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Use of wearable sensors for continuous field monitoring of upper arm and trunk postures among construction workers

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Abstract

Construction is considered amongst the highest risk sectors for the development of work-related musculoskeletal disorders (MSDs) considering the large number of unfavorable environmental and task-specific factors typical in this sector. Thus, it is important to have quantitative tools to support the assessment of the exposure to physical MSD risk factors. We employed wearable inertial sensors (ISs) to perform a real-world characterization of static postures and repetitive movements involving the trunk and upper arms (UA), among 15 workers during 2 hours of their regular shifts. IS data were processed according to ISO 11226 and EN 1005-4 standards. We found that workers spent ~25% of the monitored time in static trunk flexion >20° and more than 50% of the time with UA elevations >20°. The ability to assess working postures for prolonged periods may represent a useful tool for different stakeholders involved in the protection of construction worker health.

Keywords

Posture, field study, inertial sensors, construction

Practitioner summary

We demonstrated that a simplified setup comprising three miniaturized wearable inertial sensors can quantify trunk and upper arm postures among workers of the construction sector during actual shifts, with limited task interference and a good level of acceptability.

• Introduction

Construction is considered amongst the work sectors with highest of developing work-related musculoskeletal disorders (MSDs) (Yu et al, 2021). Indeed, workers are frequently exposed to overexertion, non-neutral posture, and repetitive motions, all of which are recognized risk factors for work-related musculoskeletal disorders (Wang et al., 2015; Wang et al., 2017). All these characteristics make the construction sector increasingly unattractive for younger individuals (Maqbool et al., 2024) and, in older workers, increase the possibility of early retirements due to the combination of general high physical requirements (Szubert and Sobala, 2005; Jebens et al., 2014) and repeated extreme bending of the back (Lund et al., 2001). It is thus crucial to improve working conditions in construction to the extent possible, both to promote health and workability among older workers, and to make the job more attractive for young apprentices. In this context, it is extremely important to have available tools able to collect reliable and quantitative information about exposure to physical factors at the workplace, as such data can effectively facilitate the identification of working conditions that require ergonomics interventions, and support the development of interventions, such as through task redesigns or the use of more complex assistive devices (e.g., exoskeletons).

In the last decades, both the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) in the U.S. have highlighted the importance of a correct assessment of exposure to physical risk factors to minimize the impact of occupational hazards on the development of MSDs among construction workers (Albers, 2007). Recently, an interesting analysis of traditional methods and emerging trends for the assessment of risk factors for the development of MSDs in construction was reported (Vijayakumar and Choi, 2022). The most common approaches involve self-report and observational methods, such as the Posture Activity Tools Handling (PATH, Buchholz et al., 1996), the Ovako Working posture Analysis System (OWAS, Scott and Lambe, 1996), the Rapid Entire Body Assessment (REBA, Hignett and McAtamney, 2000), and the Rapid Upper Limb Assessment (RULA, McAtamney and Corlett, 1993). While these tools offer the advantage of being versatile and not requiring specific equipment, they are less applicable in cases of non-repetitive and/or highly dynamic tasks that are typical of many construction activities. In fact, the complex nature of much construction work makes it difficult to standardize the evaluation process and to extend the results of a brief assessment to a whole work-shift (Wang et al., 2015).

To help overcome such limitations, there have been recent effort to introduce the use of quantitative instrumentation methods, such as motion capture systems (based on inertial sensors or depth and RGB cameras) and surface electromyography, which can be useful to support the assessment of

physical risk factors (Yu et al.,2021). However, applications to construction activities have been mostly conducted in controlled laboratory environments with samples often including novice and young participants, thus limiting the generalizability of the obtained results to real-life conditions (Antwi-Afari et al., 2023). Indeed, the use of such techniques in a real working context, particularly a construction site, must address important specific challenges. First, most construction sites include large outdoor areas, making it difficult to use depth cameras due to lighting conditions (Yu et al.,2021). Second, the type, number, and placement of sensors can influence or constrain worker movements, or could be incompatible with personal protective equipment. Third, in real working environment there is limited time available for the setup and calibration of sensors. As a consequence, a practical data collection setup for in-field assessment requires a compromise between best accuracy (achievable in laboratory) and best utility (to support an assessment by ergonomics practitioners).

Based on these considerations, our main purpose in the present study was to obtain quantitative data about trunk and upper arm (UA) postures in “real-world” working environments during regular shifts, which was considered useful to support a more accurate assessment of biomechanical factors important in the development of MSDs. We used a setup comprising a reduced number of wearable inertial sensors (ISs), characterized by limited intrusiveness for the workers, compatible with personal protective equipment, and suitable to ensure freedom of movement in large outdoor environments. The raw data obtained by the sensors were processed according to the international standards to provide information easily interpretable and useful to design ergonomic interventions aimed at reducing MSD risk.

• Methods

2.1. Participants

Fifteen male professional full-time construction workers participated in the study on a voluntary basis. All were full-time, professionals who were employed by two different small companies (staff sizes of approximately 10 each) operating in Sardinia, Italy. According to the construction site schedule, the workers were assigned to the same series of activities, though for different time periods, which included excavation, concrete work, brick masonry, plastering, smoothing, and painting walls. After a detailed explanation of the purposes and methodology of the study, participants reviewed and signed an informed consent form. The study was carried out in compliance with the ethical principles for research involving human subjects expressed in the Declaration of Helsinki and its later amendments and received approval from the Ethical Commission of the University of Cagliari (UniCa - Prot. n. 0112541 del 01/06/2023 - [Classif. II/9]). Prior to data collection, all workers attended a brief meeting

during which we collected demographic and anthropometric characteristics (Table 1) as well as information about past and current MSDs.

Please insert Table 1 approximately here

- *Posture Assessment*
- *Data collection*

A simplified measurement setup (Figure 1), based on a limited number of ISs, was used to monitor trunk and upper arm (UA) postures during two hours of a regular work-shift. A 6-axis IS (3-axis accelerometer + 3-axis gyroscope, G-Sensor2, BTS, Bioengineering, Italy) was employed to assess trunk posture, which we have used previously (Porta et al., 2021; Porta et al., 2022). Two 3-axis ISs (3-axis accelerometer, GT3x-BT, Actigraph, Pensacola, USA) was used to assess UA elevation, and which was previously used with similar aims (Jakobsen et al., 2018; Villumsen et al., 2017; Schall et al., 2015; Korshøj et al., 2014). The G-Sensor2 was placed approximately at the level of the first lumbar vertebrae (Faber et al., 2009) using a dedicated semi-elastic belt, while the GT3x-BT sensors were placed on the UA, laterally, at the deltoid insertion (Korshøj et al., 2014) using a latex belt. Both devices had the ability for on-board data collection, which was set to 50 Hz.

Before any experimental session, participants were requested to stand still for 10s in a neutral, upright posture with their arms by sides; this activity was used to remove both subject-specific angular offsets and to calibrate the sensor relative to the anatomical axis. At the end of data collection, each worker participated in a brief interview aimed at understanding their experiences with wearing the sensors for two consecutive hours.

Please insert Figure 1 approximately here

- *Data processing*

Raw data collected by the three ISs were processed initially to obtain interpretable parameters in terms of posture. In particular, the G-Sensor2 provided Cardan angles (i.e. roll, pitch, and yaw). These angles were processed using a custom routine developed in Matlab (R2020b, MathWorks, Natick, MA, USA) to obtain trunk flexion-extension and lateral bending. Accelerations collected from the GT3x-BT were processed following the procedure suggested by Korshøj et al. (2014) to obtain UA elevation. For the UA, our analysis did not discriminate flexion from adduction, as these movement are not distinguished in the ISO 11226 standard. UA elevation with respect to a global reference frame was obtained using:

where a indicates acceleration signals and subscripts V , ML , and AP indicate the vertical, medio-lateral, and antero-posterior directions, respectively. Subsequently, UA elevation with respect to the global reference frame was corrected by considering the corresponding trunk inclination (Figure 2).

