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Investigating different manual picking workstations for robotized and automated warehouse systems: Trade-offs between ergonomics and productivity aspects

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ABSTRACT

Robotized and Automated Warehouse Systems are widely used in logistics systems due to their efficiency and compactness. Among all aspects to include during tactical and strategic decisions, the number and the design configuration of the picking workstations represent the most critical decision since they influence the conveyor system path and length and the efficiency and productivity of the entire logistics system. Further, the proper workstation design reduces ergonomics risks and, thus, ensures a better quality of work and safety. Nevertheless, many studies on parts-to-picker systems have focused on global system performance, while ergonomics and their influence on system efficiency have often been neglected.

For these reasons, in this paper, we aim to close the gap by investigating both ergonomic assessment and picking workstation configurations in an integrated way. Based on the results obtained, managerial guidelines are provided by highlighting the pros and cons of each configuration. Results demonstrate that the suitable solution depends heavily on the delivery order profile and on the time necessary to pick a customer order line. Configurations with the storage bins placed inclined, placed above the order bin and in front of the worker lead to better posture and lower picking time. Further, additional parameters, such as the time required to change the storage bin, the number of items to pick from each storage bin, strongly influence the choice of the most suitable configuration. The results of this paper represent fundamental guidelines to allow managers to carry out correct feasibility studies in terms of expected costs, performance and required spaces.

1. Introduction

Warehouses represent the intermediate storage of goods between two successive stages of a supply chain (Bartholdi & Hackman, 2016). Today, they play a crucial role in the competitive environment since goods must be delivered quickly to customers by ensuring high-quality service and low cost. Furthermore, in the e-commerce markets, these requirements represent important drivers to manage. For this reason, in the last decade, companies have been forced to manage their warehousing activities appropriately to guarantee an even higher level of efficiency and productivity (Schiffer et al., 2022).

In such a context, Industry 4.0 and automation solutions help practitioners achieve their goals, and in several manufacturing and logistics contexts, automated systems are replacing traditional ones (Kadir et al., 2019). However, as Azadeh et al. (2019) defined, not all warehousing activities can be easily replaced by robots or automated solutions, especially in small and medium companies. In fact, the initial investment required for robotization and automation of all warehousing tasks could not have a short-term return on investment. Further, the picking task robotization should have some ad-hoc requirements that do not always fit with the customer's order profile. Thus, hybrid solutions, with both automatized and manual tasks, are designed. It is the case of Robotized and Automated Warehouse Systems with manual picking workstations. Such types of systems are categorized as parts-to-picker systems. Generally, they consist of 1) robotized or automated storage and retrieval systems, 2) a conveyor system with shuttles or mini-loads that retrieve one or multiple loads (pallets or bins) and 3) a pick position (i.e. a depot or a picking workstation). Once the bin arrives at the picking workstation, the worker involved in the process takes the required number of items, and then the bin is stored again (de Koster et al., 2007). Such a type of system is used in a high-intensity context, with many order lines per hour (above 1500). Thus, they require a high

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level of automation and several picking workstations to guarantee high efficiency.

To maintain high standard levels and due to the increased investment cost required in implementing this type of solution, practitioners should design or select appropriate manual picking workstations by including both ergonomic and economic aspects. Further, the design of the picking workstation influences the efficiency of the whole parts-to-pickers system. The higher the number of storage bins arriving simultaneously in the picking workstation area, the higher the number of conveyors required and, thus the total conveyor length. Additionally, the higher the number of picking workstations, the higher the investment for such an automation system. Finally, once the whole storage and picking system is designed, adding additional picking workstations or changing the configuration of each workstation becomes challenging.

In Robotized and Automated Warehouse Systems with manual picking workstations (parts-to-picker systems), pickers are not more involved in walking or driving as in manual and traditional warehouses (picker-to-parts systems). The ergonomic effort mainly guarantees suitable and comfortable postures for the upper extremities while performing repetitive movements for a long time. Consequently, different picking workstation configurations often lead to different ergonomics working assessments and, therefore, to different workers' efficiency, costs, and performance.

Nevertheless, research in this field is still scarce, as stated in the recent survey by Boysen et al. (2019).

Starting from these initial considerations, in this work, we conduct an ergonomic and production efficiency analysis for several picking workstations that can be designed and implemented as the final stage of robotized or automated warehouse systems. In particular, we investigate how the number of storage bins, their arrival position and their inclination when they arrive in the picking workstation influence the posture and the time while performing picking.

The methodology consists of replicating advanced picking workstations, simulating the picking tasks and collecting all relevant data (posture, joint angles, distances, time) with a motion capture system connected to the Workforce Ergonomics and Management (WEM) Platform (Battini et al., 2022).

The main novelties of this work can be summarized as follows:

1) Sixteen picking workstation configurations are considered and compared. Each configuration derives from a designed picking workstation by companies' leaders in this field. In this way, our work can provide practical insights for practitioners who are asked to select the proper picking workstations. Contrary to previous works, which mainly focused on one picking workstation, we can provide a global overview for different configurations.
2) Detailed analysis of postural scores and joint angles, hands and pelvis movements for each configuration is done. In this way, we provide a global and critical ergonomics overview combined with time analysis.
3) A parametrical analysis is provided for practitioners to choose the suitable picking workstations to implement the parts-to-picker system. The decision about the proper picking workstation selection is influenced by several factors that are not directly connected to ergonomics and time efficiency. We demonstrate that additional objective factors, like the number of items to pick, the number of rows per order and the time required to change the storage bins lead to selecting one configuration instead of another.
4) Finally, this work moves toward the recent paradigm of Operator 5.0 defined by the European Commission EC (2021, 2022), which aims at creating more resilient, sustainable, and human-oriented manufacturing, production, and logistics systems.

The remainder of this paper is structured as follows. Section 2 investigates previous works focused on parts-to-picker workstation design. Section 3 reports the problem description, a short description of the system we use to collect relevant data and the differences between the compared picking workstations. Section 4 reports a detailed analysis and discussion of the results and managerial insights derived from collected data. Finally, Section 5 concludes our work by providing future research directions.

2. Literature review

In this section, we provide an overview of the ergonomic assessment tools that can be used to investigate postures and other ergonomics risks during tactical, strategic and operational decisions. Further, existing works, focused on integrating ergonomics in picking workstation design are presented.

2.1. Ergonomic assessment in logistics systems

Several tools and assessment methods exist to quantify the ergonomics and the postural risk associated with manual and repetitive tasks. These tools can be divided into three main categories: self-reports, observational methods, and direct/instrument-based methods (David, 2005). Self-assessment tools involve workers directly. They collect data on risk exposure using questionnaires, checklists, or interviews. These reports are based on workers' perceptions and feelings.

For this reason, the results are imprecise and too subjective. To overcome this limit, observational methods allow analysts to make postural evaluations based on direct observations or videos. Moreover, thanks to the advancement of new technologies like motion capture systems, the ergonomic score can be continuously computed in real-time by saving efforts for ergonomists and giving a more precise and detailed result (Battini et al., 2022).

The most used and widely known observational methods follow international standard ergonomic indexes, such as the Occupational Repetitive Actions (OCRA) (Occhipinti, 1998), NIOSH lifting equation (National Institute of Occupational Safety and Health Lifting Index) (Waters et al., 1993) and Job strain Index (JSI) (Moore & Garg, 1995). Additionally, simplified ergonomics methods can be adopted in the initial ergonomics analysis due to their simplicity and short computational time (ISO, 2007). In such a context, the Rapid Upper Limb Assessment (RULA) (McAtamney & Corlett, 1993), the Rapid Entire Body Assessment (REBA) (Hignett & McAtamney, 2000), the Ovako Working posture Assessment System (OWAS) (Karhu et al., 1977) can be used.

RULA and REBA are two similar methods for screening and identifying harmful postures. RULA is more suitable for intensive hand-arm activities, such as sitting assembly work. At the same time, REBA evaluates the entire body and is more appropriate when both upper and lower body are involved, such as during picking or construction activities.

RULA worksheet evaluates position deviation in six body regions (upper arm, forearm, wrist, neck, trunk, and legs) from their neutral position as well as the carried weight and the type of movement (static or dynamic). The final score varies from 1 to 7, where 1 describes a work situation without risk and 7 highlights the need to act via immediate adjustments. REBA worksheet evaluates the same body regions as RULA, but it also includes grips and coupling in the analyses. The final score ranges from 1 to 5. As long as the score is lower than 3, minor corrections are necessary. Conversely, a score ranging from 4 to 7 requires corrective actions. Whenever the score exceeds 7 points, corrective interventions must be implemented as soon as possible, as the repetitiveness of the analysed work posture can cause ergonomics diseases over time.

Finally, the OWAS score analyses the position of both upper and lower body parts. It provides one single-digit score for each part of the body, starting from the back, arms, legs and the loads carried during the activity. These four digits are used as an input for the table that includes all possible digit combinations and their corresponding ergonomic risk.

OWAS classifies action risk into four categories ranging from 1 = no risk to 4 = high risk.

2.2. Ergonomics integration in picking workstations design

Order picking (OP) is the process of retrieving items from storage locations and bins to fulfil customer orders (Tompkins et al., 2010). According to several studies (Calzavara et al., 2017; Calzavara et al., 2019; Glock et al., 2019), OP represents the most laborious and expensive warehousing process activity, mainly performed manually due to its features (Grosse et al., 2015; De Koster et al., 2007). Such a process involves lifting, moving, selecting, placing, and packing items to fulfil customer orders (Richards, 2017). These activities are simple and easy to perform but highly repetitive and physically demanding. Furthermore, such repetitive tasks using awkward postures can strain the worker's body or cause fatigue, injuries or, worst cases, disabilities. For this reason, in the last decade, academics have paid more attention to investigating ergonomics, physical and muscular fatigue, and learning and forgetting while performing OP tasks (Battini et al., 2016; Finco et al., 2021; Grosse et al., 2017; Rinaldi et al., 2022). Improving ergonomics led to greater worker well-being and enhanced performance goals by reducing illnesses and absences from work (Grosse et al., 2015). Furthermore, according to several previous works (Digiesi et al., 2009; Katiraee et al., 2021; Simonetto et al., 2022), throughput and system efficiency strongly influence worker satisfaction, motivation, and physical stress. Therefore, it is necessary to include ergonomics aspects during strategic, tactical, and operational decisions, which refer to long- and short-term decisions, respectively.

