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Applied anthropometry for common industrial settings design: Working and ideal manual handling heights

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ABSTRACT

Anthropometry has been used extensively for designing safe and sustainable products and workplaces. However, it is common that designers need straightforward guidelines and dimensions, which they often lack, for specific design situations. Anthropometric data are usually presented in tables that summarize percentile values, separated by gender, of a specific population, which makes it difficult for designers to generate applications for mixed populations, such as industrial settings. Using a recently collected anthropometric database of Chilean workers (male and female), international standards of dimensions for working height, depth, and ideal manual handling height are tested with univariate and bivariate methods. Alternative dimensions are presented for both adjustable and non-adjustable designs. Additionally, procedures to combine samples, and for knowing how many users match with a particular design are explained using the sample data. As expected, adjustable designs proved to match with higher numbers of users, while non-adjustable dimensions recommended by ISO presented low levels of matching. Furthermore, the non-adjustable design achieved 83% of matching, which increased to the desired levels (90%) with the inclusion of a 50 mm increase platform. Finally, the Z-Score equation proved to be a useful tool to know the percentages of the population that are matched with a particular design dimension.

Relevance for the industry: Dimensions for working height, depth, and ideal manual handling heights, which are currently not available, are provided for Chilean workers. A method to determine the matching percentage in a population is explained, in order to assess matching probabilities when having only summarized anthropometric tables and the dimensions for the design itself.

1. Introduction

Ergonomics and Human Factors as a scientific discipline aims to achieve safe and productive workplaces for everyone (Kroemer, 2006). In that regard, several factors - physical layout and dimensions of the working space being critical ones - can either enhance or hinder health and performance (Kroemer and Grandjean, 1997; Mandal, 1991; Marras and Kim, 1993; Molenbroek et al., 2003; Rohlmann et al., 2011). Working spaces and tools need to be suited to the end user's anthropometric dimensions in order to obtain healthy and productive working places (Marras and Kim, 1993; Pheasant and Haslegrave, 2006; Pheasant and Steenbekkers, 2005), but additionally adapting the design to the end user's anthropometry enhances sustainability, mainly because this reduces raw material consumption, increases usage lifetime and incorporates ethical human resource considerations into design (Nadadur and Parkinson, 2013). Several applications of anthropometry are reflected in a variety of reports and applications such as school furniture (Castellucci et al., 2016; Castellucci et al., 2014, Castellucci et al., 2015a; Mokdad and Al-Ansari, 2009), agricultural tools (Dewangan et al., 2010; Syuaib, 2015b, 2015a), car assembly (Castellone et al., 2017), personal protective equipment (Choi et al., 2009; Coblentz et al., 1991; Hsiao, 2013; Laing et al., 1999; K. M. Robinette and Branch, 2008;

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Stirling, 2005; Vergara et al., 2019), public transport seats (Molenbroek et al., 2017; Porta et al., 2019), domestic settings (Dawal et al., 2015) and even space shuttles and suits (NASA, 1978).

Additionally, some of the most comprehensive assessment methods for industrial manual handling, such as NIOSH original equation and subsequent updates, have used referential anthropometry in their rationale (Dempsey et al., 2005; Frost, 2011; Waters et al., 2009; Waters et al., 2007; Waters et al., 1993). For example, NIOSH's Variable Lifting Index (Waters et al., 2009), considers both horizontal and vertical distances of load displacement that, when surpassed, significantly increases the risk of lower back injury. This is mainly attributed to the biomechanics of handling loads outside “safe” zones that use anthropometry as a limit. According to NIOSH, if the horizontal distance is more than 63 cm, it is likely that most people will handle the load further away from their center of mass, beyond the anthropometric dimensions minimum functional grip, thus increasing the risk. Similarly, if the vertical distance is above 175 cm, the load will probably be handled above shoulder height by most subjects, increasing even further the risk of injury. Liberty Mutual uses force application height, similarly based on anthropometry, differentiating heights and risk level for both women and men (Snook and Ciriello, 1991).

