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Older workers spend less time in extreme trunk and upper-arm postures during order-picking tasks: Results from field testing

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ABSTRACT

Order picking tasks require repetitive trunk and upper arms movements that may increase the risk of developing musculoskeletal disorders, particularly among older workers due to the decline of their physical capabilities with aging. We proposed an approach based on a limited number of wearable inertial sensors to assessed exposures to non-neutral trunk and upper arms postures among both older and young workers during their regular work-shifts. The obtained data were processed accordingly to international standards (ISO 11226 and EN 1005-4) to detect the existence of possible differences associated with age-specific working strategies. While the results indicate similar trunk and upper arms movement frequencies in both groups, older workers spend a significantly smaller percentage of time in the most demanding (>60°) postures for both districts. Such findings suggest the adoption of specific strategies to reduce the biomechanical risk which might be originated by a combination of awareness of physical limits and superior working experience. In this context, the instrumental monitoring of upper body in the logistic sector may result useful to highlight critical conditions potentially able to promote the onset of musculoskeletal disorders, thus supporting the decision processes pertaining to workers' health management and aging worker retainment.

1. Introduction

Warehouse order-picking is the process of retrieving items stored in various locations to fulfill customer orders (Battini et al., 2016). Despite improvements in technology and the corresponding advantages offered by automation in terms of improved efficiency, accuracy, and productivity, the order-picking processes still relies largely on manual human work, as it ensures high levels of flexibility and avoids costly investments (Napolitano, 2012; Richards, 2014). During order-picking, workers walk or drive along the aisles of a warehouse to pick items from storage locations. As a result, tasks like grasping, lifting, lowering, sorting, pushing, and pulling are frequently required during a typical work shift. Picking and placing are the most common tasks associated with the order-picking process, and previous evidence indicates that up to 1000 picks/hour can be required (De Koster et al., 2007).

Such tasks involve frequent and extensive trunk flexion and upper arm elevation that, if excessive in amplitude and in frequency, can increase the risk of developing back and upper arm musculoskeletal disorders (MSDs; Punnett and Wegman, 2004). Indeed, prolonged back flexion and non-neutral shoulder postures during occupational tasks appear to be consistently associated respectively with an increased risk of developing low back pain (Norman et al., 1998; Hoogendoorn et al., 2000; Punnett et al., 1991; Coenen et al., 2014; Swain et al., 2020), and developing shoulder injuries and chronic musculoskeletal pain (Hagberg and Wegman, 1987; Winkel and Westgaard, 1992; Punnett et al., 2000, van Rijn et al., 2010; Dalbøge et al., 2018; Riddervold et al., 2022). Such findings are also consistent with survey evidence from workers aged between 15 and 64 years, which concluded that the "transportation and storage" occupational sector is among the economic activity with the highest prevalence work-related health problems (work-related MSDs in particular) in the previous 12 months (Eurostat, 2020).

It is also important to consider that the composition of the working population is rapidly ageing. Data from U.S. Bureau of Statistics (BLS) indicate that, regardless of the occupational sector, workers aged over 45 represent 43.2% of the total workforce and 31.7% in warehousing and storage (BLS, 2024). These proportions are expected to rise in the

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coming decades, both due to a global aging phenomenon and to recent pension reforms that have pushed the retirement age forward in several Organization for Economic Cooperation and Development countries (OECD, 2023). Having increasing numbers of older workers (i.e., those aged 50 years and over, McCarthy et al., 2014) engaged in physically-demanding occupation represents a potential cause of increases in MSDs. Due to physiological changes associated with the ageing process, older workers are likely to experience reductions in muscular strength, mobility (da Costa and Vieira, 2010; Coenen et al., 2014) and more general work ability (van den Berg et al., 2009; El Fassi et al., 2013; Pensola et al., 2016).

However, despite the potential risks associated with the presence of older workers in warehouse order-picking tasks, most existing literature on order picking focused on design and control aspects of the process, including layout, storage allocation policy, routing, picking problems, and different operating strategies (Grosse et al., 2015; Casella et al., 2023). While there has been some emphasis on ergonomic factors (e.g., Calzavara et al., 2017; Glock et al., 2019; Lavender et al., 2012; Lavender et al., 2021), to the best of our knowledge there are no reports of work that investigated postural strategies associated with aging workers specifically engaged in order-picking activities. While there appears to be increasing interest in investigating age-related differences in the strategies adopted to perform manual material handling tasks, most findings reported in the literature stem from simulated tasks completed in laboratory setting (Boocock et al., 2020; Song and Qu, 2014; Shojaei et al., 2016; Zhou et al., 2024). In contrast, few reports are from studies in actual working conditions (Jakobsen et al., 2022; Porta et al., 2021).

Given evidence regarding the effect of age on postural strategies during the performance of manual material handling tasks, and given the scarcity of information acquired in real working contexts, we thus aimed to assess age-related differences in postural exposures involving the trunk and upper arm, among workers engaged in order-picking activities. We used instrumentation comprising a limited number of wearable sensors, which was previously applied in similar studies (Porta et al., 2021; Korshøj et al., 2014; Schall et al., 2016) and which provides quantitative data on the trunk and upper arms movement during a regular shift. The acquired data were processed and interpreted according to the international standards (i.e., ISO 11226 International Organization for Standardization, 2000, and European Committee for Standardization, 2009 EN 1005-4). Any age-related differences that emerge were expected to be useful in supporting the development of age-specific and/or more age-inclusive ergonomic interventions aimed to prevent the onset of MSDs.