The proper design of the picking strategy and, thus, the related picking system (i.e., workstation design, number of picking workstations, automation level) represents a tactical decision. It is influenced by several factors, like the number of items to pick per hour, the customers' orders profile, and the number of items. Further, it represents a long-term decision; thus, the features of the workers involved in picking are unknown at this stage (Finco et al., 2020). For this reason, at this stage, ergonomics aspects, which refer to a generic worker, must be included as essential drivers in selecting the proper picking workstation (Battini et al., 2011, Battini et al., 2020). Other issues, such as differences among workers and working periods, refer to operational decisions, thus, short-term period decisions. All these aspects can be included in job rotation scheduling models aiming to smooth workload balance among workers with different experience levels (Wang et al., 2022). Two standard picking methods are picker-to-parts and parts-to-picker (Boysen et al., 2019). Most of the existing works on ergonomics in picking design are related to picker-to-parts systems where workers walk or drive through the warehouse aisles to retrieve items from shelves or pallets (e.g. Grosse et al., 2015; Grosse et al., 2017; Sgarbossa et al., 2022).

Moving to parts-to-picker systems, only the works here summarized include and provide suggestions for properly designing advanced picking workstations. Wakula et al. (2021) offered an ergonomic analysis for eight configurations by focusing on the picking workload for eight subjects.They used the Captive Motion capture system and investigated the Ergonomic Assessment Worksheet (EAWS, Schaub et al., 2013). They stated that low weights and not high pick frequency do not cause high physical stress since the computed EAWS was less than 25 points. On the other hand, a higher picker frequency or higher weights increase physical workload (EAWS higher than 25 points). Lee et al. (2020) conducted a virtual workplace assessment simulation for a robot-human co-work order-picking system by investigating RULA index for two order picking systems (moving robot vs. AS/RS). The AS/RS order picking system was shown to have lower risk factors for human workers. On the other hand, the picking station in MR-type order picking systems required critical changes concerning human postures. Lee et al. (2016) conducted selection tests and descriptive surveys with 30 participants. Different postures with two picking workstation configurations (different height positioning of the bin in the workstation) were tested and analyzed. Ergonomic tests also included electromyography tests. No discussion and data on economic and performance aspects were considered. Könemann et al. (2015) investigated the effects of horizontal bin locations on upper arm elevation, trunk inclination, and hand use in an order-picking workstation in eight subjects by changing the weight of the product to pick and the pick and place position. They stated that a far place position requires more upper arm elevation and trunk inclination while hands movements are not influenced by the pick and place positions. Finally, Könemann et al. (2012) studied the movement strategies for a specific picking workstation, the underlying factors, and their impact on performance. From an ergonomic point of view, they stated that allowing more movement variation in the picking-workstation analyzed without a performance reduction represents a benefit for designers.

All previous works focus on measuring ergonomics and postural scores, muscle fatigue, or psychological aspects, but other important aspects, such as economic measures, are often neglected. As an example, the picking time has never been considered. Moreover, a single picking workstation system (or configuration) is investigated in each work. Only Wakula et al. (2021) considered several picking workstation configurations, but no details and differences among workstations are provided, and consequently, their work is not replicable. Each work investigated ergonomic posture via an ergonomic index (i.e. RULA, EAWS), but none proposed an integrated approach in which several ergonomic aspects are investigated jointly. Finally, none investigated how a customer's order profile influences the choice of a picking workstation instead of another one. In fact, the proper selection of the number of storage and order bins for each workstation could deal with different ergonomics levels, costs and performance.

3. Problem description and laboratory tests assessment

3.1. Problem description

We aim to investigate how the design of advanced picking workstations influences postural ergonomics scores and picking time. In such a way, we can select the proper picking workstation configuration and design the system by including the conveyor and storage sub-systems.

Fig. 1 reports an example of an automated warehouse that consists of four main sub-systems: 1) storage, 2) conveyors for storage bins, 3) conveyors for packaging boxes and 4) picking workstations.

Such types of systems are implemented in e-commerce distribution centres which are characterised by: 1) small orders, 2) large assortment, 3) tight delivery schedules, and 4) varying workloads (Zennaro et al., 2022; Boysen et al., 2019).

Further, Fig. 2 reports an example of a picking workstation. In such a configuration, items arrive on the right and left side of the picker through a conveyor and into bins (called storage bins, blue boxes in Fig. 2). The worker takes an empty order bin from the upper level (according to the size of items to pick). Then the worker picks the items and places them in order bins (the yellow box in Fig. 2) associated with customer orders. Additionally, the storage and order bins are placed on a workstation that is adjustable in height according to the anthropometric features of the picker. A monitor in front of the picker helps identify how many items are requested for each order. One after another, storage bins arrive at the station and are processed by the picker until an order bin is completed, and automatically swapped with a new (empty) order bin.

According to Fig. 1, we can state that there are several complexities in such a type of storage automation since all required systems are related to each other. Thus, once the whole system is designed, it is no longer possible to redesign it by adding more workstations or changing the number of storage bins arriving in front of the worker. It is mainly due to the complexity of the conveyor sub-system, which is required to: 1) move storage bins from the storage area to the proper picking workstation, 2) move empty order bins from their preparing area to the

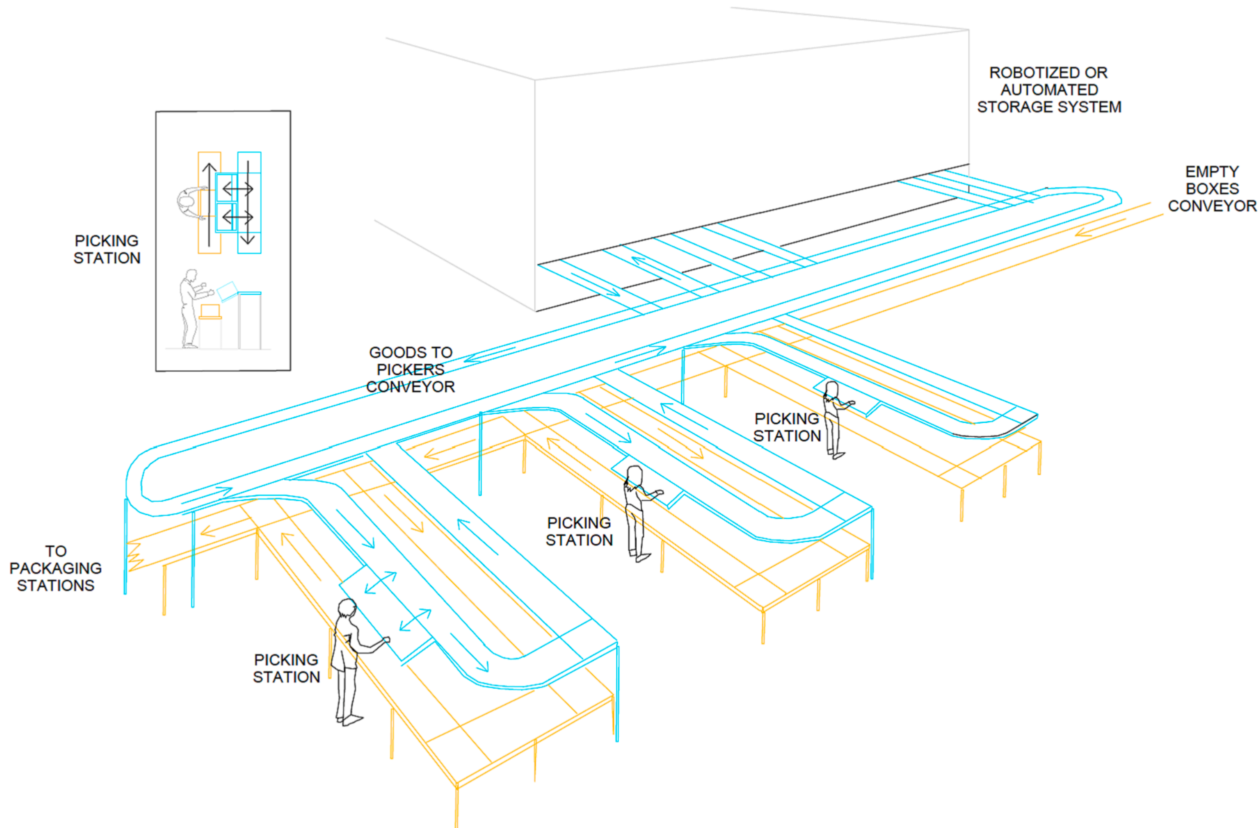

Fig. 1. An example of an automated warehouse system.

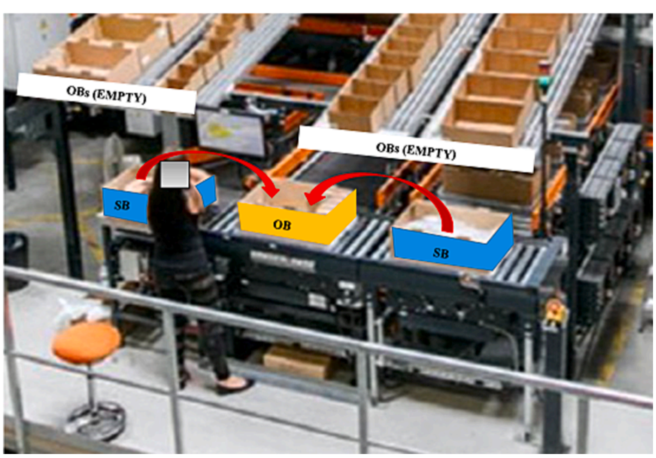

Fig. 2. An example of an advance picking workstation (SB: storage bin; OB: order bin).

picking workstation and 3) move order bins from the picking workstation to the final packing area. Further, the costs associated with conveyor systems for such a system represent a significant percentage of the entire investment, as also reported in Table 1.

Table 1
Cost categories for parts-to-picker systems.