Commonly, the anthropometric dimensions are extracted from tables that express the distribution of the population in percentiles. This should be used by designers and ergonomics specialists to give preventive recommendations, where in an ideal design process anthropometry is compared with relevant product and workplace measurements (Hanson et al., 2009; Pheasant and Haslegrave, 2006). This approach is not without limitations since it depends on the design and its associated dimensions to be either simple or complex. For example, when the design involves only one dimension, (e.g. door clearance or reaching for an object), using the highest or lowest percentile value ensures a match for almost everyone (Kroemer, 2006). In practice, however, there are cases where more than one dimension needs to be used, hence the process is more complex and requires using both minimum and maximum values of different anthropometric dimensions (e.g. attaining certain postures), thus the interaction between those dimensions and their specific values requires more complex calculations (Kroemer, 2006; Robinette, 2012). In those applications, two (bivariate) or more (multivariate) parameters must be considered since two/multiple anthropometric dimensions are relevant to the function of a product. In such cases, standard anthropometry tables could not adequately address the design applications involving bivariate or multivariate applications. Examples of bivariate anthropometric procedures are the design of garments such as helmets, which requires the dimensions of head length and width, and the design of respirators, which requires face length and width. Generally, the greater the number of involved dimensions is, the more complex the product design process (Dianat et al., 2018).

Although following the procedures stated above can ensure optimal fit, we are describing the ideal situation, and often designers do not follow this procedures and prefer ready-to-use data for specific populations in order to set the design recommendations (Ranger et al., 2019). Chilean workers anthropometric dimensions used until today were collected more than 20 years ago, thus they are probably out of date. Additionally, at the moment, there are no specific dimensions recommended to fit Chilean working population in common industrial tasks such as manual handling of loads, assembly lines, among others.

The aim of this study is to apply the anthropometric dimensions to two common industry-related designs, namely Production Line height and depth as per task type and Manual Material Handling heights, using a newly constructed database of Chilean workers. Additionally, recommendations for the targeted population and general straightforward calculation methods are provided for designers to easily calculate working heights for any population that has standard anthropometric tables.

2. Materials and methods

2.1. Sample

During 2016, anthropometric dimensions were collected by the authors of this article as part of a larger research project, ending with 32 anthropometric measures. Data were collected on 2,946 workers (600 women and 2,346 men) from the two most populated regions of Chile (Valparaíso and Metropolitan), distributed among 9 economic activity sectors (Agriculture and Fishing; Mining; Manufacturing; Electricity; Construction; Commerce; Transport and Communications; Financial Services; Communal and Personal Services).

Measurements were made manually by specialized teams of physiotherapists. These teams underwent training and performed pilot studies to assess both inter- and intra-measurer reliability, in order to obtain high-quality measurements (Viviani et al., 2018). The measurement procedure was conducted by two survey teams, each one composed of three individuals, namely a measurer, a data collector and an organizer. The measurers were in charge of doing the measurements, the data collectors entered the data in a computer, and the organizers were responsible for accommodating the subjects to ensure that the standard measuring postures were achieved.

Before the survey was initiated, the measurement teams underwent a one-week training workshop, which included discussion of the theoretical approach used for anthropometric measurements and practical instructions. The training sessions were delivered by two physical therapists with experience in ergonomics and anthropometric data collection. Both teams spent a minimum of 24 h practicing the measurements to ensure high consistency between measurers. At the end of the training week, a sample of 25 volunteers was measured twice by the two measurers, and both inter- and intra-measurer reliability were evaluated using the “two-way mixed” and “absolute agreement” Intraclass Correlation Coefficient (ICC) models. The correlations were interpreted according to the ranges suggested by Portney and Watkins (2008): ICC$\geq$0.50 was interpreted as moderate, and ICC$\geq$0.75 was interpreted as strong. The results shown in Table 1 demonstrate that the measurers exhibited strong inter- and intra-measurer reliability values, except for two dimensions that presented moderate intra-reliability (elbow grip length for measurer 1 and elbow height sitting for measurer 2).

The full list of values for the sample and more details about the procedure can be seen in a recent publication (Castellucci et al., 2019).

2.2. Anthropometric dimensions

The standard procedure proposed by ISO 7250–1 (2008) was followed for the collection of the anthropometric measurements. The procedure indicates that the anthropometric measures need to be collected from the right side of the subjects' body while they are sitting in an erect position, on a chair with a horizontal surface, with their legs

Table 1
Intra and Inter-measurer reliability (ICC).