2. Methods

2.1. Participants

A convenience sample of 32, full-time (i.e., ≥40 h per week) male workers completed the study on a voluntary basis (note that females were not excluded, but only male workers were employed at this facility). Inclusion criteria were that workers had to be: older than 18 years; have experience in manual material handling (i.e., seniority at work >6 months); be free from acute musculoskeletal disorders in the last 6 months; and be free from any work restrictions (according to the company's occupational physician). All participants were currently employed at the main regional warehouse in Sardinia of "Conad del Tirreno Soc. Coop. Srl" (the largest Italian retail supplier). Each participant was routinely assigned to assemble orders to be delivered to local stores, following instructions continuously delivered using a voice picking system that indicates the type and quantity of products that will be subsequently placed on a pallet. Data regarding the type, mass, and number of products handled by each worker, which were tracked by the company on a minute base, were used to define the activity profile of each worker. Prior to data collection, participants were given a detailed explanation of the purposes and methodology of the study, then were asked to read and sign 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, June 01, 2023).

Workers were stratified into two groups, namely young (i.e., aged between 18 and 49 years, n = 16) and older (i.e., aged ≥50 years, n = 16). At the start of an experimental session, participant demographic and anthropometric characteristics (Table 1) were collected using a questionnaire, together with information about MSDs, number of days in sick leave due to MSDs, and perceptions about the ability to continue to work in the same job in the next few years. The latter was done using the Italian version of the Work Ability Index (WAI) questionnaire (Ilmarinen, 2005; Costa and Sartori, 2007), which consists of seven subscales referring to the aspects of work ability listed below. The total score lies in the range of 7–49.

1) Current work ability compared to the best of their own lifetime
2) Work ability in relation to job demands
3) Number of current diseases
4) Estimated work impairment due to diseases
5) Sick leave during the previous 12 months
6) Own prognosis of work ability in the next 2-years
7) Mental resources.

2.2. Postural exposure assessment

Trunk and upper arms kinematics were measured using three inertial sensors (one Inertial Measurement Unit, IMU, and two tri-axial accelerometers, Fig. 1), which we selected as suitable for on-board data collection and compatibility with personal protective equipment. Trunk kinematics were recorded using a commercially available IMU (G-Sensor2, BTS Bioengineering, Italy) that includes a triaxial accelerometer, a triaxial gyroscope, and a triaxial magnetometer. This was previously employed to assess trunk postures in actual working environments and was found to be robust to magnetic interference (Porta et al., 2020, 2021, 2022). The sensor was placed approximately at the level of the first lumbar vertebrae (Faber et al., 2009) using a dedicated semi-elastic belt. Bilateral upper arm kinematics were measured using two triaxial accelerometers (GT3x-BT, Actigraph, Pensacola, USA) that have been previously employed in ergonomics research (Korshøj et al., 2014; Schall et al., 2015; Villumsen et al., 2017; Jakobsen et al., 2018). Both sensors used for the assessment of angular data were validated vs. optical by motion capture system (please see Porta, 2021 for trunk posture validation and Korshøj et al., 2014, for upper limb posture validation). An accelerometer was affixed laterally on each upper arm, at the level of the deltoid tuberosity insertion (Korshøj et al., 2014). All three sensors were set to acquire data at 50 Hz.

Based on previous similar studies (Porta et al., 2020), workers were continuously monitored for 2.5 h of a regular work shift, and data collection was typically completed during the first half of the shift. At the start of an experimental session, participants were requested to stand still for 10 s in a neutral, upright posture with their arms hanging laterally; the angles recorded during this period of time were used to remove both subject-specific angular offsets and possible errors caused by incorrect sensor alignment from the acquired data. Additionally, data on trunk mobility were obtained using the IMU placed on the trunk, as a proxy measure of workers' musculoskeletal function (Bryant et al., 2018). In particular, we calculated the active trunk range of motion (ROM, that is, the difference between the maximum forward inclination angle and the minimum backward inclination angle) by asking workers to perform (three times), starting from the neutral upright posture, a maximal trunk forward inclination followed by the return to neutral posture and by a maximal trunk backward inclination, avoiding excessive non-natural movements and knees flexion.

Table 1
Anthropometric and demographic characteristics of participants.

	Young (n = 16)		Older (n = 16)	
	Mean (SD)	**Range**	**Mean (SD)**	**Range**
Age (years)	37.1 (5.6)	27.7–47.7	57.2 (4.0)*	52.0–63.7
Height (cm)	171.1 (7.4)	150.0–185.0	170.4 (7.2)	155.0–180.0
Body mass (kg)	70.0 (10.9)	60.0–98.0	74.5 (8.5)	63.0–92.0
BMI (kg/m^2)	23.9 (3.0)	20.0–30.1	25.6 (2.2)	22.5–30.1
Trunk Active Range of Motion (°)	120.6 (18.6)	79.8–157.2	110.6 (16.6)	83.7–134.7
Work seniority (years)	10.2 (4.2)	0.8–16.0	22.4 (7.7)*	11.0–33.0
Number of items handled (#)	319.5 (85.9)	137–499	320.4 (67.7)	186–406
Mass of items handled (kg)	1788.4 (418.0)	720.5–2467.9	1977.3 (526.0)	953.5–2702.9

The symbol * denotes a statistically significant difference vs. young workers as determined using an unpaired t-test ($p < 0.05$).