Cost category	Impact on the total investment
Storage sub-system	56 %
Picking & Packing (10 picking workstations)	22 %
Conveyor & Sorting sub-system	12 %
Software	9 %
Initial setting & ramp-up	1 %

Table 1, derived from the authors' experience and collaboration with companies' leaders in designing such systems, summarizes cost distributions and their impact on the total cost for an automated solution, as reported in Fig. 1, with ten picking workstations.

Costs can be clustered into five main categories: 1) storage subsystem (i.e., racks, lifts, shuttles), 2) picking and packing (i.e., picking workstations, carton erector, labelling, weight scales), 3) conveyor and sorting sub-system, 4) software and 5) initial setting and ramp-up. The impact of each cost family derives from the main company leaders in this field.

According to Table 1, picking and packing cost significantly influences the total cost of implementing parts-to-picker systems.

For this reason, it is necessary to include ergonomics and technological aspects during the design phase of picking workstations by following the methodology proposed by Battini et al. (2011).

3.2. Motion capture system and WEM platform

Aiming to record the movements performed by the order picker involved in the experiments, an Inertial Motion Unit (IMU) based suit, called MTw Awinda (Xsens), is used.

The MTw Awinda has 17 IMUs (see Fig. 3). Each wireless sensor contains a gyroscope, magnetometers, and accelerometers. The system includes a shirt with IMUs for the trunk and shoulder placed on special straps, a headband, two hand bands, and 11 strips for the rest of the body. It provides data up to 60 Hz; further, the external antenna of the Awinda station enables an indoor wireless range of 20 m and an outdoor range of 50 m.

All data are collected with the motion capture system and processed in real-time using WEM-Platform software (Battini et al., 2022). This platform uses joint angles related to the neck, shoulder, elbow, wrist, and trunk as input data to compute the RULA, REBA, OWAS, and PERA

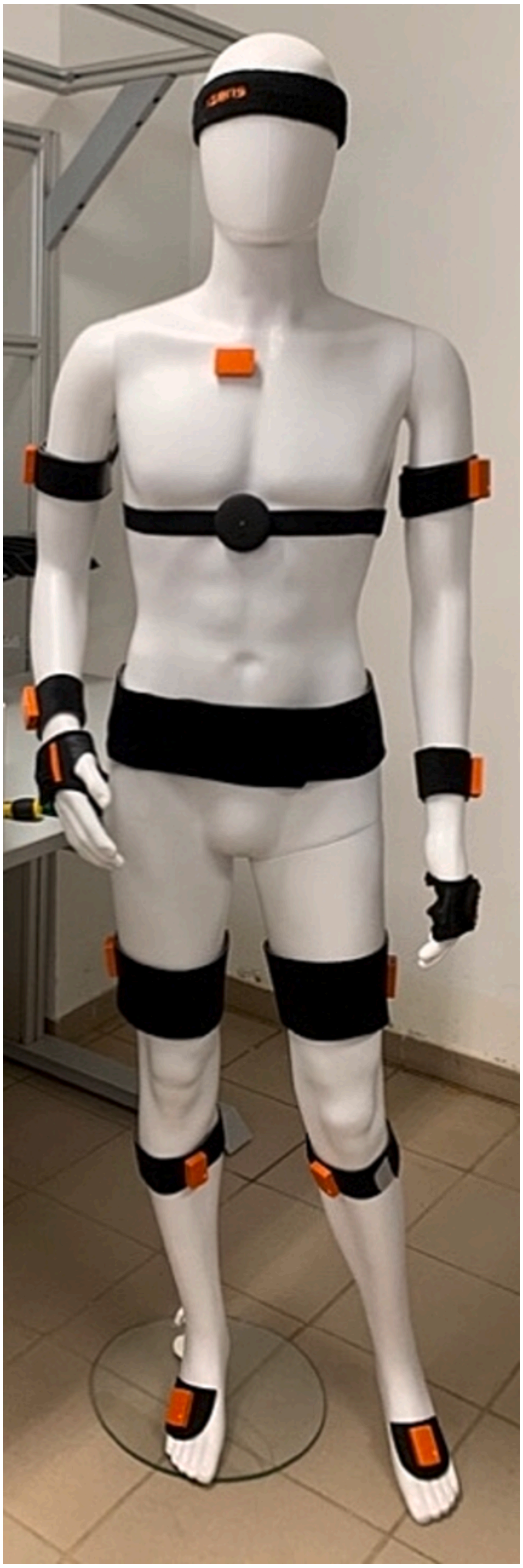

Fig. 3. The Mocap system used to collect postural data (the orange parts are the IMUs).

ergonomics indexes and the percentage of time the worker is involved in hazardous working postures. Furthermore, the WEM Platform defines the average and total pick time and the lengths of the order picker pelvis and hands path. Finally, all joint angles and positing data can be used for post-processing.

In our specific case, as postural analysis, we select and evaluate the following:

1) RULA as ergonomics index due to the feature of the advance picking workstations we analyzed. The RULA index is mainly used when the upper part of the body is highly involved in tasks.
2) The postural coefficient of OCRA.
3) NIOSH angles (ISO 11226) since they provide a direct measure of joint angles related to the upper part of the body (Battini et al., 2022).
4) The average distance of the hands and centre of gravity (COG) while performing picking since they provide details about the worker's movement. In such a context, we expect that the lower the hands and COG distance, the shorter the picking time.

3.3. Experimental design and assumptions

The experimental analysis was performed by replicating and testing 16 advanced picking workstation configurations, as reported in Fig. 4. Differences among the configurations can be set according to:

1) The level of storage and order bins: one level in case storage and order bins are at the same height (i.e., aligned), and two levels in case their height differ (storage and order bins can be placed at an upper or lower level). In Fig. 4, front view A represents the case with storage and order bins aligned, while front view B (resp. C) represents the case with storage bins placed under (resp. upper) the order bin.
2) The number of storage bins. For example, configurations 2.B and 3.B and 2.C and 3.C differ in the number of storage bins. In fact, in configurations 2.B and 2.C, there are four storage bins while two storage bins can arrive in the picking workstation for configurations 3.B and 3.C. Further, we assume that we have one order bin for each configuration. In this way, batch picking is avoided, and only one order can be processed at one time.
3) The inclination of storage bins: 0° or 30°. These inclinations align with those given by company leaders in designing such workstations and those that provide solutions for assembly workstations. Further, inclination levels higher than 30° could lead to a fall of items from the storage bins, which must be avoided.
4) The lengthwise (or widthwise) orientation of storage and order bins differ accordingly to the configuration.

Finally, the storage bins arrive at the workstation and are placed 100 mm apart.

Since the workstation height is adjustable based on the picker characteristics, Table 2 summarizes the measures and additional features among the storage and order bins for each configuration.

The vertical distance between the storage and order bins is computed by considering the centre of gravity of the bins and a fixed length of 100 mm. In the Appendix section, Table 1A reports additional measures and data which can help replicate the simulation environment.

Further, the human picker involved was a man 1.75 m tall and 27 years old who gave his informed written consent before starting the study. For each configuration, he picked and placed items 50 times per configuration. The Mocap and WEM platforms collected postural data, joint angles, and time (Battini et al., 2022).

Fig. 5 reports an example of two advanced picking configurations. The picker wears the Xsens Mocap that is connected to the WEM Platform, aiming to collect all necessary data for our analysis. The height of the simulated workstation is set according to the size of the picker

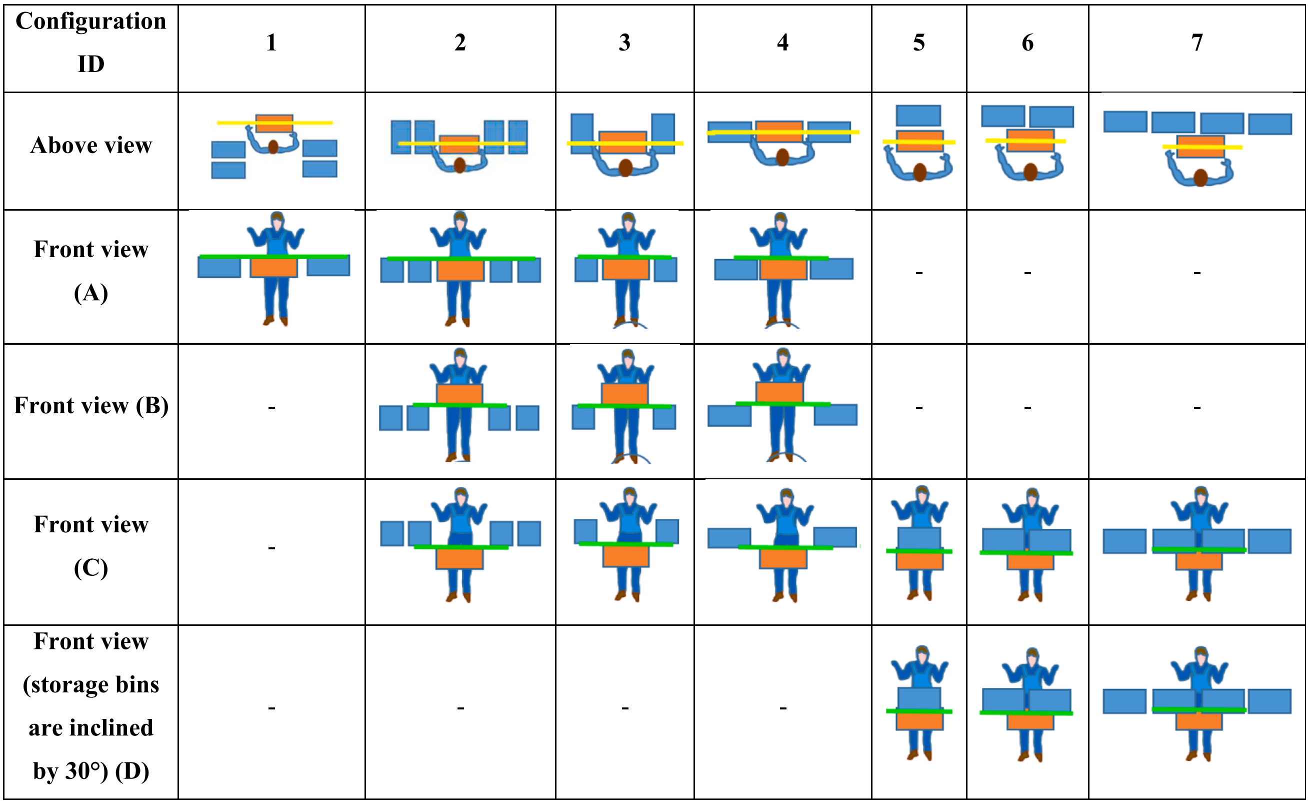

Fig. 4. Schematic representation of the configurations of the advance picking workstations considered in the current study (blue bins are the storage bins, the orange bin is the order bin).