	Anthropometric dimension	Intra-measurer reliability Measurer 1	Intra-measurer reliability Measurer 2	Inter-measurers reliability
1	Stature	0.999	0.996	0.984
2	Knuckle height	0.980	0.983	0.970
3	Sitting height	0.951	0.936	0.937
4	Shoulder height sitting	0.941	0.912	0.930
5	Grip reach; forward reach	0.941	0.923	0.950
6	Elbow grip length	0.737	0.943	0.901
7	Elbow height sitting	0.901	0.703	0.793
8	Knee height	0.836	0.986	0.959

flexed at a 90° angle and their feet flat on the floor. During the measurement procedures, the subjects did not wear shoes and wore light clothing (short pants and t-shirts). The following dimensions were used for the current research:

1 . Shoulder height standing (ShStand): calculated through (Stature – (Sitting height – Shoulder height sitting)).
2 . Elbow height standing (EHStand): calculated through (Stature – (Sitting height – Elbow height sitting)).
3. Elbow grip length: horizontal distance from back of the upper arm (at the elbow) to grip axis, with elbow bent at a right angle.
4 . Grip reach; Forward reach: horizontal distance from a vertical surface to the grip axis of the hand while the subject leans both shoulder blades against the vertical surface.
5 . Knuckle height (KnuH): vertical distance from the floor to metacarpal III (i.e. knuckle of the middle finger).
6 . Knee height (KH): vertical distance from the floor to the highest point of the superior border of the patella.

2.3. Procedure

Mainly two methods were used: univariate and bivariate methods. A univariate approach was used for assessing the matching and elaborating proposals for working heights in standing assembly tasks according to task type, namely: high manual and visual precision (e.g. electronic device assembly), moderate level of force and precision (e.g. gear box assembly) and high force (e.g. woodworking or other manual material handling). Within that framework, method of limits was used, a model or analogue of the fitting trial in which anthropometric criteria and data are used as substitutes to 'stand for' the subjective judgements of real people (Pheasant and Haslegrave, 2006). It is worth mentioning that even if only one dimension is used, the method of limits in this case is two-fold, where both an upper and lower limit need to be respected in order to achieve the desired effect, hence it behaves as a bivariate dimension. As a checking method, percentile values using specific criteria were used, this being quite common when designers only have summarized tables instead of raw data. Comparisons were made against dimensions present in ISO 14738:2012 for both adjustable and fixed designs. In fixed designs a wider range was established in order to allow higher matching percentages. Quoting Pheasant and Haslegrave (2006): *Since we may reasonably assume that users may be prepared to accept less than absolute perfection, we may well find it useful to consider two further zones above and below the optimum, which we would characterize as 'satisfactory but not perfect'*. Additionally, a proposal was made, and in both cases the Z-score equation was used to start from a design and then assess the level of matching (see section 2.3.1.1 for details):

$$Z(p) = \frac{Z(p) - \bar{x}}{s}$$

In order to visually represent the levels of matching, ellipse methods to further test these levels using the raw data were performed on the key anthropometric measure, Elbow height standing (EHStand), cross-checking it against Stature, for the mere reason that the method itself requires the use of two anthropometric dimensions.

Both bivariate and univariate methods of limits and approaches were used for ideal manual handling height and depth, respectively (Fig. 5a). For ideal manual handling height, the bivariate approach was used on the two key anthropometric dimensions, EHStand and KnuH. For depth, a one-way criterion was used, and the method of limits was applied using percentiles. As mentioned in the introduction, using percentile values is quite simple, as only the selection of one dimension will ensure the recommended matching percentage, as long as said dimension does not conflict with the other ones. In the case of the current study, it can be seen in the use of depths in ideal manual handling, where if the designer wishes to accommodate most users, the 5th female percentile (lowest) for Elbow Grip Length and Grip Reach should be used, thus if the person with the shortest reach is matched, so are the ones with the longest reach.

A calculation method is explained through example (see section 2.3.1.1), using working heights for tasks with high force requirement as a reference for a very common problem, often in need to be tackled by designers. The problem arises when they (designers/ergonomists) need to know how many people are matched to a specific design dimension, but they only have the anthropometric tables and not the raw data.

For all of the values presented that consider height, a shoe correction value of 2.5–4 cm should be used, depending on the footwear that is being used in any particular work setting, especially considering the high variability of shoes needed or used in industrial contexts. For this study a 3 cm shoe correction (SC) was used, since the focus is on industrial settings (ISO, 2012). For any application (univariate or bivariate), a level of accommodation of 90% was deemed acceptable (Bridger, 2003).