Fig. 1. Example of sensor placements. See text for details.

2.3. Data processing

Raw acceleration, angular velocity and magnetic data collected by the IMU were internally preprocessed by a Digital Motion Processor (DMP™), which provides rotational angles (i.e., roll, pitch, and yaw). Then, they were further processed "offline" by a custom routine developed under Matlab™ environment (R2020b, MathWorks, Natick, Massachusetts, USA) to obtain Cardan angles referred to a global reference system. Trunk inclination and trunk lateral bending were assessed as deviations from a reference position, which was assessed by having participants stand for 10 s in a neutral, upright posture as previously described. Instead, the accelerations collected by the two tri-axial accelerometers were processed following the procedure suggested by Korshøj et al. (2014). Upper arm inclination with respect to a reference position was obtained using the following equation:

$$Upper\ Arm\ inclination = \operatorname{acos}\left(\sqrt[2]{\frac{a_V}{a_V + a_{ML} + a_{AP}}}\right)$$

where: a indicates acceleration signals and subscripts V, ML. and AP indicate vertical, medio-lateral, and antero-posterior directions, respectively. To obtain the actual upper arm inclination values, the upper arm elevation with respect to the reference position was corrected by considering the corresponding trunk inclination (Fig. 2).

The time series of angular data were further processed according to the requirement of the standard ISO 11226 standard for assessing exposures to static posture and the EN 1005-4 standard for exposure to repetitive movements According to the ISO 11226, static postures occur when a posture is maintained longer than 4 s, and we calculated these similarly to the approach described by Valero et al. (2017). Specifically, a posture was considered static until its amplitude exceeded a lower (or upper) limit that modifies its class and the value defined as the weighted average of the measured angle calculated within the selected time window. In particular, the ISO 11226 defines the following classes for trunk inclination and upper arm postures.

- Inclination angle <0° – always unacceptable
- Inclination angle between 0 and 20° – always acceptable
- Inclination angle between 20 and 60° – conditionally acceptable following a linear relationship showed in Fig. 3.
- Inclination angle >60° – always unacceptable

In addition, the ISO 11226 defines always unacceptable trunk lateral bending (asymmetric trunk posture).

From the EN 1005-4, the classes of movement are defined as follows.

2.3.1. Trunk movements

- Inclination angle <0° – always unacceptable
- Inclination angle between 0° and 20° – no frequency limit
- Inclination angle between 20° and 60° – frequency ≤2 movements per minute is considered acceptable
- Inclination angle >60° – always unacceptable
- Lateral bending between 0° and 10° – no frequency limit
- Lateral bending between 20° and 20° – frequency ≤2 movements per minute is considered acceptable.
- Lateral bending >20° – always unacceptable