Table 2
Summary of the main features for each configuration.

Configuration ID	Storage bin (qty)	Level	Storage bin level (compared to order bin)	Vertical distance [mm]	Storage bins inclination	Storage bin orientation
1.A	4	1	Same level	0	0°	Lengthwise
2.A	4	1	Same level	0	0°	Widthwise
2.B	4	2	Lower	320	0°	Widthwise
2.C	4	2	Upper	320	0°	Widthwise
3.A	2	1	Same level	0	0°	Widthwise
3.B	2	2	Lower	320	0°	Widthwise
3.C	2	2	Upper	320	0°	Widthwise
4.A	2	1	Same level	0	0°	Lengthwise
4.B	2	2	Lower	320	0°	Lengthwise
4.C	2	2	Upper	320	0°	Lengthwise
5.C	1	2	Upper	320	0°	Lengthwise
5.D	1	2	Upper	320	30°	Lengthwise
6.C	2	2	Upper	320	0°	Lengthwise
6.D	2	2	Upper	320	30°	Lengthwise
7.C	4	2	Upper	320	0°	Lengthwise
7.D	4	2	Upper	320	30°	Lengthwise

involved. In such a way, we can provide general guidelines that are not influenced by the subject involved in the experimental procedure.

Further, for all tests, we make the following assumptions:

1) Only lifting, moving, picking and placing activities are simulated. Order packing, labelling, inspection and quality control, scanning and button-pushing activities are performed similarly for each configuration. Thus, they do not influence the choice to select the appropriate advanced picking workstation from an ergonomic point of view.
2) No replication of a functioning conveyor system was established. This means we replicate only movements linked to the picker (e.g., lift, move, pick and place) and, thus, their influence on the postural scores.
3) Picker takes an ergonomic and neutral posture during idle times caused by storage bin changes.
4) The time required for the replacement of storage bins can be done while he is performing picking; thus, it can be considered a masked time.
5) The height of each workstation is adjusted according to the anthropometric features of the picker (see Fig. 6). This is in line with the real functioning of such systems since they can be adjusted according to the worker's physical features.

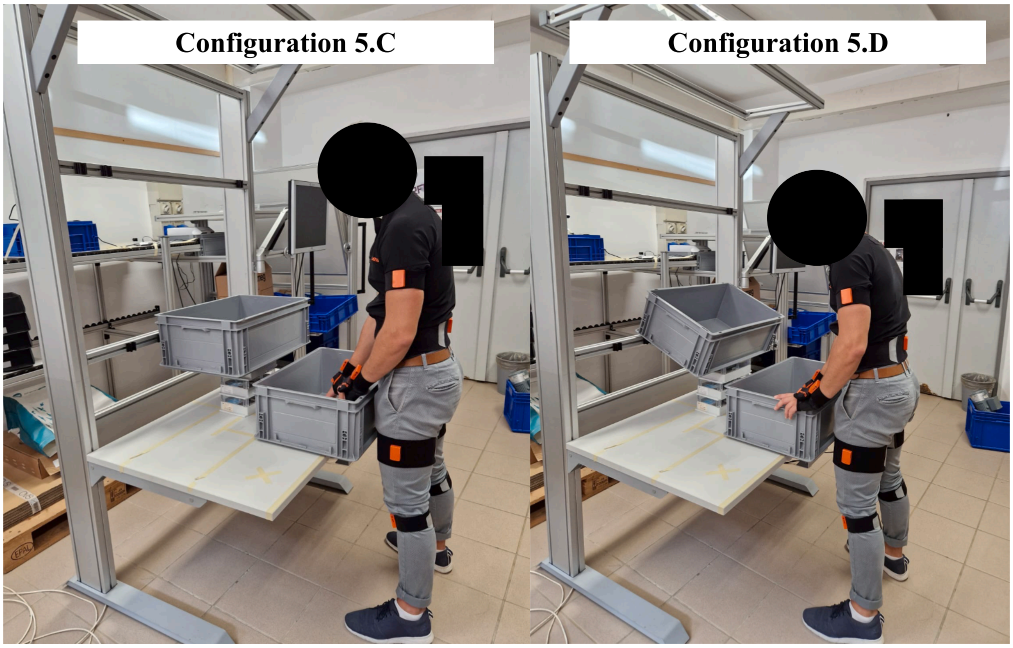

Fig. 5. Example of advanced picking workstations simulated in our Ergo lab (the picker wears the Xsens Mocap).

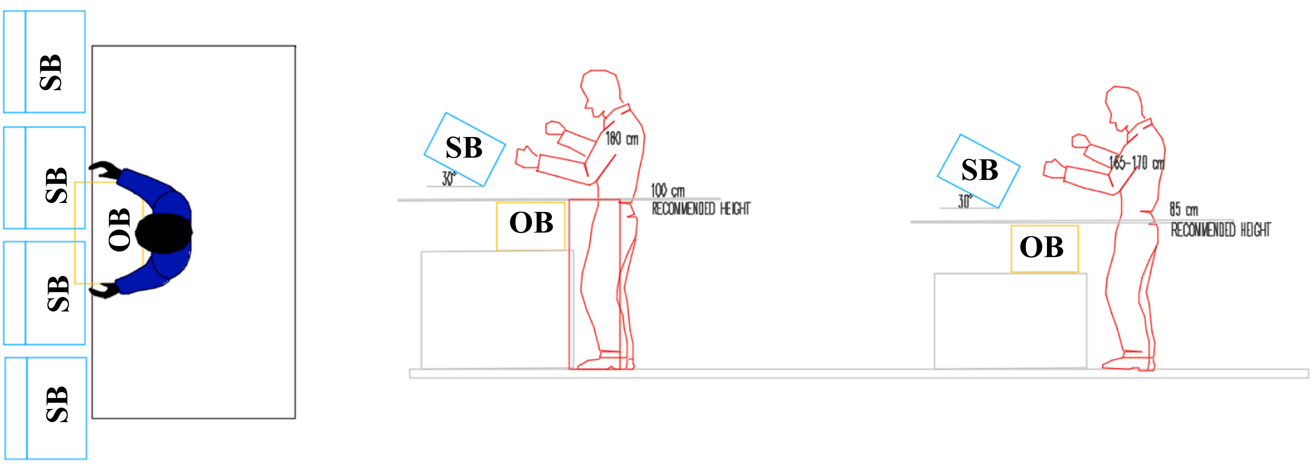

Fig. 6. Height definition for each configuration according to workers' features (SB: storage bin, OB: order bin).

6) In all cases, both storage and order bins are dimensioned as follows: 60 cm (length), 40 cm (width), and 22 cm (height). We select these bins since they are widely used in this type of parts-to-picker system.
7) The picked parts were small, light boxes (weighing less than 0.5 kg).

4. Results analysis and discussion

4.1. Hands and centre of gravity traveling distance

The motion capture system tracks the global positions of all joints of the body parts in every time frame (set at 40 Hz in our case). Since then, a tracking algorithm has calculated the Euclidean distances covered by the hands and the operator's centre of gravity (COG) while picking 50 times. The position data expressed in meters are reported in Table 3, where the distances of the tracked and mean rectangular hands per pick are also reported. Finally, a distance comparison between all configurations and one that provides the minimum hands and COG distance is reported. We can see that the percentage difference between all configurations and the one with the lower value is very considerable by focusing on the COG distance.

Focusing on the COG travelling distance, configurations 5.C and 5.D do not require a movement of the legs while performing picking, and, for this reason, they are those with a lower COG travelling distance. Moreover, in such configurations, there are a storage bin and an order bin positioned on different levels, and the picker needs to move his/her shoulders and hands to position items from one bin to the other. In the 5.D configuration, the storage box is inclined by 30°; for this reason, there is also a slight reduction of the total and mean hands distance (5.21 % lower).

On the other hand, configurations 7.C and 7.D lead to a higher COG travel distance, slightly higher than configuration 2.A (+5.71 %). However, for configurations 2.A, 7.C, and 7.D, pickers must move on the right or left side to collect items from the storage bin and place them into the order bin. For configuration 7.C, there is also a higher value of the travelling distance of the hands. In configuration 7.D, the travel distance of the hands is less than 3.14 % due to the inclination of the storage bins.

Further, configuration 1.A leads to the travelling distance of the hands being very close to configuration 7.D even if the travelling distance of the COG is lower. In fact, in this configuration, the storage bins arrive parallel and on the left and right sides of the picker. Thus, leg

Table 3
Hands and COG travel distances (in bold minimum values, underlined maximum values).

ID	Left-hand distance [m]	Right-hand distance [m]	COG distance [m]	Mean hand distance per pick [m]	Mean rectangular distance per pick [m]	Mean COG distance [m]	Percentage difference with the lower hand distance	Percentage difference with the lower COG distance
1.A	91.3	91.3	25	1.83	3.1	0.5	101.10 %	900 %
2.A	87.5	91.3	35	1.79	2.1	0.7	96.70 %	1300 %
2.B	66.3	68.8	31.3	1.35	2.7	0.63	48.35 %	1160 %
2.C	78.8	80	33.8	1.59	2.7	0.68	74.73 %	1260 %
3.A	60	68.8	18.8	1.29	1.6	0.38	41.76 %	660 %
3.B	57.5	63.8	21.3	1.21	2.2	0.43	32.97 %	760 %
3.C	55	66.3	17.5	1.21	2.2	0.35	32.97 %	600 %
4.A	70	71.3	22.5	1.41	1.6	0.45	54.95 %	800 %
4.B	55	68.8	27.5	1.24	2.2	0.55	36.26 %	1000 %
4.C	71.3	72.5	18.8	1.44	2.2	0.38	58.24 %	660 %
5.C	46.3	50	**2.5**	0.96	1.6	**0.05**	5.49 %	0 %
5.D	**43.5**	**47.2**	**2.5**	**0.91**	1.52	**0.05**	0.00 %	0 %
6.C	48.8	50	3.8	0.99	2.3	0.08	8.79 %	60 %
6.D	46.5	47.5	3.8	0.94	2.22	0.08	3.30 %	60 %
7.C	95	95.5	36.9	1.91	3	0.74	109.89 %	1380 %
7.D	92.2	93	36.9	1.85	2.92	0.74	103.30 %	1380 %

movements are limited, but it is not the same for hands since she/he picks items from both sides of the workstation.