Design recommendations were made considering the entire sample (mixing women and men) for both assembly tasks and ideal manual handling height/depth. In the case of ideal manual handling, recommendations were also made for females and males separately.

2.3.1. Working height and depth

It is important to distinguish between working height and work-surface height. The first may be higher than the latter if hand tools or other equipment are being used for the task (Pheasant and Haslegrave, 2006). Other authors refer to working height as Hand Reference Point (HARP) (Helander, 2006). It is possible that the working height may be lower than the work surface; for example in the case of a person washing dishes in the kitchen sink, the task is performed at the bottom of the sink (working-surface height) but at the working height of the object that is being washed. Therefore the height of the object being manipulated should be considered as the working height.

Different recommendations have been made for different task types. Each one will be detailed in the following subsections.

2.3.1.1. Working height for tasks with high force requirements. For these types of tasks, ISO standard 14738:2012 considers criteria for adjustable and fixed designs (see values on Table 3):

- Adjustable:
  - Min: 0.9 x EHStand (P5) + SC
  - Max: 0.9 x EHStand (P95) + SC
- Non-adjustable:
  - 0.9 x EHStand (P95) + SC

For this research, the criteria set by Helander (2006) for tasks with high force requirements were used:

- Max: EHStand −100 + SC
- Min: EHStand - 200 + SC

It must be remembered that for all fixed designs, and according to Pheasant and Haslegrave (2006), two further zones were used, extending 50 mm above and below the optimum.

A common problem, which needs to be addressed by designers, is knowing how many potential users could be matched with a particular design dimension (i.e.: working height of "x" cm). This can be difficult to know, especially when only having summarized anthropometric data of separate males and females. In order to reverse-engineer how many people are matched using a particular dimension, the Z-score or distribution is needed. Simply put, a Z-score (also called a standard score) gives an idea of how far from the mean a data point is. But more technically, it is a measure of how many standard deviations below or above the population mean a raw score is. When data distribute normally, as do almost every anthropometric dimension, Z-scores allow us to determine any percentile value using the mean and the standard deviation. Any statistics book or even the internet can be consulted for the standard Z-scores, which can be used to determine to which percentile a specific value corresponds.

The first equation can be used to define how many people will be matched, for example, with a particular current working height (it is worth remembering that the working height is different to working surface height). Let say that a worker in a production line needs to move a heavy box. The surface height is 700 mm and the box's handles are at 210 mm from the bottom, hence the working height will be 910 mm. This example is not arbitrary, since in current research it is the value that is calculated and recommended for the sample, for tasks involving high force requirements. Full results and accommodation rates can be seen in Table 3. Fig. 1 depicts more clearly the situation that is addressed in the example.

According to the example, how many workers will be matched with a working height of 910 mm for this type of task? (The value corresponds to the fixed proposal, see 3.2.1). It is already known that EHStand is the key anthropometric dimension. Since a mixed population was considered, a combined EHStand for the entire sample of 1029 ± 54.4 was used. Details about this and other combined dimensions can be seen in Table 2 and calculation on combining sample dimensions in section 3.3. Therefore, the steps to be followed are:

1. Determine the criteria. The type of work needs high force, and the principles to define the dimensions are the previously used principles, considering the extension of 50 mm up and down for acceptable zones:
   - Acceptable high: max limit: EHStand −50 + SC; min Limit: EHStand −100 +SC
   - Optimal: max limit: EHStand −100 + SC; min: EHStand −200 +SC
   - Acceptable low: max limit: EHStand −200 + SC; min Limit: EHStand −250 +SC