The time series of angle data were processed further to provide easily interpretable information in terms of “acceptable” or “not recommended” conditions, based on reference values presented in the ISO 11226 and EN 1005-4 standards. In particular, ISO 11226 indicates the maximum acceptable holding time for a static posture (longer than 4s), using a linear relationship (Figure 3), whereas EN 1005-4 defines the maximum number of movements considered acceptable for each class of inclination. Calculated parameters are reported in Tables 2 and 3. We also calculated the percentage of time spent in a non-neutral posture during the 2-hour monitoring periods.

Please insert Figure 2 approximately here

Please insert Figure 3 approximately here

Please insert Table 2 approximately here

Please insert Table 3 approximately here

- *Data Analysis*

Descriptive statistics for each parameter were obtained (mean, standard deviation, and range). To provide a better understanding of the exposures, the data were also summarized as follows:

- For each static trunk flexion and UA inclination, the frequency of movement was calculated and graphically represented as a function of amplitude and duration.
- For each class of movement indicated in EN 1005-4, the number of times a certain frequency of movements occurred was calculated (e.g., a frequency of 1 movement per minute occurred 100 times, a frequency of 2 movements per minute occurred 80 times, a frequency of 3 movements per minute occurred 80 times).
- For each class of movement indicated in EN 1005-4, the percentage of workers who carried out a certain number of movements per minute was calculated (e.g., 100% of workers carried out at least once 1 movement per minute, 100% of workers carried out

at least once 2 movements per minute, and 6.3% of workers carried out at least once 40 movements per minute).

• Results

Summary results regarding trunk and UA postures for the tested workers are provided in Tables 4 and 5

3.1. Trunk

Overall, the workers spent 29.5% of the working time with their trunk flexed $>20^\circ$; this proportion decreased to 23.7% when considering only static trunk flexion (i.e., longer than 4 seconds). In particular, 14.2% of the time involved static trunk flexion between 20 and 60° , only rarely exceeding the maximum acceptable holding time (mean of 0.3 times with a maximum of 2 times), while 9.5% (5.0%) of the monitored time was spent in flexion $>60^\circ$, which was equivalent to a mean (SD) of 42.9 (25.2) flexions exceeding 60° per worker.

The frequency of trunk flexion $>20^\circ$ varied depending on the specific amplitude and duration (Figure 4). Trunk flexion was typically between 20 and 70° and with a duration shorter than 20s. Also evident is that the construction workers spent 18.4% of the working time in an asymmetric trunk posture in terms of static lateral bending. However, the percentage was 5.5% when only lateral bending $>20^\circ$ was considered.

Please insert Figure 4 approximately here

Regarding the frequency of trunk movements, the threshold of two movements per minute for trunk flexion between 20 and 60° , and lateral bending between 10 and 20° (as per EN 1005-4), were generally exceeded; the mean number of flexions per minute was 2.4 and the mean number of lateral bendings per minute was 2.7 (Figures 5-6). However, it is noteworthy that there was large variability, as indicated by the values ranging between 0 and 24 for flexion, and between 0 and 28 for lateral bending. While the EN 1005-4 standard indicates that trunk flexion $>60^\circ$ and lateral bending $>20^\circ$ should be avoided, our data also indicate that such thresholds were frequently exceeded.

Please insert Figure 5 approximately here

Please insert Figure 6 approximately here

- *Upper arms*

Overall, construction workers spent 66.2% of the working time with their UA $>20^\circ$, though this proportional was reduced to 54.8% when considering only static elevation. Specifically, 31.3% of the monitored period was spent in static UA inclination between 20 and 60° , exceeding on average the maximum acceptable holding time by 1.2 times, and 23.5% in static UA inclination over 60° , which is equivalent to a mean of 87.6 UA inclinations over 60° per worker. Most static UA inclinations had an amplitude between 20 and 60° and with a duration shorter than 30s (Figure 7).

Please insert Figure 7 approximately here

Regarding the frequency of UA movements, the EN 1005-4 standard has different thresholds depending on the amplitude of the movements. Movements over 60° should be always avoided, while for movements between 20 and 40° frequencies between 2 and 10 per minute are considered acceptable and, for movements between 40 and 60° , the frequency should be fewer than 3 movements per minute. Such thresholds were not exceeded in our sample, except for the case of movement over 60° , with a mean of 4.9 movements per minute for inclination angles between 20 and 40° , and 1.3 movements per minute for inclination angles between 40 and 60° . However, these thresholds were exceeded several times by multiple workers (Figure 8).

Please insert Table 4 approximately here

Please insert Table 5 approximately here

- Discussion

We aimed to develop and employ a practical configuration of wearable sensors for “in-field” assessment of postural risk factors for the development of MSDs, balancing the need for providing quantitative exposure data (using sensors) with practical issues associated with the construction working environment (large outdoor areas, compatibility with personal protective equipment, etc.). In particular, we investigated the feasibility of use and effectiveness of an approach using ISs, to assess trunk and UA movements in terms of amplitude, frequency, and duration, among workers engaged in actual construction working tasks. Such information has been recognized as essential to detect potentially harmful behaviors in terms of work-related MSD risks, which are among the factors associated with the premature retirement of older workers (Lund et al., 2001). In particular, the interpretation of ISs data in the context of recommendations proposed by the ISO 11226 and EN

1005-4 standards may represent an effective, field-based approach to support the assessment of non-neutral postures and to then design targeted interventions among workers in the construction sector.

Data obtained from our monitoring showed that the workers spent an important part of their working time in non-neutral postures – approximately 30% with the trunk flexed $>20^\circ$ (of which $\sim 11\%$ over the non-recommended threshold of 60°) and more than 60% with the UA elevated $>20^\circ$ (of which more than 24% were over 60°). Such results are particularly concerning, as it was reported previously that workers who spend either more than 10% of their daily shift with trunk flexion exceeding 30° , or more than 5% of the time with trunk flexion exceeding 60° , are at an increased risk of low back disorders (Hoogendoorn et al., 2000; Coenen et al., 2013). Similar concerns exist regarding the data we obtained about UA elevation: van Rijn et al. (van Rijn et al., 2010) reported that working with the hand above shoulder level and working with the UA flexed over 45° for more than 15% of working time results in increased risk of shoulder MSD development.

To the best of our knowledge, no previous studies assessed construction worker trunk and/or UA postures in actual working environment using ISs; it is thus difficult to have a direct comparison with existing data. However, it is noteworthy that the values we obtained for trunk posture are similar to those reported using the PATH method (Buchholz et al., 1996). Specifically, workers employed in drywall settings were found to between 6 and 36.5% of the monitored time in severe ($>45^\circ$) trunk flexion (Dasgupta et al., 2014), while among those employed in constructing residential building the values were between 8.2 and 17.5% (Hajaghazadeh et al., 2019). Regarding asymmetrical trunk posture (e.g., trunk lateral bending), the same studies found that such postures were rarely observed (Dasgupta et al., 2014) or non-frequent (percentage of time ranging between 2 and 14%, Hajaghazadeh et al., 2019), while our results indicate that they occur quite often (35% of the monitored time). Since participants were observed under different conditions across each study, we cannot rule out that such contrasting results were influenced by the nature of the specific tasks performed. However, it is also possible that an observational assessment (using PATH) underestimates exposure to asymmetrical postures. Such errors could occur due to difficulties in capturing postures while the worker is wearing bulky clothes, or simply because these postures occur simultaneously with other investigated aspects (as trunk flexion) that are considered more relevant (Takala et al., 2010).