Moving to other configurations, 6.C and 6.D are similar to 5.C and 5.D. There is a slight increase in both hands and COG travel distance since there are two storage bins instead of one.

Comparing configurations belonging to families 3 and 4 with two storage bins and different orientations (widthwise for configuration 3 and lengthwise for configuration 4), we can say that a widthwise orientation leads to lower hands and COG travelling distance (see Table 3).

Finally, comparing configurations belonging to the same family, we can say that positioning storage bins in a lower level despite the order bin leads to lower hands travelling distances.

The distances covered by the COG and the hands were also tracked in a 3D spaghetti chart for each configuration. Figs. 7 and 8 report the spaghetti chart of the COG, and the hands obtained during the test are represented. We report and compare two configurations 2.A and 5.D. It can be seen that the amplitude of the chart is reduced in configuration 5.D compared to 2.A for COG and hands, as confirmed by the values reported in Table 3.

4.2. *NIOSH angles analysis*

The NIOSH angles were also collected and analyzed to further support the analysis with the WEM platform. Thus, we investigated them by computing the percentage of time spent in the different position ranges. No substantial differences are detected between the different configurations regarding trunk flexion and lateral bending; thus, we do not report them in this work. Furthermore, the shoulder abduction for both arms had no variations between configurations. The main differences have been found concerning both arms' shoulders and elbow flexions (as reported in Table 2A and 3A in the Appendix).

For the shoulders, we can say that for both left and right sides, no time is spent in a highly risky position with an angle flexion greater than 90° for all configurations. However, for all cases where storage bins are placed at an upper level despite the order bin (thus 5.C and 5.D, 6.C and 6.D, 7.C and 7.D), we have the higher values. Furthermore, for configuration 2.C (left shoulder), for the 6.11 % picking time, the shoulder reports a flexion greater than 60°.

Moving to the elbows, the right one reports a higher flexion since the picker uses the right hand for picking. Also, in this case, the storage bins' inclination reduces the flexion angle (compare 5.C and 5.D, 6.C and 6.D, 7.C and 7.D).

However, for cases where storage and order bins are placed at the same level, the elbow flexion reaches higher values for a lower amount of time and, consequently, configurations 2.A, 3.A and 4.A could be preferable compared to 2.B or 2.C (resp. 3.B or 3.C and 4.B or 4.C).

In addition, configurations 5.C and 5.D have a good balance among all different angles.

4.3. *RULA analysis*

The RULA index is computed for each configuration. We select RULA since it focuses more on the upper part of the body, which could also be

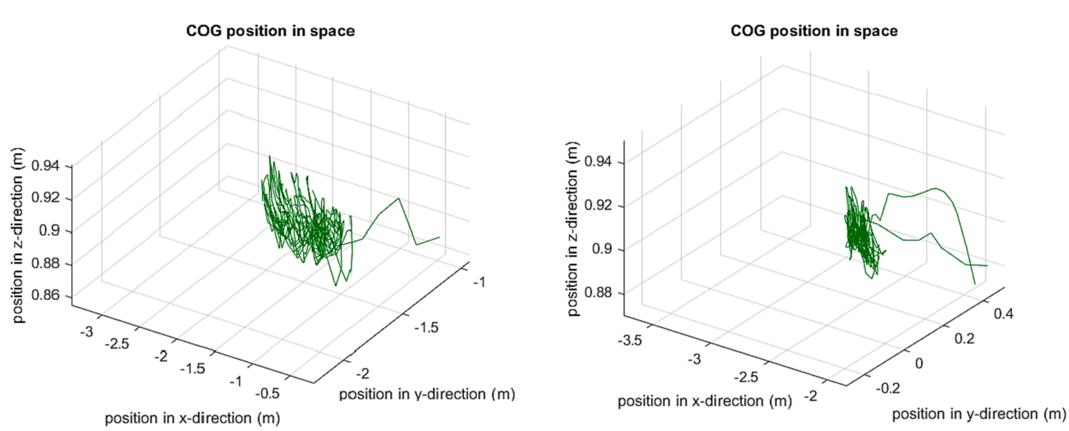

Fig. 7. COG spaghetti chart of configurations 2.A and 5.D.

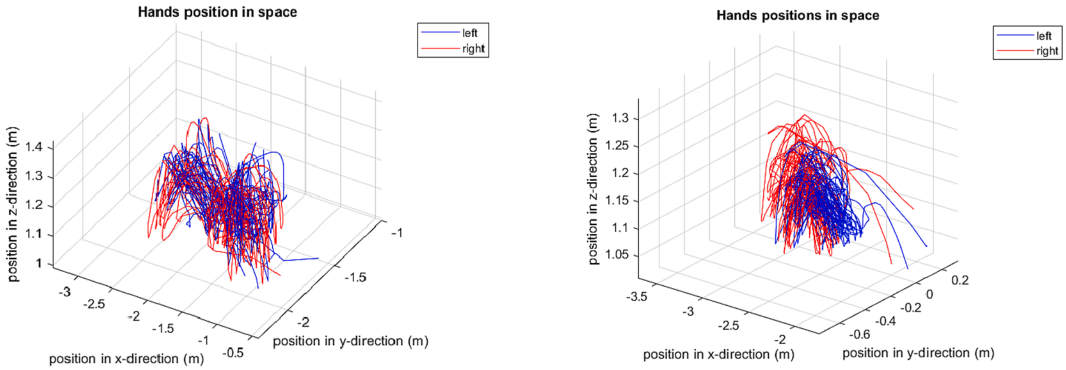

Fig. 8. Hands spaghetti chart of configurations 2.A and 5.D.

Table 4
RULA risk levels for each configuration.

ID	RULA LEFT [1–2]	(2–4]	(4–6]	6+	Mean Value	Std. Dev.	RULA RIGHT [1–2]	(2–4]	(4–6]	6+	Mean Value	Std. Dev.
1.A	1.72 %	49.87 %	45.85 %	2.56 %	4.4	1.1	1.90 %	52.43 %	45.01 %	0.67 %	4.4	1
2.A	0.76 %	54.64 %	44.39 %	0.21 %	4.5	1.2	1.36 %	57.88 %	40.77 %	0.00 %	4.4	1.1
2.B	0.98 %	73.63 %	25.39 %	0.00 %	4	1	1.36 %	72.86 %	25.78 %	0.00 %	3.9	0.9
2.C	3.67 %	86.97 %	9.36 %	0.00 %	3.5	0.8	5.73 %	74.39 %	19.84 %	0.05 %	3.6	1
3.A	0.46 %	59.10 %	40.43 %	0.00 %	4.4	1.2	1.35 %	60.62 %	38.03 %	0.00 %	4.2	1.1
3.B	1.16 %	76.59 %	22.25 %	0.00 %	3.8	1	1.80 %	73.83 %	24.36 %	0.00 %	3.8	0.9
3.C	1.99 %	73.13 %	24.89 %	0.00 %	3.9	1	2.36 %	70.03 %	27.60 %	0.00 %	3.9	1
4.A	0.43 %	49.50 %	47.65 %	2.43 %	4.7	1.2	0.43 %	49.62 %	49.95 %	0.00 %	4.6	1.1
4.B	2.56 %	65.39 %	31.97 %	0.08 %	4	1.1	2.04 %	62.78 %	35.18 %	0.00 %	4	1
4.C	2.05 %	84.54 %	13.41 %	0.00 %	3.6	0.9	1.97 %	79.18 %	18.84 %	0.00 %	3.6	0.9
5.C	3.34 %	88.80 %	7.86 %	0.00 %	3.4	0.7	11.16 %	83.18 %	5.66 %	0.00 %	3.3	0.8
5.D	2.69 %	93.94 %	3.37 %	0.00 %	3.2	0.6	8.24 %	86.35 %	5.41 %	0.00 %	3.2	0.7
6.C	8.47 %	89.30 %	2.22 %	0.00 %	3.2	0.6	16.28 %	78.93 %	4.79 %	0.00 %	3.1	0.8
6.D	5.24 %	91.07 %	3.69 %	0.00 %	3.2	0.6	16.62 %	78.19 %	5.19 %	0.00 %	3.1	0.8
7.C	8.56 %	81.66 %	9.76 %	0.03 %	3.4	0.6	3.96 %	79.45 %	16.59 %	0.00 %	3.5	0.8
7.D	2.46 %	73.93 %	23.42 %	0.19 %	3.5	1.1	2.81 %	75.53 %	21.56 %	0.11 %	3.8	1

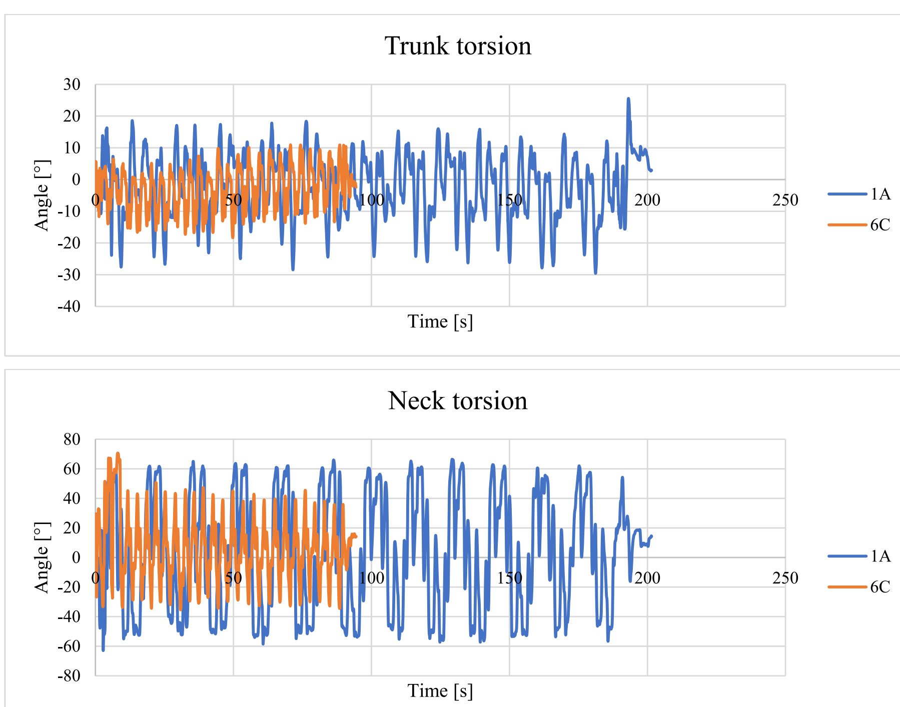

Fig. 9. Trunk and neck torsion evolution for 1.A and 6.C configurations.

riskier in the configurations proposed here. We saw that the travelling distance of COG is not significant for all configurations, which means that the lower part of the body is not exposed to postural risk.