2 Calculate/replace the new values to define the Z-value (percentile):

$$Z(p) = \frac{Z(p) - \bar{x}}{s}$$

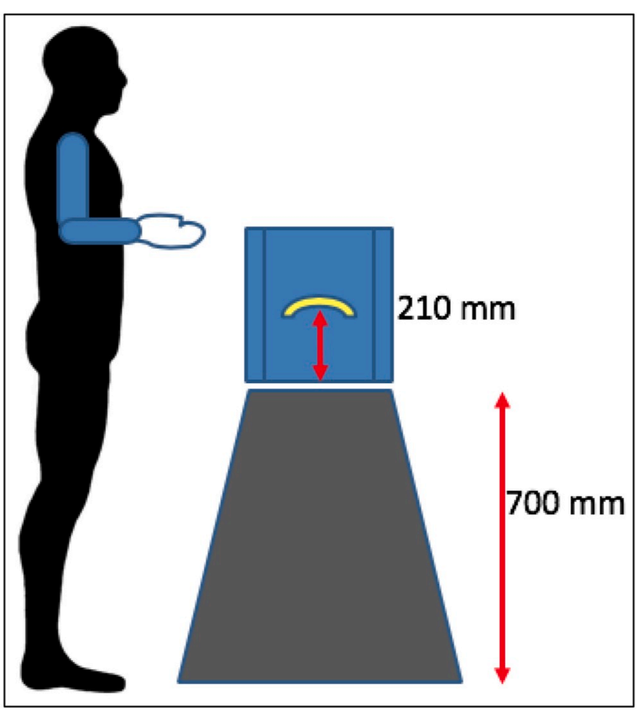

Fig. 1. Example for working height calculation.

- Acceptable high:

- max limit: 910 + 50–30: 930

$$Z(p) = \frac{930 - 1030}{54.4}$$

$$Z(p) = -1.83$$

After consulting from the Z-score table: Z-score value corresponds to P3.

- min limit: 910–30 + 100: 980

$$Z(p) = \frac{980 - 1029}{54.4}$$

$$Z(p) = -0.90$$

After reviewing the value in the Z-score table, Z-score corresponds to P18: therefore, a total of 15% (P3–P18) of the population match this condition.

- Optimal:

- max limit: 910–30 + 100: 980

$$Z(p) = \frac{980 - 1029}{54.4}$$

$$Z(p) = -0.90$$

After consulting the table, the respective Z-score value corresponds to P18.

- min limit: 910–30 + 200: 1080

$$Z(p) = \frac{1080 - 1029}{54.4}$$

$$Z(p) = 0.93$$

After consulting the table, the respective Z-score value corresponds to P82, therefore a total of 64% (P18–P82) of the population match the optimal condition.

- Acceptable low:
  - max limit: 910–30 + 200: 1080

$$Z(p) = \frac{1080 - 1029}{54.4}$$

$$Z(p) = 0.93$$

After consulting the table, the respective Z-score corresponds to P82.

- min limit: 910–30 + 250: 1130

$$Z(p) = \frac{1130 - 1029}{54.4}$$

$$Z(p) = 1.85$$

After consulting the table, the respective Z-score value corresponds to P97; therefore, a total of 15% (P82–P97) of the population match the acceptable low condition.

2.3.1.2. Working height for tasks requiring moderate level of force and precision. Similar to tasks with high force requirements, the ISO standard 14738:2012 recommends both adjustable and fixed design criteria, which can be seen below (see values on Table 3):

Table 2
Anthropometric dimensions used.

Anthropometric measurements	Female (mm) (n:600)				Male (mm) (n:2346)				Mixed (mm) (n:2946)			
	Mean	SD	P5	P95	Mean	SD	P5	P95	Mean	SD	P5	P95
Shoulder height standing	1316.0	55.8	1221.1	1407.0	1416.2	59.9	1320.0	1518.0	1396.0	71.5	1278.8	1513.5
Elbow height standing	977.3	46.3	902.0	1053.9	1041.9	48.3	965.0	1123.0	1029.0	54.4	939.6	1118.4
Elbow grip length	311.4	17.7	282.0	341.0	340.3	18.5	311.0	371.0	335.0	21.7	298.9	370.1
Grip reach; Forward reach	681.5	36.1	625.1	749.0	740.9	39.0	680.4	807.0	729.0	45.2	654.8	803.3
Knuckle height	711.4	34.8	656.1	771.0	758.8	38.3	699.0	824.0	749.3	42.2	680.1	818.5
Knee height	482.8	23.5	445.0	524.0	522.6	25.7	481.0	567.0	514.6	29.9	465.6	563.7

- Adjustable:
  - Min: EHStand (P5) + SC
  - Max: EHStand (P95) + SC
- Non-adjustable:
  - EHStand (P95) + SC