Regarding UA posture, Dasgupta et al. (2014) reported that workers spent between 22 and 25% of the monitored time in elevation above 60° during drywall layout and installation, similar to that reported here (23.5%). In contrast, Hajaghazadeh et al. (2019) found that UA postures above 60° were rare, while in our study the time spent with UA elevation $>60^\circ$ was 23.5% of the monitored time. Such differences can likely be explained by the different approaches used to assess exposure. Indeed, Dasgupta et al. (2014) and Hajaghazadeh et al. (2019) assessed exposures only during the execution of specific and well-defined working tasks, while data in our study refer to the overall 2-hour monitoring periods, during which a variety of tasks were likely performed. Although this hypothesis needs to be

confirmed in future studies (for instance by combining instrumental monitoring with objective video recording to precisely discriminate each task), it is reasonable to assume that the complexity of the construction activities, which are often articulated into multiple and varied tasks (Moriguchi et al., 2013), led to an overall physical exposure that is independent of the specific task. Taken together, these results suggest that ergonomic interventions to adapt both workplace and work demands for construction workers are needed to maintain their health, safety, and productivity as long as possible (Choi, 2009; Fan et al., 2023; Kowalski-Trakofler et al., 2005; Ranasinghe et al., 2023;), especially when considering their average high age (Ranasinghe et al., 2023; Choi, 2009).

Strengths and limitations of the study

The primary contribution of this study is in demonstrating the feasibility of using wearable ISs during construction field data collection to assess exposure to non-neutral postures associated with MSDs. Unlike many previous construction-relevant studies, which were based on experiments conducted with student/non-professionals participants and/or in controlled laboratory environments (Lim and D'Souza, 2020; Martins et al., 2024), our approach should have improved generalizability and ecological validity given the involvement of experienced professional workers in real-world settings. Collecting quantitative data in the construction environment presents unique challenges due to the dynamic and unpredictable nature of construction work. The current methods overcome these challenges and offer a practical approach to ergonomics risk assessment.

Of course, some limitations of the current study should be acknowledged. First, we collected and analyzed data about only a few body segments—specifically the trunk and upper arms. These segments were chosen because they are among the most involved in the development of MSDs in construction workers (Wang et al., 2017), though the lower limbs are also affected by work-related MSDs (e.g., hips and knees). We hesitate to recommend additional sensors to monitor lower limb postures, since the main advantage of our configuration was the good level of acceptability by the workers (as reported during the interviews), while also being fully compatible with all the challenges associated with the harsh conditions typical of the construction settings, such as an outdoor environment and variable working scenarios. In our approach, we excluded trunk rotation. Although certainly of interest, the latter was not considered due to the inability of our measurement setup to distinguish between **trunk rotations caused by rotations of the spine vs. rotations generated by the lower limbs (e.g., moving the feet)**. Using additional sensors on the pelvis or thighs would overcome this limitation, though again we are hesitant to recommend this. Second, we did not obtain concurrent video data along with that from the ISs. Our decision to not obtain video recordings was based on the typical conditions of construction sites making it difficult to obtain such data. While valuable for assessing overall ergonomic risks, the absence of detailed video-based task analysis makes it challenging to associate specific exposures with well identified tasks performed during the workday.

Third, our sample size was somewhat limited, primarily due to two factors. One factor was the inherent complexity of conducting quantitative measurements in field settings and the logistical challenges, such as requiring the availability and cooperation of workers and companies. The second factor was the typical structure of construction companies in Sardinia—and Italy more broadly—namely the small number of staff per company. These businesses are predominantly micro or small enterprises (Eurostat, 2024), often employing only a few workers and lacking dedicated Health & Safety departments, which further constrained participation.

Future directions

As previously mentioned, it would be desirable to include ISs to monitor additional body segments (e.g., hip and knee angles) during postural assessment. To achieve this goal, though, future research should focus on improving the wearability and comfort of the sensors to ensure worker comfort and compliance. Moreover, integrating sensor data with task logs could allow researchers to link specific postural behaviors to specific tasks, which would improve the precision of risk assessments and help design more effective interventions. Finally, while current results provide a snapshot of posture data, long-term longitudinal studies are needed to assess the cumulative effects of non-neutral postures over time on the development of MSDs. Such studies should track workers over months or years, providing deeper insights into the chronic effects of poor ergonomics.

• Conclusions

We present an approach for assessing postural exposures among construction workers, based on the use of a limited number of ISs. This approach offers a more feasible and reliable alternative to traditional methods such as observational assessments, which can be inaccurate and are time-consuming. Our results suggest that wearable ISs are suitable for application in harsh, dynamic environments such as construction sites. Many prior studies have focused on controlled laboratory settings or small, non-representative samples. By collecting data from workers in real-world environments, our research helps bridge the gap between theoretical models and practical applications in ergonomics, with multiple advantages for different stakeholders involved in the protection of construction workers' health. In particular, the availability for researchers of exposure data collected under actual working environments should support a better understanding of the dose-response relationships affecting the development of MSDs. At the same time, practitioners may find such data valuable to improve quality, reliability, and sensitivity of their assessments, making it possible to identify particularly critical working processes and supporting the possibility of refining and improving the work organization (e.g., in terms of breaks or repetitions) to protect worker health and

increase efficiency. Additionally, this data can be helpful to the workers themselves, as they could increase their awareness about performing unsafe or harmful actions.

CRedit authorship contribution statement

Micaela Porta: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Funding acquisition, Project administration. Giulia Casu: Investigation, Formal analysis, Data curation, Software. Sol Lim: Writing – review & editing. Maury A. Nussbaum: Writing – review & editing, Funding acquisition. Massimiliano Pau: Writing – review & editing, Resources, Methodology, Formal analysis, Conceptualization.

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Table 1:	Participant demographic and anthropometric characteristics.	
	Mean (SD)	Range
Age (years)	50.0 (8.8)	34.8 – 62.8
Height (cm)	169.1 (5.1)	162.0 – 179.0
Body mass (kg)	76.7 (7.8)	70.0 – 95.0
Seniority at work (years)	23.4 (11.4)	2 – 48.0

Table 2:	Description of parameters calculated accordingly to ISO 11226 for the assessment of static (longer than 4 s) non-neutral posture		
Body segment	Movement	Angle thresholds	Description
Trunk	Flexion-Extension	$\alpha < 0^{\circ}$	Extension – Not recommended posture
		$0^{\circ} < \alpha \leq 20^{\circ}$	Class of flexion always acceptable
		$20^{\circ} < \alpha \leq 60^{\circ}$	Class of flexion acceptable for a limited amount of time**
		$\alpha > 60^{\circ}$	Class of flexion Not recommended
	Lateral Bending	$\alpha > 0^{\circ}$	Asymmetric posture Not recommended
Upper Arm	Elevation*	$0^{\circ} < \alpha \leq 20^{\circ}$	Class of elevation always acceptable
		$20^{\circ} < \alpha \leq 60^{\circ}$	Class of elevation acceptable for a limited amount of time**
		$\alpha > 60^{\circ}$	Class of elevation Not recommended

* the ISO 11226 does not distinguish between flexion-extension and adduction-abduction