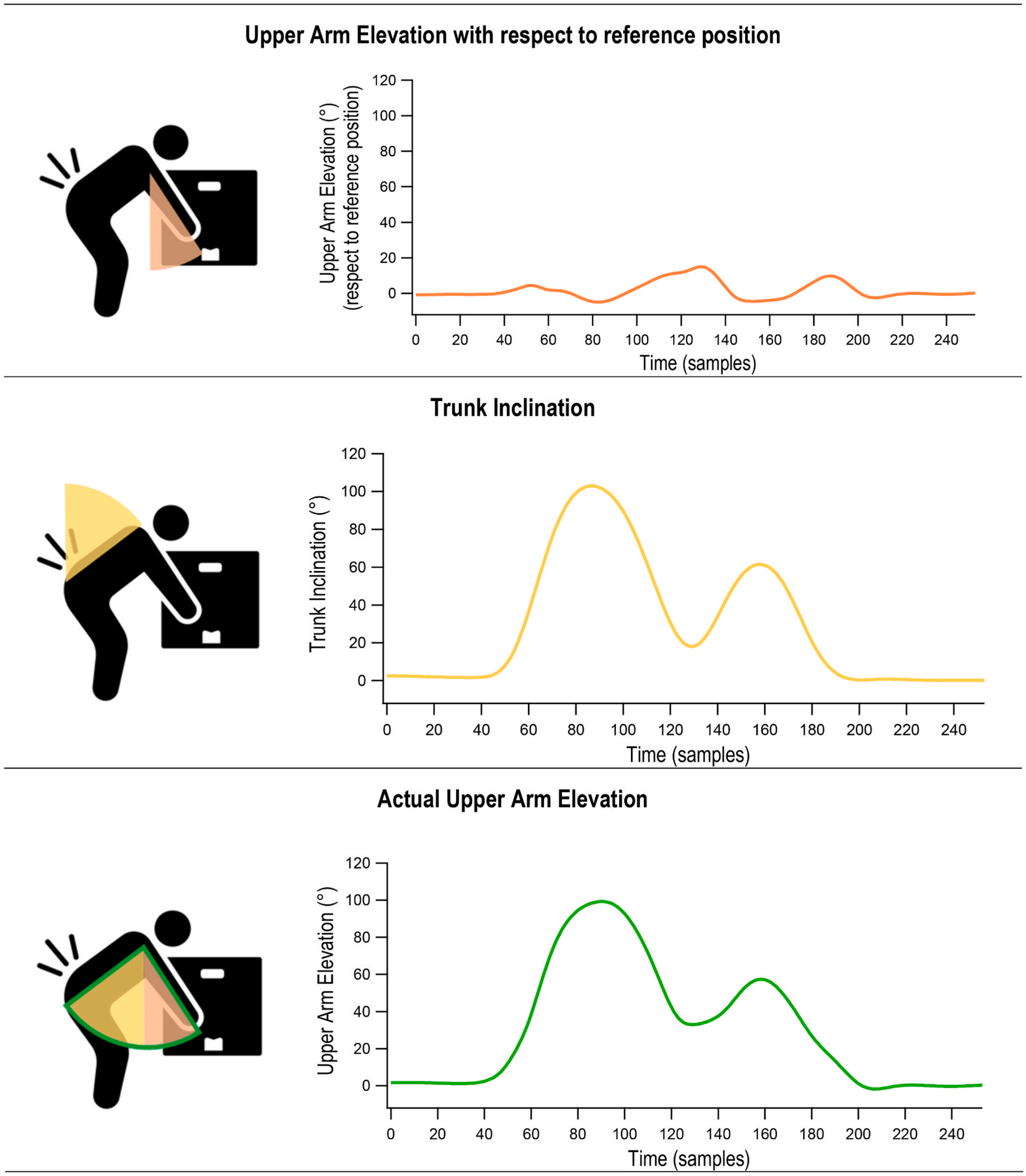

Fig. 2. Definition of upper arm inclination starting from data collected by the triaxial-accelerometers on the upper arms and then corrected on the basis of trunk posture.

Since the ISO 11226:2000 refers to unsupported trunk conditions, the possible use of any kind of trunk support was visually verified before accelerometer and IMU placements on the participants. Participants were also instructed to inform us if any kind of assistance was externally provided during the monitoring period. None of the workers reported the use of trunk support during our data collection.

2.3.2. *Upper arms movements*

- Inclination angle $<0^\circ$ – always unacceptable
- Elevation angle (there is no distinction between flexion and abduction) between 0° and 20° – no frequency limit.
- Elevation angle between 20° and 40° – frequency between 2 and 10 movements per minute is considered acceptable.
- Elevation angle between 40° and 60° – frequency ≤ 2 movements per minute is considered acceptable.
- Elevation angle $>60^\circ$ – always unacceptable

Even in this case, all data processing was performed by means of a custom routine developed under Matlab™ environment (R2020b, MathWorks, Natick, Massachusetts, USA).

2.4. *Data analysis*

Descriptive statistics for each variable of interest were calculated.

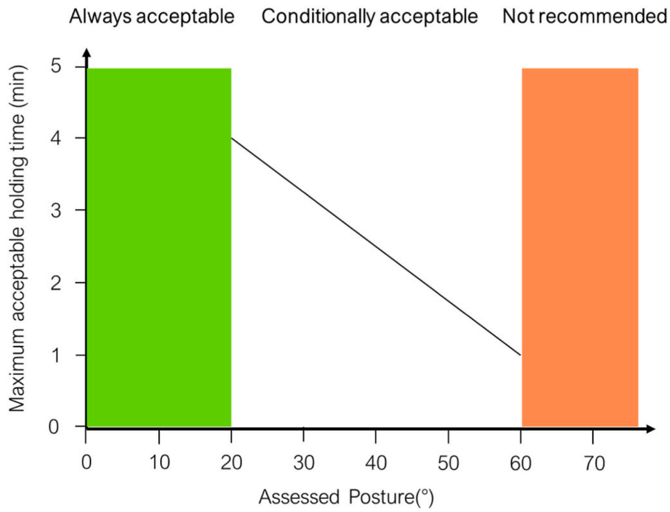

Fig. 3. Maximum acceptable holding time recommended by the ISO 11226 for different postures. Adapted from International Organization for Standardization 11226 (2000).

Following a testing of the variables for normality (using the Shapiro-Wilk test) and homogeneity of variances (Levene's test) potential differences between age group in terms of postural exposure and work ability were explored using separate multivariate analyses of variance (MANOVA). These MANOVAs were used to assess the following groups of dependent variables: 1) trunk posture (i.e., percentage of time spent in different classes of forward inclination, backward inclination, and lateral bending); 2) trunk frequency of movement (i.e., number of forward inclination and lateral bending per minute); 3) upper arm posture (i.e., percentage of time spent in different classes of elevation and backward inclination); 4) upper arm frequency of movement (i.e., number of upper arm elevations, in different classes, per minute); 5) number and masses of the handled goods; and 6) WAI overall and subscale scores. In all cases, statistical significance was concluded when $p < 0.05$ and effect sizes were assessed using eta-squared (η^2). Following a significant MANOVA, univariate ANOVAs were carried out as *post hoc* tests. All statistical analyses were performed using SPSS software (v.20, IBM, Armonk, NY, USA).

