0 | 0 | 0 | 0,5 | 1 | 1,5 | 2 | | | | |
| 8 | Upright no back support (for other restriction see Extra Points) | | 0 | 0 | 0,5 | 1 | 1,5 | 2 | 3 | 4 | 5,5 | 7 | | | | |
| 9 | Bent forw ard | | 0,7 | 1 | 1,5 | 2 | 3 | 4 | 6 | 8 | 11 | 13 | | | | |
| 10 | a | Elbow at / above shoulder level | 2,7 | 4 | 7 | 10 | 13 | 16 | 23 | 30 | 40 | 50 | | | | |
| | b | With certif. exoskeleton | 1,6 | 2,4 | 4,2 | 6,0 | 7,8 | 9,6 | 13,8 | 18,0 | 24,0 | 30,0 | | | | |
| 11 | a | Hands above head level | 4 | 6 | 10 | 14 | 20 | 25 | 35 | 45 | 60 | 75 | | | | |
| | b | With certif. exoskeleton | 2,4 | 3,6 | 6,0 | 8,4 | 12,0 | 15,0 | 21,0 | 27,0 | 36,0 | 45,0 | | | | |
| **Kneeling or crouching** | | | | | | | | | | | | | | | |
| 12 | Upright | | 3,3 | 5 | 7 | 9 | 12 | 15 | 21 | 27 | 36 | 45 | | | | |
| 13 | Bent forw ard | | 4 | 6 | 10 | 14 | 20 | 25 | 35 | 45 | 60 | 75 | | | | |
| 14 | a | Elbow at / above shoulder level | 6 | 9 | 16 | 23 | 33 | 43 | 62 | 80 | 108 | 135 | | | | |
| | b | With certif. exoskeleton | 4,9 | 7,4 | 13,2 | 19,0 | 27,8 | 36,6 | 52,8 | 68,0 | 92,0 | 115 | | | | |
| **Lying or climbing** | | | | | | | | | | | | | | | |
| 15 | (Lying on back, breast or side) arms above head | | 6 | 9 | 15 | 21 | 29 | 37 | 53 | 68 | 91 | 113 | | | | |
| 16 | Climbing | | 6,7 | 10 | 22 | 33 | 50 | 66 | | | | | | | | |
| | | | | | | | | | | | | | ∑ (a) | ∑ (max.=15) | ∑ (max.=15) | ∑ (max.=10) |
| | | | | | | | | | | | | | | ∑ (max. = 40) (b) | | |

1) Trunk

| | | 0 | 1 | 3 | 5 |
|---|---|---|---|---|---|
| Trunk | int | slightly ≤10° | medium 15° | strongly 25° | extreme ≥30° |
| | | 0 | 1,5 | 2,5 | 3 |
| | dur | never 0% | 4 s 6% | 10 s 15% | ≥ 13 s ≥ 20% |

2) Far Reach

| | | 0 | 1 (0,7) | 3 (2) | 5 (3,3) |
|---|---|---|---|---|---|
| Far Reach | int | close | 60% | 80% | arm stretched |
| | | 0 | 1 | 1,5 | 2 |
| | dur | never 0% | 4 s 6% | 10 s 15% | ≥ 13 s ≥ 20% |

note: Max. duration of evaluation = duration of task or 100%!

note: correct evaluation, if task duration ≠ 60 s

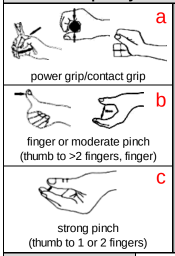
| | | | | | |
|---|---|---|---|---|---|
| **Postures = ∑ lines 1 - 16** | (a) | + | (b) | = | |

*Figure 25 - ESO-EAWS form, Section 1*

# Paexo ESO-EAWS form – Section 4

| Upper limb load in repetitive tasks | Upper Limbs |
|---|---|

**Force & Frequency & Grip (FFG)** — Basis: number of real actions per minute or percent static actions (analyze only the most loaded limb)




| Legend | | |
|---|---|---|
| | %SA = Percentage of Static Actions | %DA = 100% - %SA |
| | FDS = Force-Duration Static | FFD = Force-Frequency Dynamic |
| | GS' = Modified Grip Points Static (Grip x %SA) | GD = Grip Points Dynamic |
| | %FLS = Percentage of Static Actions at force level | %FLD = Percentage of Dynamic Actions at force level |
| | SC = Static Contribution | DC = Dynamic Contribution |
| | FDGS = Sum of Static Contributions | FFGD = Sum of Dynamic Contributions |