The RULA index is calculated and recorded by the WEM platform frame per frame, enabling continuous index analysis during the entire task execution. Since then, it has been possible to map the percentage of time spent in each of the index's four risk levels. Table 4 reports the percentages of time spent on each risk level on the left and right sides of the body for each configuration. Further, the mean value and the standard deviation of the RULA index while performing the whole picking activity are computed (for the mean value, we associate the corresponding colour by considering continuous values).

As we can see, for most configurations, the percentage of time spent in a postural risk greater than 6 tends to be zero. Only for configurations 1.A, 4.A and 7.D, we have a small percentage of time in a postural zone higher than 6. In all cases, the reason is mainly traceable to the neck joint angles tracked by the mocap system and configuration 1.A to the trunk torsion, which highly influences the RULA score.

Comparing different configuration families, we can see that families 5, 6 and 7, characterized by storage bins placed at a higher level despite order one, have lower RULA scores. In such configurations, pickers do not incline the neck while performing picking. Thus, the postural score always assumes a low value. Moreover, little changes could be made, but they are not mandatory.

On the other hand, families 1, 2, 3 and 4 report higher values for RULA when storage bins are placed at the same level as the order bin. In these cases, the neck is inclined more than 20° while picking, and this causes a significant increase in the RULA score and, thus, the postural risk. Therefore, to reduce the risk, placing storage and order bins at different levels leads to a RULA score reduction, confirmed by the values we computed.

To investigate how trunk and neck torsion influence the RULA index in Fig. 9, we report the shape of the related angles while performing the entire picking activity 50 times. We compare configuration 1.A and configuration 6.C since the gap between these two configurations is considerable. For configuration 1.A the trunk torsion reaches almost $+20^\circ$ or -25° with a pick greater than $+25^\circ$ at the end of the picking process (probably due to a wrong movement of the picker).

On the other hand, configuration 6.C leads to lower trunk torsion maximum values ($+10^\circ$ or -15°). Of course, the same considerations, with different maximum values, can be done for neck torsion. For these reasons, the higher values of the RULA index for configuration 1.A are justified.

Moreover, in both cases, we can see the shorter time required for picking in configuration 6.C and the cyclicity in performing picking.

4.4. OCRA postural multiplier analysis

The postural parameters related to the OCRA are analyzed for their importance in evaluating the ergonomics of workstations (Occhipinti, 1998). Based on this analysis, some considerations need to be made. The OCRA index comprises many multiplier coefficients that are not correlated with the postural parameters and are assumed to be the same for each configuration. The aspect that changes between the configurations is the postural one. For this reason, it has been taken into account for the analysis. Fig. 10 reports the awkward postures indicated in the OCRA guidelines followed in this study. The awkward posture evaluation includes the elbow, wrist, and hand as part of the body (it is more focused on the arms, while RULA considers the upper part of the body). Going in-depth, the supination, pronation, and flexion (or extension) need to be evaluated for the elbow. Moving to the wrist, the flexion (or extension) and the radio/ulnar deviation are the movements to investigate. Finally, we need to evaluate the grip or the pinch of the hands.

There are two groups of parameters that are used to determine the multiplier for the calculation of the OCRA index. Based on the rule in the second column (see Fig. 10), each group determines its multiplier by selecting the lowest one. Finally, the weakest of the two multipliers of the two groups is chosen as the overall multiplier.

Another assumption is made in the method proposed here. The picking task comprises several subtasks such as reaching, grasping, transporting and releasing the object to be picked, the palmar grip, and the hand pinch. We assume that they are present for 50 % of the total time and are the same for each configuration. Finally, the time spent in each above-mentioned awkward posture is recorded, and the maximum value is selected as the representative for each configuration. Table 5 reports the percentage of time in an awkward position based on the OCRA index.

Furthermore, the RULA index and the average time required to pick and place an item for each configuration are provided according to the measures taken with the MOCAP system. The average picking time represents only the amount required to pick an item from a storage bin and place it into the order bin. It does not include all additional times, such as pushing the bottom, looking at the screen, packing, and labelling, since we assume these times are always the same for each configuration. For this reason, the percentage of time spent in awkward posture also refers only to pick and place tasks, and it could be smoothed when all activities belonging to picking tasks are jointly investigated.

Table 5 allows investigating trade-offs between postural scores and time.

Configurations 1.A and 7.D are the best solutions considering the OCRA postural coefficient, as they report less time spent in an awkward body posture. However, 1.A also requires the longest picking time on average, while configuration 7.D has an average picking time of almost half of configuration 1.A. However, comparing postural scores (OCRA postural coefficient vs RULA) for both configurations, we can say that a lower percentage of time spent in awkward posture does not lead to lower RULA scores. Considering the other configurations, we have the same trend as we previously found from a postural point of view. For families 2, 3 and 4, the case where storage and order bins are on the same level (sub-category A) leads to a higher percentage of time spent in an awkward posture. However, the average picking time for configurations 2.A and 4.A is lower than for configurations 2.B or 2.C and 4.B or

Awkward posture and/or movement [10]		Portion of cycle time: Less than 1/3 from 1 % to 24 %	1/3 from 25 % to 50 %	2/3 from 51 % to 80 %	3/3 more than 80 %
Elbow	supination (⩾ 60°)	1	0,7	0,6	0,5
Wrist	extension (⩾ 45°) or flexion (⩾ 45°)				
Hand	hook grip or palmar grip (wide span)				
Elbow	pronation (⩾ 60°) or flexion/extension (⩾ 60°)		1	0,7	0,6
Wrist	radio/ulnar deviation (⩾ 20°)				
Hand	pinch				

Fig. 10. OCRA postural guidelines ().
Source: Occhipinti, 1998

Table 5
Time spent in awkward position, RULA index and average picking time (in bold minimum values, underlined the maximum values).

ID	% of the time in awkward position (based on OCRA)	RULA index	Average picking time [s]
1.A	**11 %**	4.40	3.82
2.A	41 %	4.50	1.80
2.B	34 %	4.00	2.02
2.C	37 %	3.60	2.04
3.A	52 %	4.40	1.84
3.B	38 %	3.80	2.00
3.C	21 %	3.90	2.02
4.A	49 %	4.70	1.74
4.B	40 %	4.00	1.72
4.C	26 %	3.60	1.84
5.C	42 %	3.40	1.78
5.D	37 %	**3.20**	**1.62**
6.C	30 %	**3.20**	1.86
6.D	27 %	**3.20**	1.66
7.C	41 %	3.50	1.98
7.D	**11 %**	3.80	1.82

4.C.

Further, the storage bins' inclination for families' configurations 5, 6 and 7 leads to reduced time spent in an awkward position and a reduction in picking time. In fact, for configuration 5.D, we have an 8.98 % picking time reduction compared to configuration 5.C, for configuration 6.D a decrease of 10.75 % compared to 6.C, and, finally, for configuration 7.D a reduction of 8.10 % compared to 7.C.

Finally, comparing all configurations, we can say that configuration 6.D could represent the most suitable since both the percentage of time spent in awkward posture and the average picking time are among the lower values we have obtained.

An interesting aspect emerging from the analysis is configuration 1.A. This configuration leads to less time spent in an awkward posture when considering OCRA. However, moving to the RULA index, we can

Table 6
Summary of ergonomics and picking time analysis.

ID	Consideration of Ergonomic Analysis	Consideration of Picking Time Analysis
1.A	Torsion of the neck and trunk greatly influences the RULA score	Not convenient, higher picking time compared to all configurations
2.A	Neck torsion greatly influences the RULA score (>4)	Storage and order bins are aligned, picking time is slightly reduced if compared to 2.B and 2.C
2.B	Acceptable RULA score (=4) Reduction of time in awkward posture compared to 2.A	Picking time > 2 s/pick
2.C	Acceptable RULA score (<4) Reduction of time in awkward posture compared to 2.A	Picking time similar to 2.B (about 2 s/item)
3.A	Neck torsion greatly influences the RULA score (>4)	Storage and order bins are aligned, picking time is slightly reduced if compared to 3.B and 3.C
3.B	Acceptable RULA score (<4)	Picking time > 2 s/pick
3.C	Acceptable RULA score (<4) Reduction of time spent in awkward posture compared to 3.A and 3.B	Picking time similar to 3.B (2 s/item)
4.A	Neck torsion greatly influences the RULA score (>4) Higher percentage of time spent in awkward posture	Storage and order bins are aligned, picking time is slightly reduced if compared to 3.B and 3.C
4.B	Acceptable RULA score (<4)	Picking time reduction compared to 2.B and 3.B (15 % reduction for each picked item)
4.C	Acceptable RULA score (<4) Reduction of time spent in awkward posture compared to 4.A and 4.B	Picking time reduction compared to 2.C and 3.C (9 % reduction for each picked item)
5.C	Acceptable RULA score (<4)	Not convenient compared to 5.D
5.D	Acceptable RULA score (<4) Shoulder and elbow flexion is reduced compared to 5.C Hands and COG travelling distance are minimized	Lower picking time compared to all configurationsSignificant reduction of the average picking time compared to configurations belonging to groups 1, 2 and 3 (57.6 %, 17.35 % and 17.24 %, respectively)
6.C	Acceptable RULA score (<4)	Not convenient compared to 6.D
6.D	Acceptable RULA score (<4) Shoulder and elbow flexion is reduced compared to 6.C Hands and COG travelling distance very close to 5.D	Good picking time (1.86 s/item) Significant reduction of the average picking time compared to configurations belonging to groups 1, 2 and 3
7.C	Acceptable RULA score (<4)	Not convenient compared to 7.D
7.D	Acceptable RULA score (<4) Shoulder and elbow flexion is reduced compared to 6.C Higher hands and COG travelling distance	Good picking time Significant reduction of the average picking time compared to configurations belonging to groups 1, 2 and 3. Higher if compared to 5.D and 6.D but it is influenced by the distance required to reach extremal boxes