3. Results

3.1. Trunk postures

Summary results regarding exposure to trunk non-neutral posture are presented in the appendix (Tables A.1, A.2). There was a significant main effect of group on the percentage of time spent in different class of trunk forward inclination and lateral bending [$F(8,23) = 2.696$, $p = 0.030$, Wilks' $\lambda = 0.516$, $\eta^2 = 0.484$]. *Post hoc* ANOVAs revealed that most of the differences between the two age groups were in the percentage of time spent in the most severe trunk posture (i.e., >60°), with respective values of 3.4 vs 7.1% for older and young groups ($p < 0.005$; Fig. 4a). Young workers also spent a significantly ($p = 0.043$) longer percentage of time in an asymmetrical trunk posture with respect to older individuals (33.6% vs 27.8% of lateral bending; Fig. 4b).

Regarding the overall trunk non-neutral posture, older workers spent 8.1% vs. 11.7% of young workers of the monitored time in static trunk forward inclination over 20°, and 7.3% vs. 8.0% in static lateral bending. These percentages were substantially larger for non-static posture (shorter than 4 s). Specifically, the percentage of time spent in forward inclination was about twice for both age groups (16.9 and 21.9% for the older and young group, respectively), while the

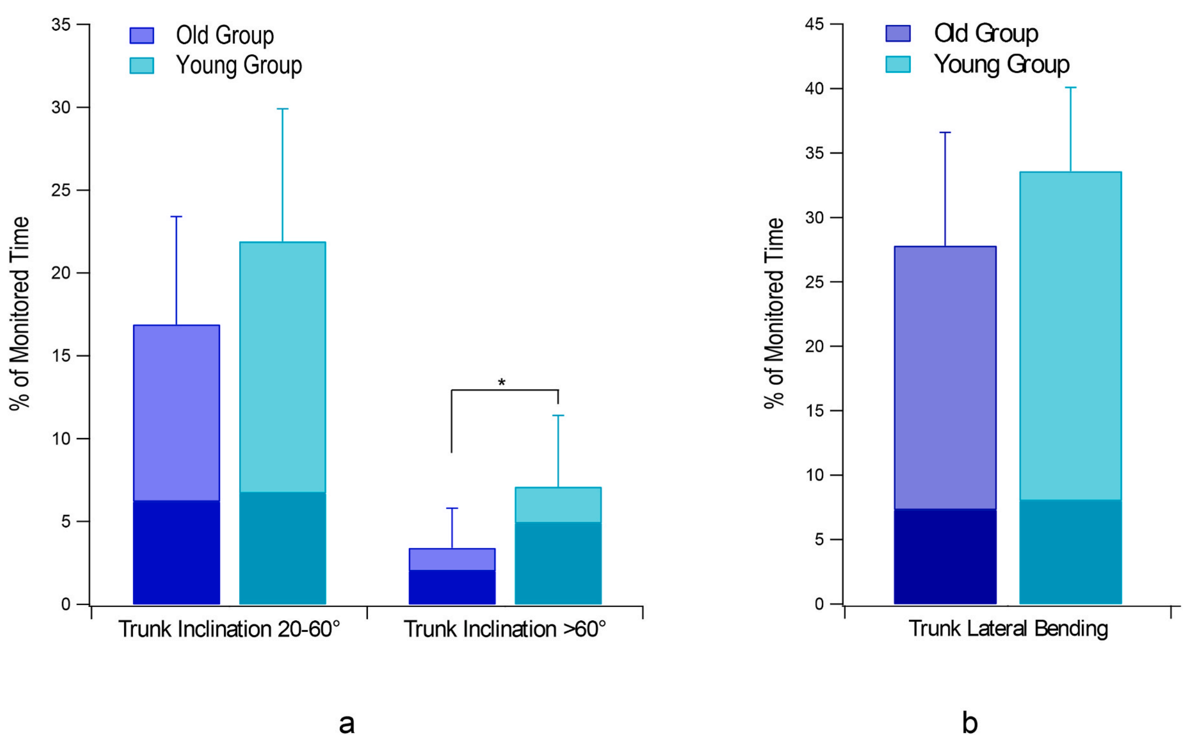

Fig. 4. Summary of the percentages of time spent in non-neutral trunk postures following the classes proposed by the ISO 11226. Light colors indicate the overall percentage of time spent in a non-neutral posture, regardless of the duration of each movement, while dark colors indicate the percentage of time spent in a static posture (longer than 4s). Results are shown for: a) percentage of time spent in trunk forward inclination; and b) percentage of time spent in trunk lateral bending. Errors bars indicate standard deviations and the symbol * indicates a significant difference between age groups (for both static and non-static movements) as determined by the post-hoc ANOVA after Bonferroni Correction (p < 0.017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

percentage of time spent in lateral bending was more than four times larger (27.8 and 33.6% for older and young group respectively).

Similar results emerged in terms of movement frequency (See Fig. 5 and Table A.5) for details). There was a significant main effect of group [$F(4,27) = 3.736$, $p = 0.015$, Wilks' $\lambda = 0.642$, $\eta^2 = 0.358$]. *Post hoc* analysis revealed that young workers performed a significantly more frequent lateral bending (4.2 vs 2.8 movements per minute for young and older workers respectively; $p < 0.001$). Younger workers also performed significantly ($p = 0.034$) more frequent trunk forward inclination exceeding 60° (1.6 vs 1.0 movements per minute for young and older workers, respectively).