** Based on the linear relationship showed in Figure 3

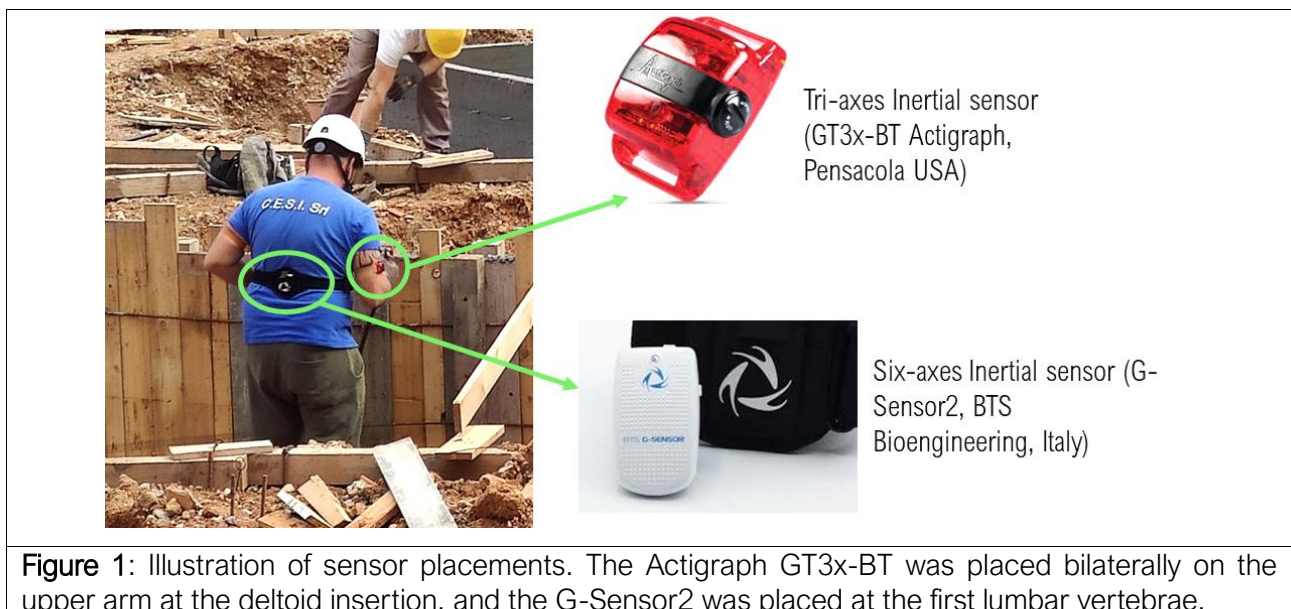
Table 3:	Description of parameters calculated accordingly to EN 1005-4 for the assessment of frequency of non-supported movement		
Body segment	Movement	Angle thresholds	Description
Trunk	Flexion-Extension	$\alpha < 0^\circ$	Extension – Not recommended movement
		$0^\circ < \alpha \leq 20^\circ$	No frequency limit
		$20^\circ < \alpha \leq 60^\circ$	frequency ≤ 2 movements per minute
		$\alpha > 60^\circ$	Not recommended movement
	Lateral Bending	$0^\circ < \alpha \leq 10^\circ$	No frequency limit
		$10^\circ < \alpha \leq 20^\circ$	frequency ≤ 2 movements per minute
		$\alpha > 20^\circ$	Not recommended movement
Upper Arm	Elevation*	$0^\circ < \alpha \leq 20^\circ$	frequency > 10 movements per minute
		$20^\circ < \alpha \leq 40^\circ$	Frequency between 2 and 10 movements per minute

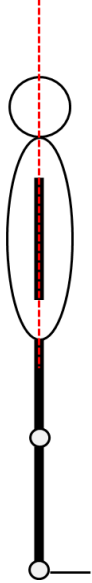
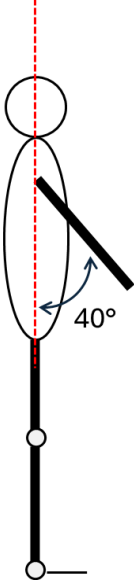
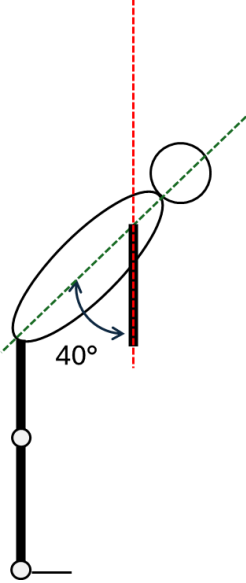
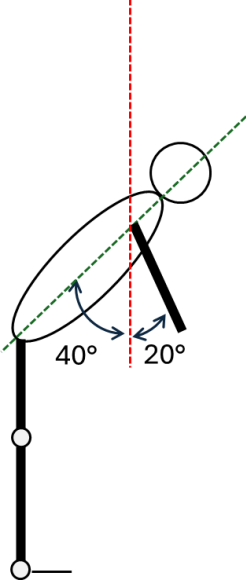
		$40^{\circ} < \alpha \leq 60^{\circ}$	frequency ≤ 2 movements per minute
		$\alpha > 60^{\circ}$	Not recommended movement
* the ISO 11226 does not distinguish between flexion-extension and adduction-abduction			