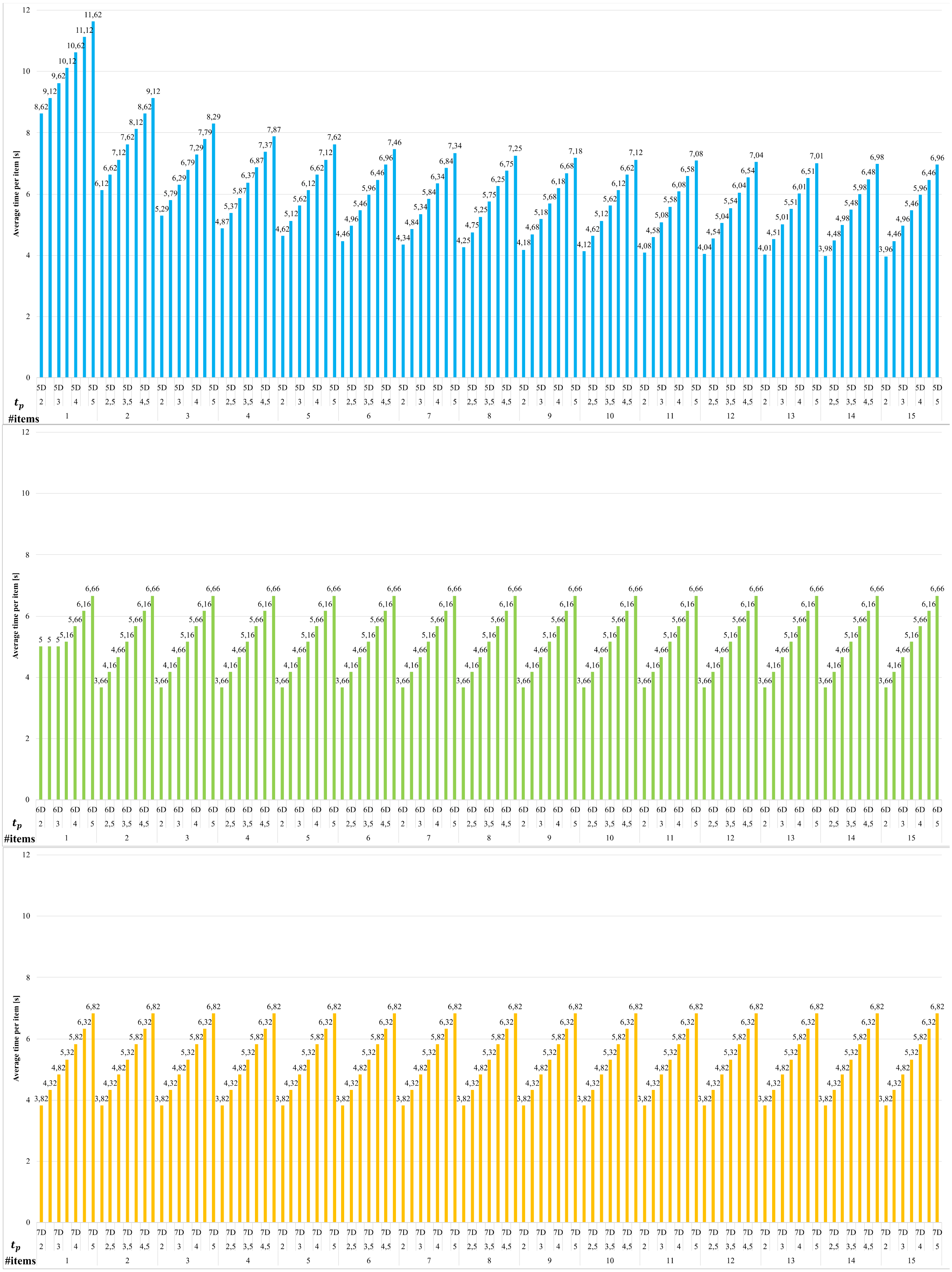

Fig. 11. Average picking time graphs for configuration 5.D, 6.D and 7.D by varying the number of items per order line and the fixed picking time.

see that configuration 1.A is that one reporting the higher percentage of time spent in class 6+ (thus requiring changes) when the RULA index is analyzed. The main reason is related to the different parts of the body involved in defining ergonomic scores. In computing the RULA index, neck and trunk torsion are also included, which are not included in the OCRA postural coefficient. Thus, selecting a suitable picking workstation should consist of several postural aspects, as we have here.

Finally, Table 6 reports the main insights for each configuration investigated here, highlighting the main outcomes derived from this work.

4.5. Managerial insights and discussion

By clustering the configurations here investigated according to the number of storage bins, we can state as follows:

1) The case with only a storage bin positioned on an upper level to order bin (configuration 5.D) represents the best solution from the ergonomics and picking time point of view. The main limitation is the time required to replace a storage bin with another one. In fact, for such a solution, workers must wait for the change of the storage bin each time they complete the picking activity for an item. Consequently, idle times occur for scenarios with more than an order line.
2) With two storage bins, it is preferable to position storage and order bins at different levels to achieve a lower ergonomic postural risk (configuration 2.B, 3.B or 4.B, 6.D). Moreover, in case of storage bins are placed at an upper level to the order bin, the inclination of storage bins leads to productivity benefits (i.e., picking time reduction). Due to the lower RULA and picking time values, configuration 6.D is suitable in configurations with two storage bins. For such a configuration, idle times, leading to storage bin changes, are reduced since they can be done while the worker picks items from the other storage bin.
3) With four storage bins, configuration 7.D leads to lower ergonomic risks and picking time compared to configuration 1.A. At the same time, there are some differences by hands and COG travelling distance point of view when 7.D is compared to configurations 2.A, 2.B, or 2.C. In such a context, idle times due to storage bin changes are avoided due to the higher number of storage bins that are simultaneously present in front of the worker.

Starting from this initial consideration, we notice that the suitable advance picking workstation should also include the features of the customer's order (i.e., the number of items to pick for each order line). Further, other tasks belonging to picking should be considered even if, in our ergonomic analysis, they have been considered as fixed values (this means that they do not influence the ergonomic assessment analysis). Moreover, the replacement time of storage bins should be included in a detailed analysis since it could strongly influence the picking process if more than one line per order is considered. Finally, thanks to the authors' experience in designing these automated systems, we highlight that investment costs differ a lot among configurations with 1, 2 or 4 storage bins due to the conveyor systems (the length of the conveyor increases by increasing the number of storage bins).

Aiming to investigate how customers' order profiles affect the picking time and, thus, the productivity, we conduct a parametrical analysis. We take into account the following:

1) The suitable configuration for one, two and four storage bins (5.D, 6.D and 7.D, respectively) according to the ergo-time analysis here conducted.
2) The average time for lifting, moving, picking and placing an item (t_p') according to the collected data (1.62 s/pick for 5.D, 1.66 s/pick for 6.D and 1.82 s/pick for 7.D)
3) Each order line has a variable number of items to pick, lift, move and place (this parameter is called x). We set it from 1 to 25 items/order line.
4) A fixed time for all additional activities (e.g., check, align, count) performed similarly for each configuration (t_p). This time varies from 2 to 5 s (with a 0.5 step) since item features could strongly influence it.
5) A time for replacing the storage bin (t_r). This time is set to 5 s according to the authors' experience and data collected from companies in this field. The replacement time differs according to the number of storage bins (i.e., the picking workstation configuration). For configurations with a storage bin, we should always include this time. Pickers must wait for a new storage bin each time they finish picking one or more items from the storage bin in front of them. For configurations with two storage bins, this time is included only if the picking time is lower than t_r seconds (in our case 5 s), while for configurations with 4 storage bins, this time can be neglected since storage bin replacement is always done while the operator is picking.

The average time per item can be defined for each configuration as follows:

1) $t_{1OB} = \frac{(t_p + t_p')x + t_r}{x}$ representing the average time required to complete the picking for × items in case of configurations with one storage bin
2) $t_{2OB} = \frac{(t_p + t_p')x + \max(0; t_r - (t_p + t_p')x)}{x}$ representing the average time to complete the picking for × item in case of configurations with two storage bins.
3) $t_{4OB} = t_p + t_p'$ representing the average time to pick configurations with four storage bins.

From a practical point of view, according to the average number of items to pick per each order line, the configuration leading to the lower time represents the one that should be selected and implemented in the design stage ($\min(t_{1OB}; t_{2OB}; t_{4OB})$).

Fig. 11 reports the results of the parametrical analysis conducted by varying the fixed time and the number of items to pick per each order line.

As the results suggest, from an efficiency point of view, configuration 7.D is preferable for all cases where a single item is picked per order line and for a fixed picked time lower than 4 s. This case could be led to e-commerce orders characterized by an order line of one item. In this way, the higher investment costs due to a more complex conveyor system are smoothed by the higher system efficiency.

The configuration with two storage bins (6.D) is preferable for all other scenarios. However, we can see that the gap between 5.D and 6.D tends to reduce with a higher number of items and a longer fixed picking time.