3.2. Upper arm postures

We found a significant main effect of age group on the percentage of time spent in different classes of upper arm elevation [$F(6,56) = 5.177$, $p < 0.001$, Wilks' $\lambda = 0.643$, $\eta^2 = 0.353$]. Specifically, older workers spent a smaller proportion of the monitored time in static upper arm elevations >20° (37.1% vs. 44.9% for young workers). When considering also non-static posture (shorter than 4 s) these percentages were larger: 53.7% for older workers and 63.8% for the young group. *Post hoc* analysis revealed that most of the differences between the two age groups involved the percentage of time spent in the most severe upper arm posture (>60°), which was 10.4% and 16.0% for older and young group, respectively ($p = 0.003$; see Fig. 6, Appendix Table A.3, A.4). We did not find a significant difference in the frequency of movements between the two groups [$F(3,28) = 2.183$, $p = 0.112$, Wilks' $\lambda = 0.810$, $\eta^2 = 0.190$]. It is noteworthy that there was substantial variability in the frequency of upper arm movements, which ranged between 0 and 42 per minute for upper arm movements between 20° and 40° and between 0 and 13 per minute for movements over 60° (See Fig. 7 and Appendix Table A.6.

3.3. Profile of order-picking tasks and WAI

There was not a significant difference in task features between

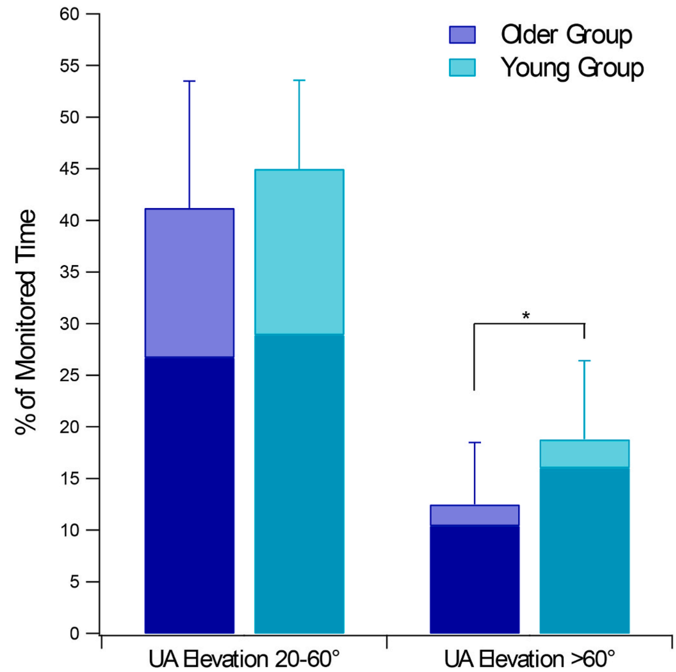

Fig. 6. Graphical representation of percentages of time spent in upper arm elevation following the classes proposed by the ISO 11226. Light colors indicate the overall percentage of time spent in a non-neutral posture, regardless of the duration of each movement, while dark colors indicate the percentage of time spent in a static posture (longer than 4s). Errors bars indicate standard deviations and the symbol * indicates a significant difference between age groups (for both static and non-static movements) as determined by the post-hoc ANOVA after Bonferroni Correction (p < 0.017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