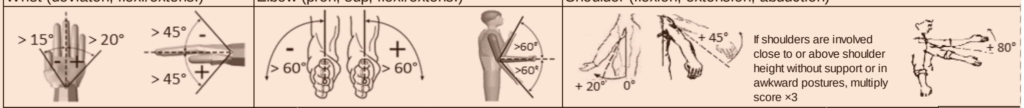
| Force [N] | Calc Stat | | | | Static actions (s/min) | | | | | | Grip | | | Dynamic actions (real actions/min) | | | | | | | | Calc Dyn | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FDS | GS' | %FLS | SC | ≥45 | 30 | 20 | 10 | 5 | 3 | 0 | 2 | 4 | 2-5 | 10 | 15 | 20 | 25 | 30 | 35 | ≥40 | FFD | GD | %FLD | DC |
| 0 – 5 | | | | | 1 | 1 | 0 | 0 | 0 | 0 | abc | | | 0 | 0 | 0 | 1 | 2 | 3 | 4 | 7 | | | | |
| > 5 – 20 | | | | | 4 | 2 | 1 | 1 | 0 | 0 | ab | bc | | 0 | 0 | 1 | 2 | 3 | 4 | 6 | 9 | | | | |
| > 20 – 35 | | | | | 7 | 5 | 3 | 2 | 1 | 1 | ab | b | c | 0 | 1 | 2 | 3 | 4 | 6 | 8 | 12 | | | | |
| > 35 – 90 | | | | | 11 | 8 | 5 | 3 | 2 | 1 | a | b | b | 1 | 2 | 3 | 5 | 7 | 9 | 12 | 18 | | | | |
| > 90 – 135 | | | | | 16 | 11 | 7 | 4 | 3 | 2 | a | ab | b | 2 | 3 | 5 | 7 | 9 | 12 | 15 | ***24*** | | | | |
| > 135 – 225 | | | | | ***21*** | 14 | 10 | 6 | 4 | 3 | a | a | b | 4 | 5 | 6 | 8 | 11 | 14 | ***20*** | ***32*** | | | | |
| > 225 – 300 | | | | | ***28*** | 18 | 12 | 8 | 5 | 4 | a | a | b | 5 | 6 | 7 | 9 | 12 | 16 | ***26*** | ***40*** | | | | |

S D

| 20a | FDGS = ∑ $SC_i$ | 100% | | **FFG** = FDGS + FFGD | FFG | %DA = ΣFLDj | FFGD = ∑ $DC_j$ | %DA | |
|---|---|---|---|---|---|---|---|---|---|

**Hand / arm / shoulder postures (use duration for worst case of wrist / elbow / shoulder)**

| | Wrist (deviaton, flex./extens.) | Elbow (pron, sup, flex./extens.) | Shoulder (flexion, extension, abduction) |
|---|---|---|---|




| 20b | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Posture points** | 10% | 25% | 33% | 50% | 65% | 85% | PP |
| | Wrist/Elbow | 0 | 0,5 | 1 | 2 | 3 | 4 | |
| | Shoulder | 0 | 1,5 | 3 | 6 | 9 | 12 | |
| | Shoulder w/exosk | 0 | 1,2 | 2,4 | 4,8 | 7,2 | 9,6 | |

**Additional factors**

| 20c | | | |
|---|---|---|---|
| | Gloves inadequate (which interfere with the handling ability required) are used for over half the time | 2 | ☐ |
| | Working gestures required imply a countershock. Frequency of 2 time per minute or more (i.e.: hammering over hard surface) | 2 | ☐ |
| | Working gestures imply a countershock (using the hand as a tool) with freq. of 10 time per hour or more | 2 | ☐ |
| | Exposure to cold or refrigeration (less than 0 degree) for over half the time | 2 | ☐ |
| | Vibrating tools are used for 1/3 of the time or more | 2 | ☐ |
| | Tools with a very high level of vibrations | 4 | ☐ |
| | Tools employed cause compressions of the skin (rednesses, callosities, blebs, etc.) | 2 | ☐ |
| | Precision tasks are carried out for over half the time (tasks over areas smaller than 2-3 mm) | 2 | ☐ |
| | More than one additional factor is present at the same time and overall occupy the whole of the time | 3 | ☐ |
| | **Additional points (choose the highest value)** | = | AF |

**Repetitive tasks duration**

| 20d | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Net Duration [min/shift] | < 60 | 90 | 180 | 300 | 420 | > 480 | | | + |
| | *Duration Points* | 1 | 1,5 | 3 | 5 | 7 | 10 | | | |
| | Work Organization | Breaks are possible at every time (Cycle time longer than 10 minutes) | | Breaks are possible at given conditions (Cycle time between 1 and 10 minutes) | | Breaks lead to a stop of the process (Cycle time shorter than 1 minute) | | | | + |
| | *Work Organization Points* | 0 | | 1 | | 2 | | | | |
| | Breaks (≥ 8 min) [#/shift] | 0 | 1 | 2 | 3 | 4 | 5 | 6 | ≥7 | + |
| | *Break points* — *cycle time ≤ 30 s* | 3 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | |
| | *cycle time > 30 s* | 0 | | -0,5 | | -1 | | -1,5 | -2 | |
| | **Duration Points** | | | | | | | | | = DP |

**Upper limb load in repetitive tasks**

| | (a) Force & Frequency & Grip | | (b) Postures | | (c) Additional factors | | (d) Duration | | Upper Limbs |
|---|---|---|---|---|---|---|---|---|---|
| **20** | ( FFG | + | PP | + | AF ) | × | DP | = | |

*Figure 26 – Paexo ESO-EAWS form, Section 4*

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