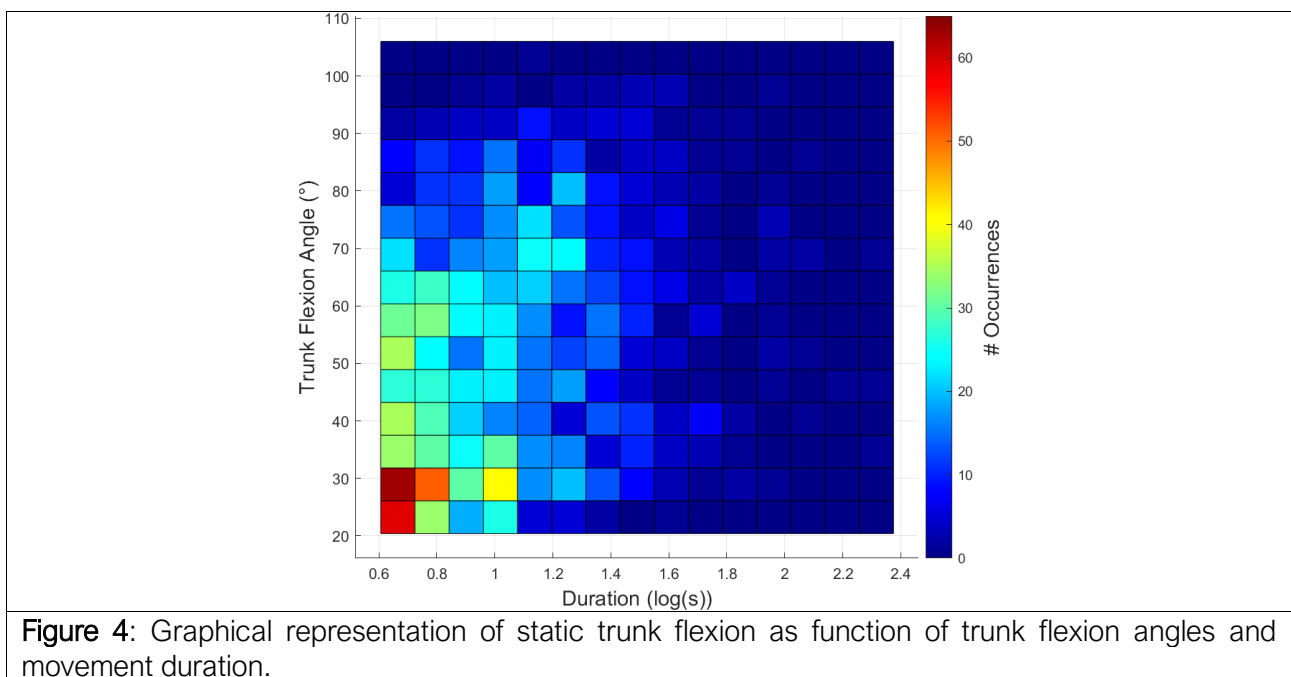
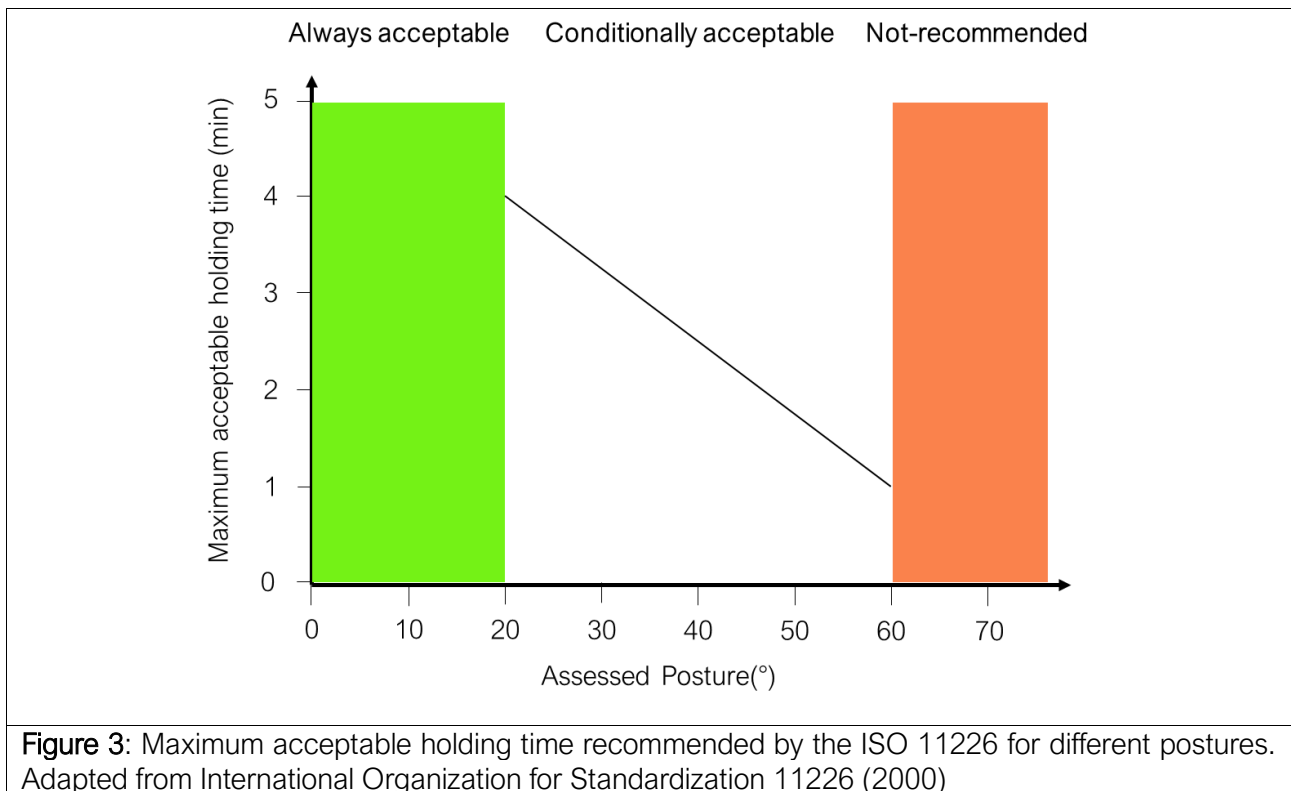
Table 4:	Description of parameters calculated accordingly to EN 1005-4 for the assessment of frequency of non-supported movement			
Body segment	Movement	Angle thresholds	Mean (SD)	Range
	Flexion-Extension	$0^{\circ} < \alpha \leq 20^{\circ}$	No frequency limit	
		$20^{\circ} < \alpha \leq 60^{\circ}$	2.4 (0.8)	0 – 24
		$\alpha > 60^{\circ}$	0.9 (0.4)	0 – 6
	Lateral Bending	$0^{\circ} < \alpha \leq 10^{\circ}$	No frequency limit	
		$10^{\circ} < \alpha \leq 20^{\circ}$	2.7 (0.8)	0 – 28
		$\alpha > 20^{\circ}$	0.7 (0.2)	0 – 8
Upper Arm	Elevation	$0^{\circ} < \alpha \leq 20^{\circ}$	No frequency limit	
		$20^{\circ} < \alpha \leq 40^{\circ}$	4.9 (1.5)	0 – 36
		$40^{\circ} < \alpha \leq 60^{\circ}$	1.3 (0.4)	0 – 12
		$\alpha > 60^{\circ}$	1.7 (0.5)	0 – 10

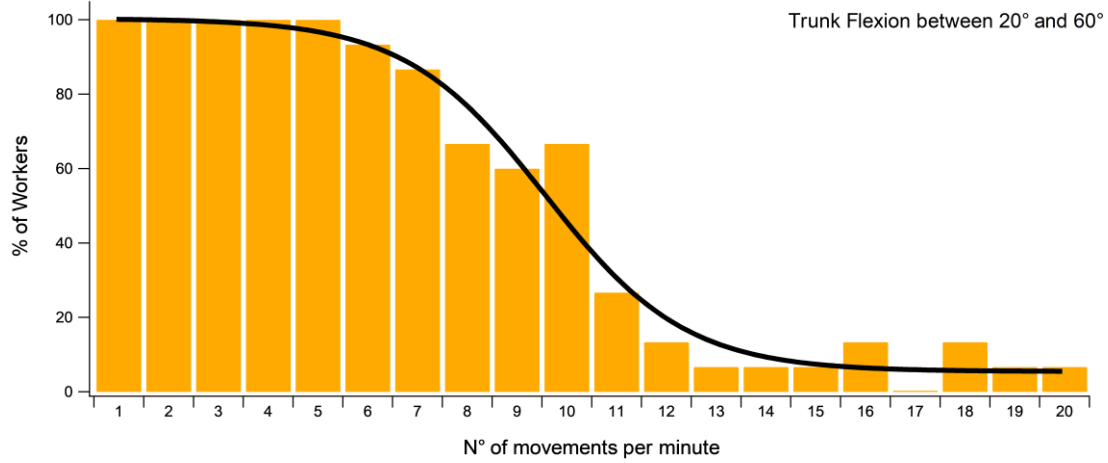
Table 5	Descriptive results of trunk and upper arm postures following the classes proposed by the ISO 11226. Values are reported as mean (SD)								
Body Segment	Movement	Mean Angle (°)	ISO 11226 Class	% of time spent in non-neutral posture		% of time spent in static non-neutral posture		# of times exceeding ISO 11226 recommendation	
				Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Trunk	Extension	6.7(0.4)	$\alpha < 0^{\circ}$	4.0 (3.4)	0.3 – 10.8	1.8 (1.6)	0 – 4.2	-	
	Flexion	36.6 (5.2)	$20^{\circ} < \alpha \leq 60^{\circ}$	19.2 (10.3)	12.0 – 32.4	14.2 (6.4)	6.9 – 28	0.3 (0.6)	0 – 2
			$\alpha > 60^{\circ}$	10.3 (5.2)	2.2 – 16.8	9.5 (5.0)	2.1 – 16.1	42.9(25.4)	2 – 79
	Lateral Bending	5.1 (1.0)	$\alpha > 0^{\circ}$	35.3 (7.1)	21.5 – 48.4	18.4 (6.5)	10.9 – 32.2	-	
Upper	Extension	27.6	$\alpha < 0^{\circ}$	1.7	0 –	1.0	0 –	-	

Arm		(4.8)		(1.7)	7.3	(1.3)	5.1		
	Elevation	36.5 (3.6)	$20^{\circ} < \alpha \leq 60^{\circ}$	41.7 (7.7)	29.9 – 58.9	31.3 (8.1)	19.2 – 49.9	1.2 (1.6)	0 – 5
			$\alpha > 60^{\circ}$	23.5 (7.8)	7.0 – 39.3	22.7 (8.2)	7.0 – 39.3	87.6(32.3)	16- 144