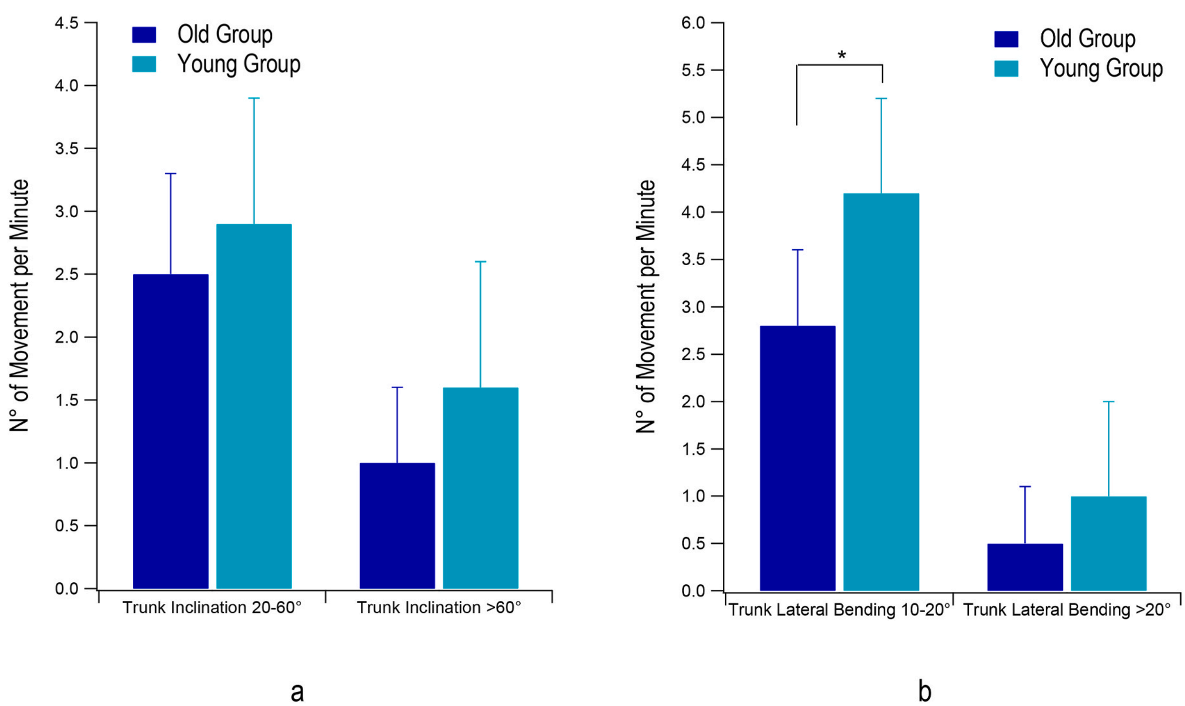

Fig. 5. Summary results regarding the frequency of movement according to EN 1005-4 for the assessment of frequency of non-supported movement. a represents trunk inclination frequency; b represents trunk lateral bending frequency. The symbol * denotes a statistically significant difference between groups as determined from post hoc ANOVA after Bonferroni correction (p < 0.017).

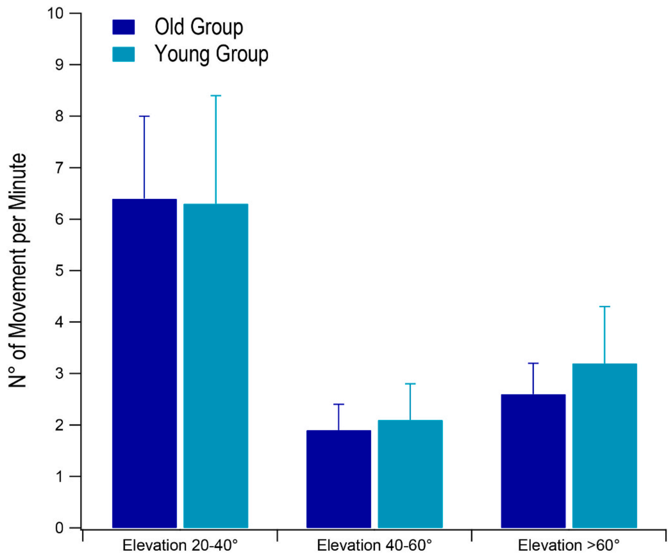

Fig. 7. Summary results regarding upper arms frequency of movement according to EN 1005-4 for the assessment of frequency of non-supported movement.

groups [$F(2,18) = 0.948$, $p = 0.400$, Wilks' $\lambda = 0.937$, $\eta^2 = 0.063$]. During the 2.5 of monitoring, older and young workers handled a mean (SD) of (320.4 (67.7) and 319.5 (85.9) packages, respectively. Respective group values for the overall handled mass were 1977.3 (526.0) kg and 1788.4 (481.0) kg. WAI scores did not differ significantly between age groups [$F(6,16) = 1.031$, $p = 0.512$, Wilks' $\lambda = 0.346$, $\eta^2 = 0.654$]. Summary results are presented in the Appendix (Table A.7).

4. Discussion

4.1. General considerations

Our main purpose in the present study was to offer insights useful to develop sustainable work environments for aging workers, by providing data on postural exposure and workability among individuals engaged in order picking tasks. We collected and analyzed trunk and upper arm postures according to ISO 11226 and EN 1005-4 — designed for the prevention of MSDs — to investigate potential differences in postural exposures between young and older workers. Identifying such difference could support future development of ergonomic interventions.

Based on data collected using the inertial sensors and interpreted according to the ISO 11226 standard for assessing static trunk and upper arm postures, we concluded that the maximum acceptable holding time was never exceeded in our cohort. However, both older and young workers used trunk and upper arm postures that exceed the recommended threshold of 60°. When also considering movements shorter than 4 s, the percentage of time spent in in non-neutral postures was much longer (by about 2.5 times for trunk posture and 1.4 times for upper arm posture in both groups of workers). Specifically, young and older workers respectively spent 29.0% and 20.3% of the monitored time in trunk forward inclination over 20° (of which 3.4% and 7.1% exceeded the recommended threshold of 60°). Such results are of some concern, as it was previously reported that workers who spend either more than 10% of their daily shift with trunk inclination exceeding 30°, or more than 5% of the time with trunk inclination exceeding 60°, are at an increased risk of low back disorders (Hoogendoorn et al., 2000; Coenen et al., 2014). Results we obtained from monitoring the upper arm are even more concerning. Both groups of workers spent more than 50% of the time with their upper arm in non-neutral postures, of which 12.5% for the older group and 18.8% for the young workers was over the recommended threshold of 60°. These percentages of time are considered to increase the risk of developing shoulder MSDs (Svendsen et al., 2004; van Rijn et al., 2010; Mayer et al., 2012).

4.2. Age-related effects on trunk and upper arm postures

We found that young and older workers had a substantially similar biomechanical profile during order picking-activities, given that both groups performed a similar number of trunk forward inclinations (2.9 vs 2.5 forward inclinations per minute between 20 and 60° for young and older workers, respectively), as well as similar rate of UA elevations (6.3 vs 6.4 movements per minute between 20 and 40°, and 2.1 vs 1.9 between 40 and 60°, for young and older workers, respectively). These results are consistent with the task profile, which indicated similarities in the number of goods handled (approximately 128 packages per hour for both groups) and the total mass handled (about 1977 kg for the older workers and 1788 for the younger workers) during the monitoring period.