5. Conclusions

Order picking represents one of the most critical tasks in traditional and automated warehousing solutions concerning time, quality, and health risks. During the last decades, most of the work has focused on integrating ergonomic aspects in order picking by considering traditional warehouses and operational decisions. However, due to market changes and increased e-commerce channels, robotized and automated warehousing solutions have been implemented in several industries and distribution centres. In such solutions, picking follows a parts-to-picker strategy in advanced picking workstations with different configurations. The literature on ergonomics and order picking is still limited in such a context. Thus, an integrated ergonomic and productivity assessment of order picking tasks in advance picking systems is necessary.

This paper proposes an approach to analyzing different advanced picking configurations from an ergonomic and time-efficiency point of view. It contributes to the literature by comparing ergonomic aspects in 16 different advanced picking workstation configurations. According to the features of the customer's orders, a configuration could be preferable to others from an ergonomic, productivity, or both point of view.

Configuration 6.D should be preferable if more items are required since productivity and ergonomics are guaranteed. On the other hand, for e-commerce orders characterized by an item, configuration 7.D is preferable since order picking lists are generally composed of one order line and just an item. Finally, this paper shows that considering only an ergonomics aspect, as commonly done in several previous works, could not guide practitioners in selecting the proper advance picking workstation. Thus, an integrated analysis including several factors simultaneously (e.g. distance, time, posture, joint angles) is necessary to take appropriate decisions. At this stage, each worker's specific features are not considered since we are in the design phase, and average features are included for each worker. Of course, for scheduling and planning decisions, which refer to a short-term period, the specific characteristics of each worker should be included to define the picking time per order line to assign to each picker. Thus, the experience of each worker, the gender, age, fatigue state, and musculoskeletal disorders should be taken into account, aiming to balance the workload from an equity perspective.

Further, not only workers' features, which are subjective factors, should be included in short-term decisions to investigate the whole amount of time for picking but also environmental factors like temperature, humidity level, lightness and item features (weight, volume, graspability), which are objective factors, and strongly influence the amount of time required to pick and place an item.

Additionally, more laboratory tests could be conducted to investigate how the inclination of storage bins in the picking workstation could influence ergonomics, by considering more different inclination values. In fact, at this stage, two inclinations 0° and 30° have been investigated since they are the ones currently in use by leading companies in this field.

Further, the proposed analysis could be extended by investigating how operational decisions and the system's efficiency could change according to pickers' features. Finally, muscular and cardiovascular fatigue and other psychological and cognitive factors such as learning and forgetting should be included in future work. In fact, due to the high task repetitiveness, it could be interesting to investigate how productivity could change.

CRediT authorship contribution statement

Serena Finco: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Gjulio Ashta:** Data curation, Methodology, Writing – review & editing. **Alessandro Persona:** Conceptualization, Methodology, Validation. **Ilenia Zennaro:** Conceptualization, Methodology.

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.

Data availability

Data will be made available on request.

Appendix

Table 1A

Length and width distance among storage and order bins (in red colour negative distances). For configurations 6.D and 7.D, the width distance considers the bin's inclination (30°).

Configuration ID	x-axis distance storage bin A [mm]	y-axis distance storage bin A [mm]	x-axis distance storage bin B [mm]	y-axis distance storage bin B [mm]	x-axis distance storage bin C [mm]	y-axis distance storage bin C [mm]	x-axis distance storage bin D [mm]	y-axis distance storage bin D [mm]
1.A	700	500	700	500	700	1000	700	1000
2.A	600	100	600	100	1100	100	1100	100
2.B	600	100	600	100	1100	100	1100	100
2.C	600	100	600	100	1100	100	1100	100
3.A	600	100	600	100	–	–	–	–
3.B	600	100	600	100	–	–	–	–
3.C	600	100	600	100	–	–	–	–
4.A	700	0	700	0	–	–	–	–
4.B	700	0	700	0	–	–	–	–
4.C	700	0	700	0	–	–	–	–
5.C	0	400	–	–	–	–	–	–
5.D	0	361.7	–	–	–	–	–	–
6.C	350	400	350	400	–	–	–	–
6.D	350	361.7	350	361.7	–	–	–	–
7.C	350	400	350	400	1050	400	1050	400
7.D	350	361.7	350	361.7	1050	361.7	1050	361.7

Table 2A

Time spent in each class of shoulder flexion.

ID	Shoulder flexion LEFT						Shoulder flexion RIGHT					
	0-30°	30°-60°	60°-90°	90°-120°	>120°	Average value	0-30°	30°-60°	60°-90°	90°-120°	>120°	Average value
1.A	86.34 %	13.49 %	0.17 %	0.00 %	0.00 %	13.00°	94.81 %	5.19 %	0.00 %	0.00 %	0.00 %	9.67°
2.A	84.72 %	13.95 %	1.33 %	0.00 %	0.00 %	15.53°	95.93 %	4.07 %	0.00 %	0.00 %	0.00 %	9.42°
2.B	68.16 %	30.81 %	1.03 %	0.00 %	0.00 %	16.19°	79.69 %	20.31 %	0.00 %	0.00 %	0.00 %	10.40°
2.C	72.16 %	21.73 %	6.11 %	0.00 %	0.00 %	21.29°	77.61 %	22.39 %	0.00 %	0.00 %	0.00 %	15.24°
3.A	85.61 %	14.39 %	0.00 %	0.00 %	0.00 %	14.15°	100.00 %	0.00 %	0.00 %	0.00 %	0.00 %	9.20°

(continued on next page)

Table 2A (*continued*)

ID	Shoulder flexion LEFT						Shoulder flexion RIGHT					
	0-30°	30°-60°	60°-90°	90°-120°	>120°	Average value	0-30°	30°-60°	60°-90°	90°-120°	>120°	Average value
3.B	68.94 %	31.06 %	0.00 %	0.00 %	0.00 %	12.41°	87.82 %	12.18 %	0.00 %	0.00 %	0.00 %	5.36°
3.C	76.16 %	23.84 %	0.00 %	0.00 %	0.00 %	14.22°	97.45 %	2.55 %	0.00 %	0.00 %	0.00 %	6.08°
4.A	80.31 %	19.69 %	0.00 %	0.00 %	0.00 %	15.67°	97.93 %	2.07 %	0.00 %	0.00 %	0.00 %	11.74°
4.B	64.33 %	35.67 %	0.00 %	0.00 %	0.00 %	18.26°	83.67 %	16.33 %	0.00 %	0.00 %	0.00 %	8.51°
4.C	77.62 %	22.38 %	0.00 %	0.00 %	0.00 %	13.74°	90.03 %	9.97 %	0.00 %	0.00 %	0.00 %	7.39°
5.C	76.80 %	23.20 %	0.00 %	0.00 %	0.00 %	17.40°	80.43 %	19.57 %	0.00 %	0.00 %	0.00 %	12.37°
5.D	78.56 %	21.44 %	0.00 %	0.00 %	0.00 %	15.43°	82.95 %	17.05 %	0.00 %	0.00 %	0.00 %	12.86°
6.C	77.42 %	19.91 %	2.67 %	0.00 %	0.00 %	19.57°	82.37 %	17.63 %	0.00 %	0.00 %	0.00 %	13.21°
6.D	78.31 %	21.23 %	0.46 %	0.00 %	0.00 %	17.72°	83.69 %	16.31 %	0.00 %	0.00 %	0.00 %	11.89°
7.C	74.72 %	14.91 %	10.37 %	0.00 %	0.00 %	22.50°	78.48 %	21.52 %	0.00 %	0.00 %	0.00 %	13.21°
7.D	75.96 %	19.10 %	4.94 %	0.00 %	0.00 %	18.29°	83.22 %	16.78 %	0.00 %	0.00 %	0.00 %	12.80°

Table 3A
Time spent in each class of elbow flexion.

ID	Elbow flexion LEFT					Elbow flexion RIGHT				
	0-30°	30°-60°	60°-90°	90°-120°	Average value	0-30°	30°-60°	60°-90°	90°-120°	Average value
1.A	74.45 %	20.66 %	4.19 %	0.43 %	17.34°	63.74 %	24.99 %	11.13 %	0.14 %	29.65°
2.A	65.78 %	28.33 %	5.74 %	0.00 %	19.30°	70.87 %	18.31 %	10.07 %	0.76 %	21.53°
2.B	55.19 %	10.54 %	23.31 %	10.96 %	21.77°	55.56 %	9.61 %	23.21 %	10.85 %	34.30°
2.C	50.13 %	22.62 %	17.87 %	9.33 %	32.54°	59.49 %	11.63 %	13.92 %	14.46 %	35.15°
3.A	71.09 %	28.91 %	0.00 %	0.00 %	20.66°	71.58 %	28.22 %	0.20 %	0.00 %	16.71°
3.B	56.94 %	15.37 %	19.52 %	8.11 %	21.14°	49.96 %	11.77 %	29.93 %	8.34 %	36.98°
3.C	55.36 %	23.25 %	15.02 %	6.37 %	21.45°	54.64 %	17.39 %	18.49 %	9.49 %	32.01°
4.A	54.54 %	43.09 %	2.37 %	0.00 %	25.04°	70.50 %	23.79 %	5.71 %	0.00 %	21.14°
4.B	54.78 %	17.88 %	20.84 %	6.37 %	19.50°	42.99 %	16.82 %	29.77 %	9.82 %	40.88°
4.C	55.11 %	18.94 %	18.46 %	7.49 %	20.89°	56.58 %	16.97 %	18.61 %	7.84 %	30.45°
5.C	64.45 %	8.65 %	20.81 %	6.09 %	24.18°	68.61 %	6.59 %	18.73 %	6.07 %	21.68°
5.D	64.76 %	11.22 %	22.32 %	1.70 %	24.32°	68.58 %	7.90 %	23.20 %	0.31 %	20.12°
6.C	56.10 %	17.84 %	20.84 %	5.22 %	31.87°	57.74 %	14.06 %	19.25 %	8.95 %	35.54°
6.D	54.45 %	22.62 %	22.82 %	0.12 %	29.38°	58.23 %	13.89 %	25.35 %	2.54 %	34.33°
7.C	47.15 %	25.18 %	17.00 %	10.19 %	36.09°	54.40 %	16.57 %	10.92 %	16.39 %	41.68°
7.D	46.03 %	46.84 %	6.48 %	0.11 %	29.41°	34.43 %	54.40 %	9.55 %	1.62 %	36.18°

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