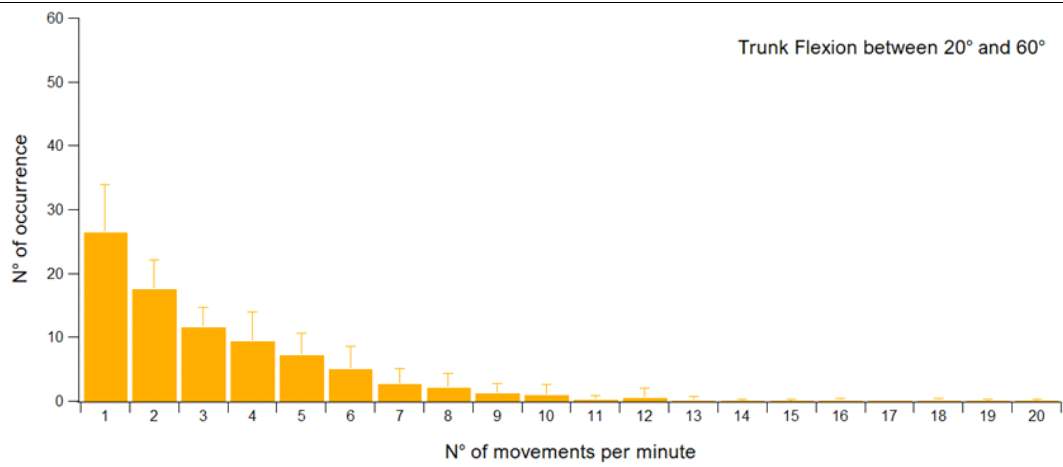


			
Reference posture	Upper Arm non-neutral posture Trunk reference posture	Upper Arm and Trunk non-neutral posture (a)	Upper Arm and Trunk non-neutral posture (b)
The actual upper arm elevation and the upper arm elevation with respect to the vertical axis coincide $\alpha = 0^\circ$	The actual upper arm elevation and the upper arm elevation with respect to the vertical axis coincide $\alpha = 40^\circ$	The upper arm elevation with respect to the vertical axis is $\alpha = 0^\circ$; the actual upper arm elevation is the sum of trunk inclination and upper arm inclination with respect to the vertical axis $\alpha = 0^\circ + 40^\circ$	The upper arm elevation with respect to the vertical axis is $\alpha = 20^\circ$; the actual upper arm elevation is the sum of trunk inclination and upper arm inclination with respect to the vertical axis $\alpha = 20^\circ + 40^\circ$
Figure 2: Definition of upper arm elevation starting from data collected by the IS on the upper arm and then corrected on the basis of trunk posture.			