However, our data also suggest that older workers used distinct postural strategies. As noted above, they spent less time in the most severe trunk and upper arm postures. This age-related difference is consistent with previous studies, which also found a lesser prevalence of demanding postures among older workers (Burr et al., 2017; Porta et al., 2021). We believe there are multiple possible explanation for this difference. First, older worker might be (consciously or unconsciously) aware of their diminished level of physical capability, which would account for the smaller observed trunk range of motion and the lower scores in WAI dimensions regarding the number of current diseases diagnosed by a physician and the estimated work impairment due to disease. On the other hand, it is also possible that the older workers used a more cautious approach, one that perhaps arises from positive aspects connected to their seniority and superior knowledge and experience making them more skilled in terms of task planning. For example, an experienced worker who is familiar with a storage location assignment may need less time to search and identify items on shelves (Grosse et al., 2015; Flower et al., 2019). Moreover, experienced workers might remember how to pick items in safer ways, improving their posture in manual handling tasks by trial and error over time.

Indeed, several previous studies have compared lifting behaviors among experienced and novice workers, though with mixed results. For example, Marras et al. (2006) reported that experienced workers had 13% less compressive load on their spine during load handling, Gagnon (2005) emphasized that experts tend to reduce asymmetrical trunk postures using more foot movements, and Plamondon et al. (2010, 2014) found that experts used less lumbar flexion than novices, but only during the performance of specific tasks. In contrast, Lee and Nussbaum (2012) found that experienced workers used more trunk flexion (of note, the experienced participants in their study were on average 26 years old with around 7 years of experience, similar to the young group in the present study). These results suggest that the behavior adopted by older workers does not result solely from more experience but is also influenced by individual characteristics. It is therefore reasonable to hypothesize that older workers cope with the usual reduction in biological functions by improving their ability to balance between job requests, functional ability, and personal resources (Roper and Yeh, 2007; Ronchese et al., 2023; Grosse et al., 2015; Flower et al., 2019; Zacher et al., 2021).

It is also important to acknowledge that the differences were observed between younger and older workers could be at least partially influenced by the 'healthy worker effect' (de Zwart et al., 1995). In brief, the workers in our older group may have been so-called 'survivors', perhaps having higher physical capacity with respect to the general populations, a fact that would attenuate possible differences with their younger colleagues. Nevertheless, as reported by Burr et al. (2017), since physically demanding postures (such as trunk flexion greater than 30°) pose greater health risks to older workers compared to younger ones, it is essential to monitor workers' postures and work ability to effectively plan job duties optimally aligned with individual physical capabilities.

Some remarks are also relevant regarding trunk backward inclination, which frequently occurred during the monitoring period. In contrast to simple observations, use of instrumentation captured relatively small trunk inclinations that are still considered unacceptable from the ISO 11226 standard. We are currently unable to hypothesize if this condition represents an additional risk factor for the development of MSD, either alone or in combination with other types of movements. We recommend future studies to verify whether new cut-off values (larger than the current 0°) should be used to make the standard more realistically applicable.

4.3. Limitations of the study

There are several limitations associated with our study that should be acknowledged. Firstly, in the physical exposure assessment we consider only kinematic variables as they are those included in the ISO 11226 and the EN 1005-4 standards. However, a more detailed analysis should also consider movement velocities, which are recognized as MSD risk factors (Marras et al., 1995; Norman et al., 1998a,b). Handled loads should also be analyzed, considering the ISO 11228-1 (for the risk assessment associated to lifting, lowering and carrying tasks, International Organization for Standardization, 2003) and the ISO 11228-3 (International Organization for Standardization, 2007) for the risk assessment of handling load at high frequency) standards. Unfortunately, data regarding the mass handled by the workers in our study was provided by company records after the experimental campaign. Thus, it was not possible to associate a specific posture assumed by participants with a mass handled in that posture. Secondly, the sample of workers included here included only men, and therefore we were unable to investigate possible gender-related effects, a factor known to influence work strategies (Burr et al., 2017). Finally, since we did not track frequency of errors during order preparation, we cannot rule out that similar physical performance in the order picking tasks is associated with different accuracy. In addition to these limitations, it should be noted that the use of a semi-elastic belt to place the IMU in the low back could lead to misplacement of the sensor (i.e., shift up and down), which requires a visual check of the angular data during the processing to ensure the validity of the acquisition process. As such, we think that the results here presented can be (cautiously) generalized to different occupational sectors, such as metalworking, automotive assembly, and food processing, which are characterized by similar features in terms of handled load and postures.

5. Conclusion

In conclusion, we applied an approach to characterize the postural exposure of workers during regular order-picking shifts, which combined information obtained by a measurement setup based on a reduced number of wearable inertial sensors (one IMU and two triaxial-accelerometers), and a data processing procedure based on the international standards (ISO 11226 and EN 1005-4). Such an approach has been proven effective in discriminating the working strategies of young and older workers, as the latter spend a significantly shorter working time in the most demanding (>60°) postures for both trunk and upper arms. The proposed method appears suitable for application in a wide range of actual working contexts, and we suggest that future studies extend its use among other occupational sectors characterized by different physical demands. The collected information might be useful to better understand some critical aspects associated with the aging workforce process, and to support future decision processes pertaining to the different stakeholders involved in worker health management and in retaining the aging worker.

CRediT authorship contribution statement

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

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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