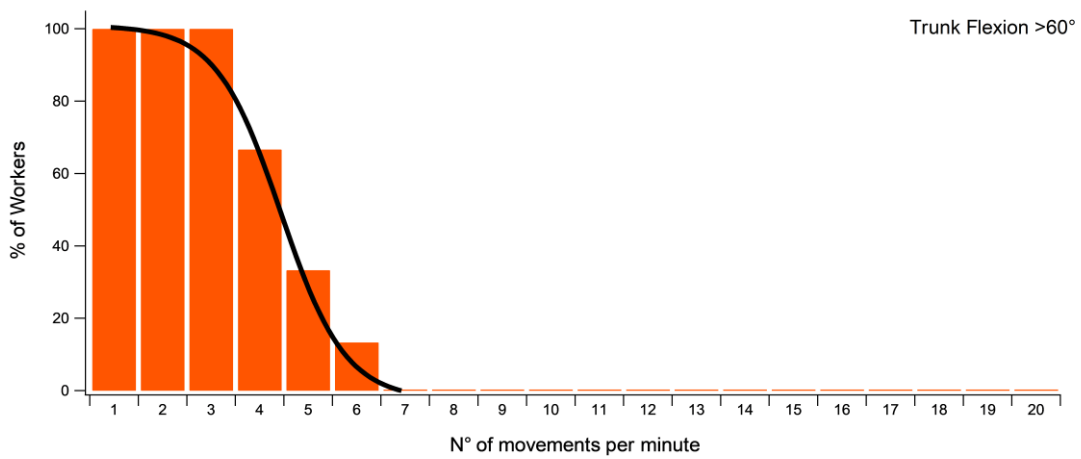




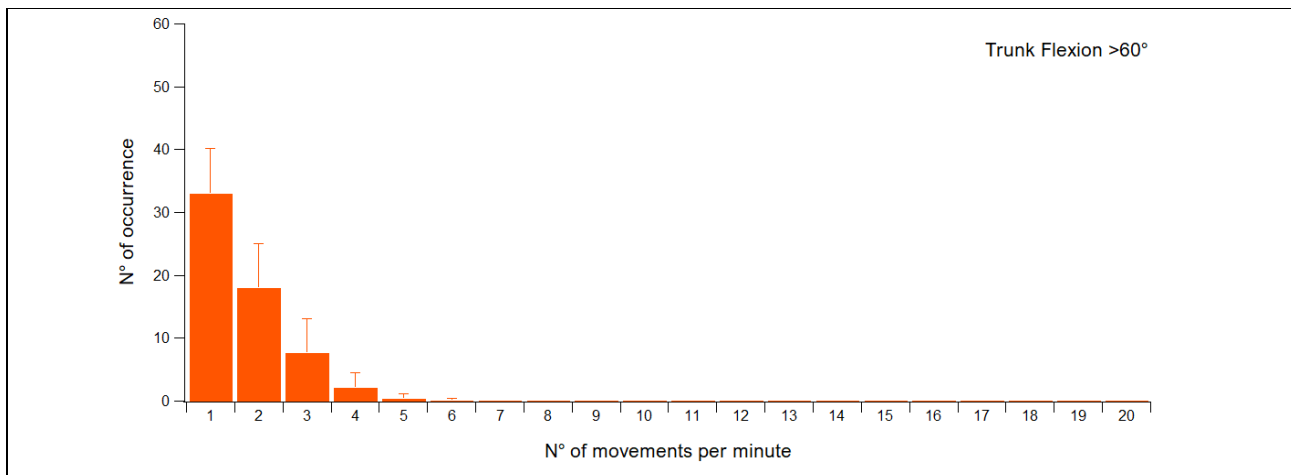
a



b

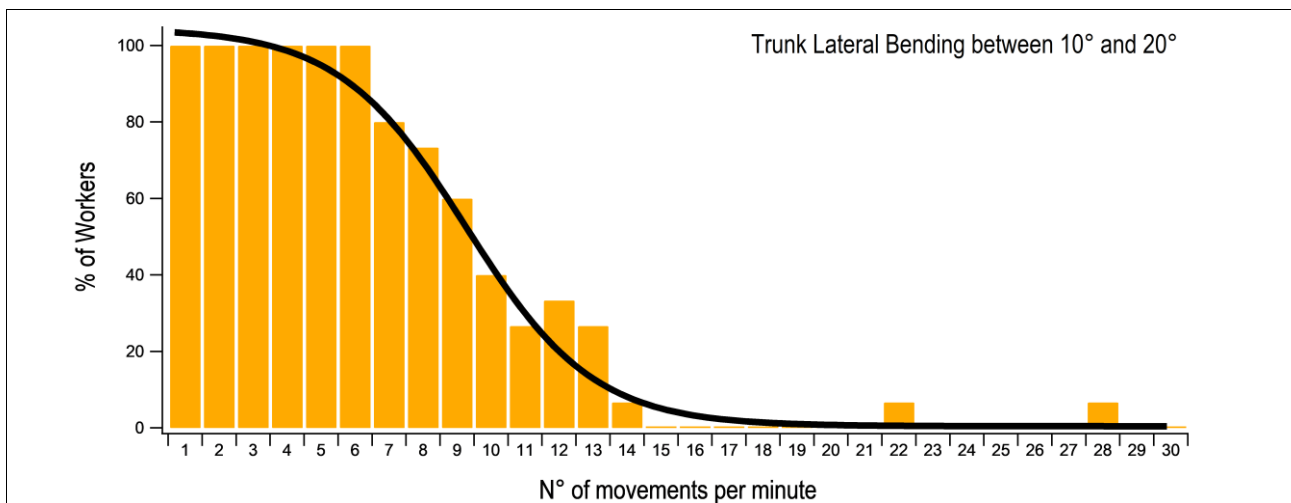


c

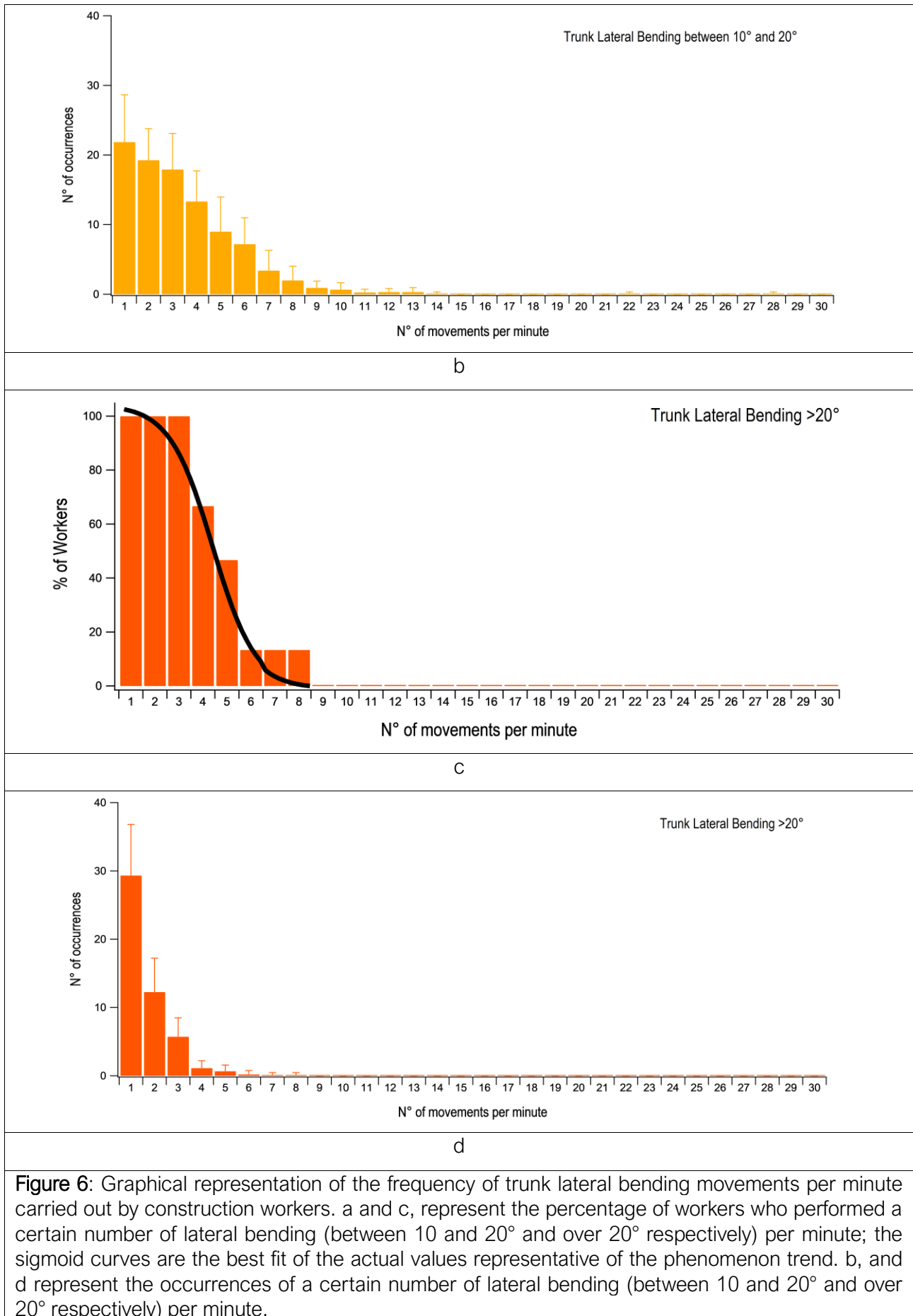


d

Figure 5: Graphical representation of the frequency of trunk flexion movements per minute carried out by construction workers. a and c represent the percentage of workers who performed a certain number of flexion (between 20 and 60° and over 60° respectively) per minute; the sigmoid curves are the best fit of the actual values representative of the phenomenon trend. b and d represent the occurrences of a certain number of flexion (between 20 and 60° and over 60° respectively) per minute.



a



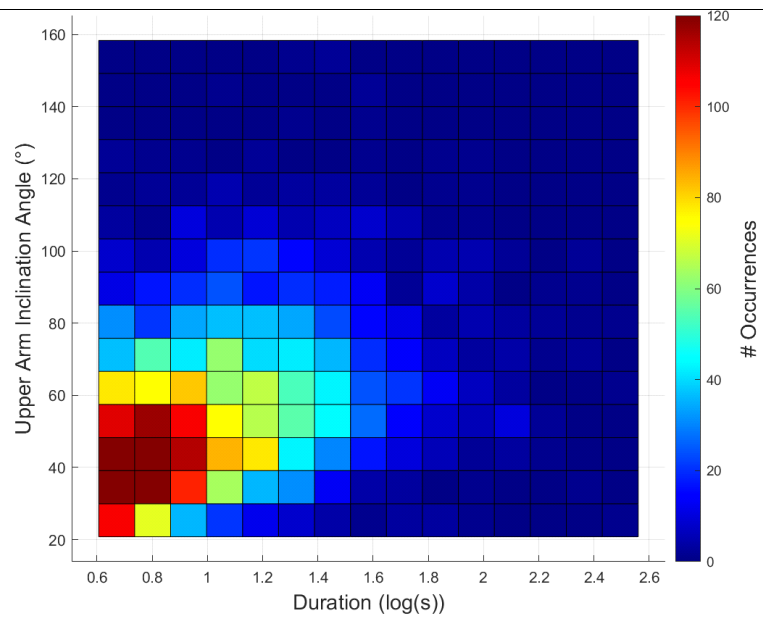
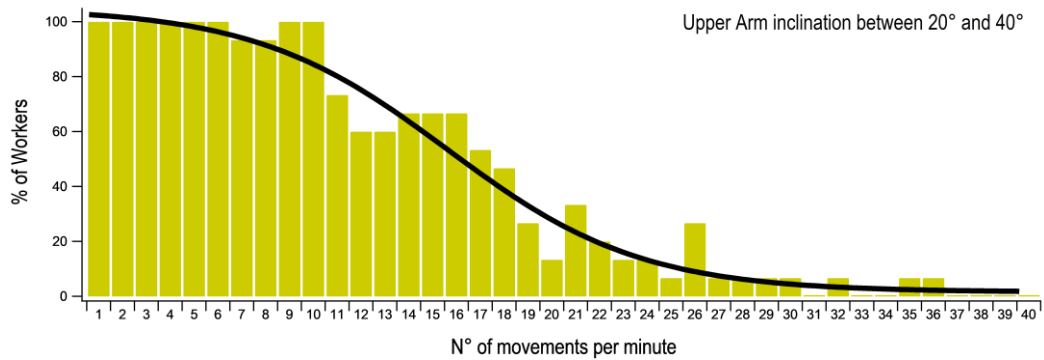
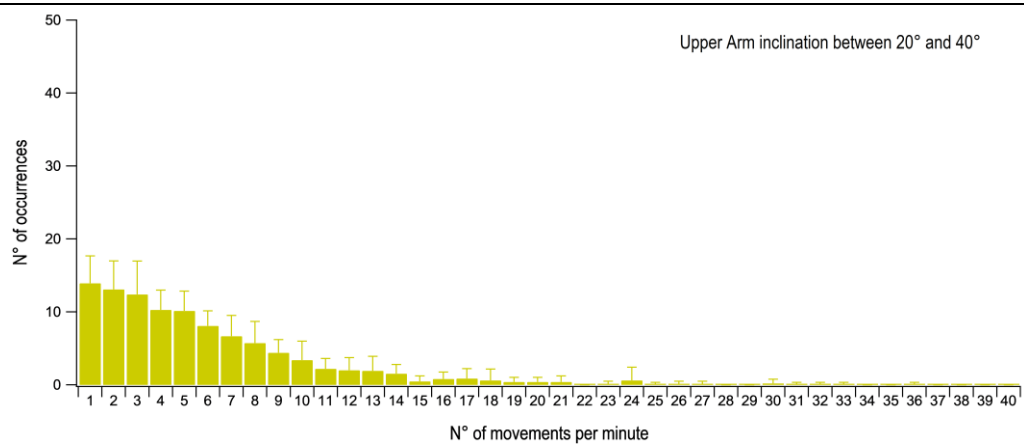


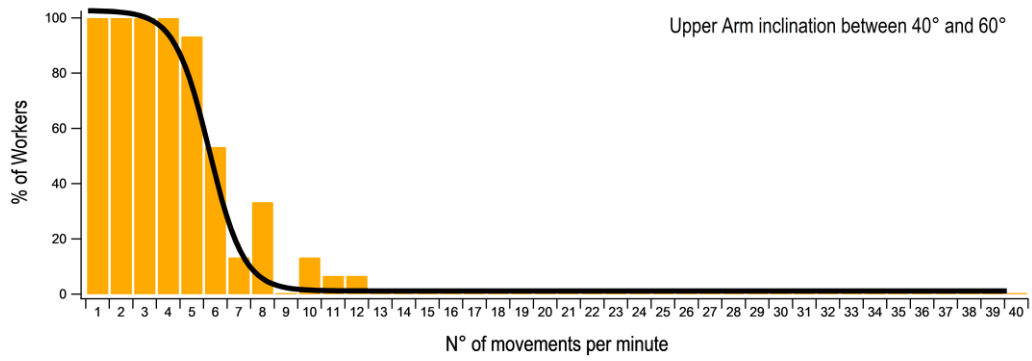
Figure 7: Graphical representation of static upper arm elevation as function of upper arm inclination angles and movement duration.



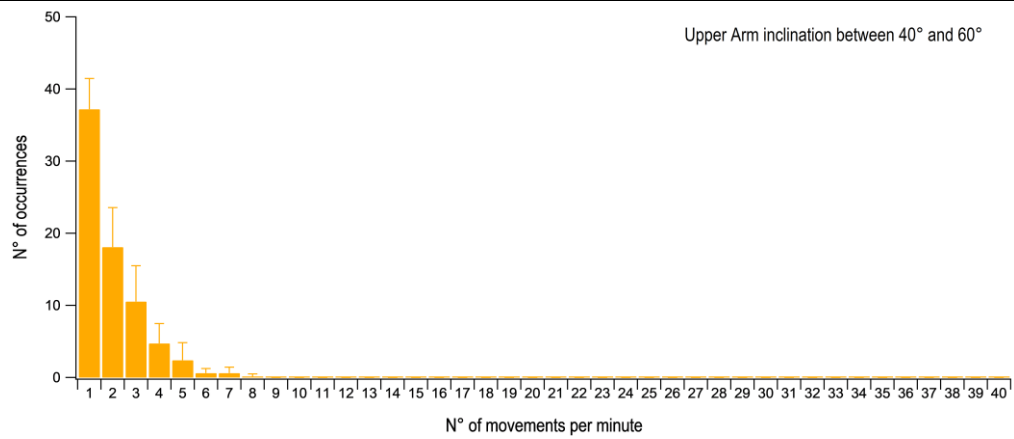
a



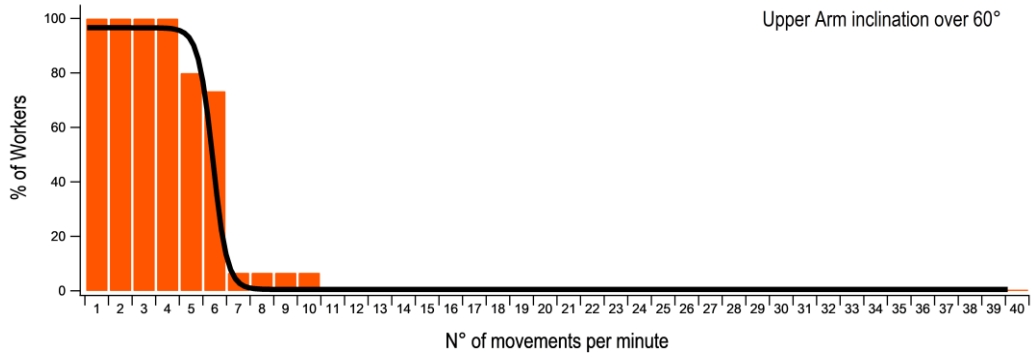
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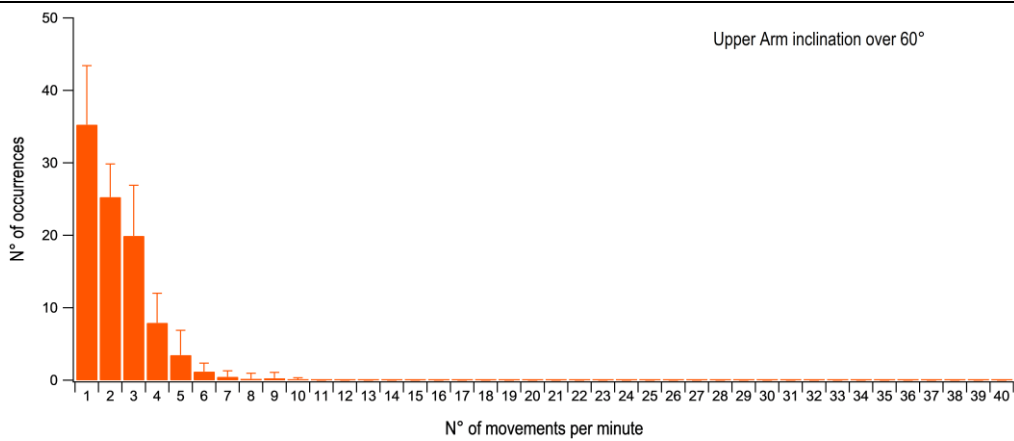
c



d



e



f

Figure 8: Graphical representation of the frequency of UA inclination movements per minute carried out by construction workers. a, c, and e represent the percentage of workers who performed a certain number of upper arm elevations (between 20 and 40°, between 40 and 60° and over 60° respectively) per minute; the sigmoid curves are the best fit of the actual values representative of the phenomenon trend. b, d and f represent the occurrences of a certain number of UA inclination (between 20 and 40°, between 40 and 60° and over 60° respectively) per minute.