For fixed designs and according to Pheasant and Haslegrave (2006), two further zones extending 50 mm above and below the optimum were considered. With that rationale in mind, the following criteria will be used:

– Max: EHStand - 50 + SC
– Min: EHStand - 100 + SC

2.3.1.3. Working height for high visual and/or precision requirements. ISO standard 14738:2012 considers design equations for both adjustable and fixed designs for this type of task (ISO, 2012) (see values on Table 3). They use Elbow height standing (EHStand) as the baseline anthropometric dimension. The criteria are:

- Adjustable:
  - Min: 1,1 EHStand (P5) + SC
  - Max: 1,3 EHStand (P95) + SC
- Non-adjustable:
  - minimum of 1315 mm

On the other hand, Pheasant and Haslegrave (2006) use different criteria for delicate manipulative tasks height (including writing), and where forearm support is encouraged: these criteria will be applied in the current research as follows:

– Min: EHStand +50 + SC
– Max: EHStand +100 + SC

2.3.2. Manual material handling height and depth

Additionally, general guidelines are provided regarding ideal and acceptable manual handling. Those general ranges are:

- Vertically (K. H. E. Kroemer and Grandjean, 1997)
  o Ideal (between knuckle height standing and elbow height standing)
  o Acceptable low (between Knee height and knuckle height standing)
  o Acceptable high (between elbow height standing and shoulder height standing)
- Horizontally (HSE, 2016)
  o Ideal (within Elbow grip length P5)
  o Acceptable (within Grip reach; Forward reach 5th percentile).

The recommended height was calculated based on that point of view and using bivariable methods (ellipse). As previously mentioned, depth (horizontal) distance considered the 5th percentile.

3. Results and discussion

3.1. Anthropometric dimensions

Dimensions used and their associated percentile values can be seen in Table 2. Where other percentile values were used, the reader can easily calculate them using the Z-score distribution using SD and average values (Bridger, 2003; Pheasant and Haslegrave, 2006), as it will be

Table 3
Working height summary per task type.

Type of task	ISO 14738				Proposal			
	Adjustable		Fixed		Adjustable		Fixed	
	Size (mm)	Match	Size (mm)	Match	Size (mm)	Match	Size (mm)	Match
High force	867–1105	94%	1075	AL: 0% (>P100) O: 1% (P98- > P100) AH: 10% (P88–P98)	770–1050	90% (P5–P95)	910	AL: 15% (P82–P97) O: 64% (P18–P82) AH: 15% (P3–P18)
Moderate force and precision (light assembly)	960–1225	84% (P18- > P100)	1195	AL: 0% (>P100) O: 0% (>P100) AH: 0% (>P100)	870–1100	90% (P5–P95)	985	AL: 23% (P68–P92) O: 36% (P32–P68) AH: 24% (P8–P32)
high visual and/or precision requirements	1053–1584	97% (P2- > P100)	1315	AL: 0% (>P100) O: 0% (>P100) AH: 2% (>P100)	1020–1250	90% (P5–P95)	1135	AL: 23% (P68–P92) O: 36% (P32–P68) AH: 24% (P8–P32)

AL: acceptable Low, O: optimal, AH: acceptable high, %: results obtained with ellipses; percentile results obtained with Z-score equations.

discussed in this section.

3.2. Working height

Table 3 summarizes the mixed population results for the different tasks. As it can be observed, the ranges indicated in the ISO standard for adjustable working height provide higher matching levels than the proposal, except for tasks with moderate force requirements, when the matching % falls below the acceptable criteria of 90%. Therefore, with a much lower range of adjustability, the proposal will provide an overall complete match, independent of the task than the ISO dimensions.

Regarding fixed designs, it can be observed that the matching levels of the ISO standard drop considerably in all task types when using a single height. This is no surprise, since Chilean workers' anthropometrics were shown to be significantly different compared with other populations used in ISO standards (Castellucci et al., 2019). It is worth to mention that in Table 3, the ISO fixed dimension practically does not match any percentage of the sample, with matching percentages from 0% to 10%. On the other hand, considering the proposals per each task type, the proposal has an 83% match in "high visual and/or manual precision," and "moderate force and precision tasks" when considering the cumulative match for both acceptable (high and low) and optimal heights. Although not ideal, the 83% is a very good match for just one design. In the current scenario, adding up a platform of 50 mm could

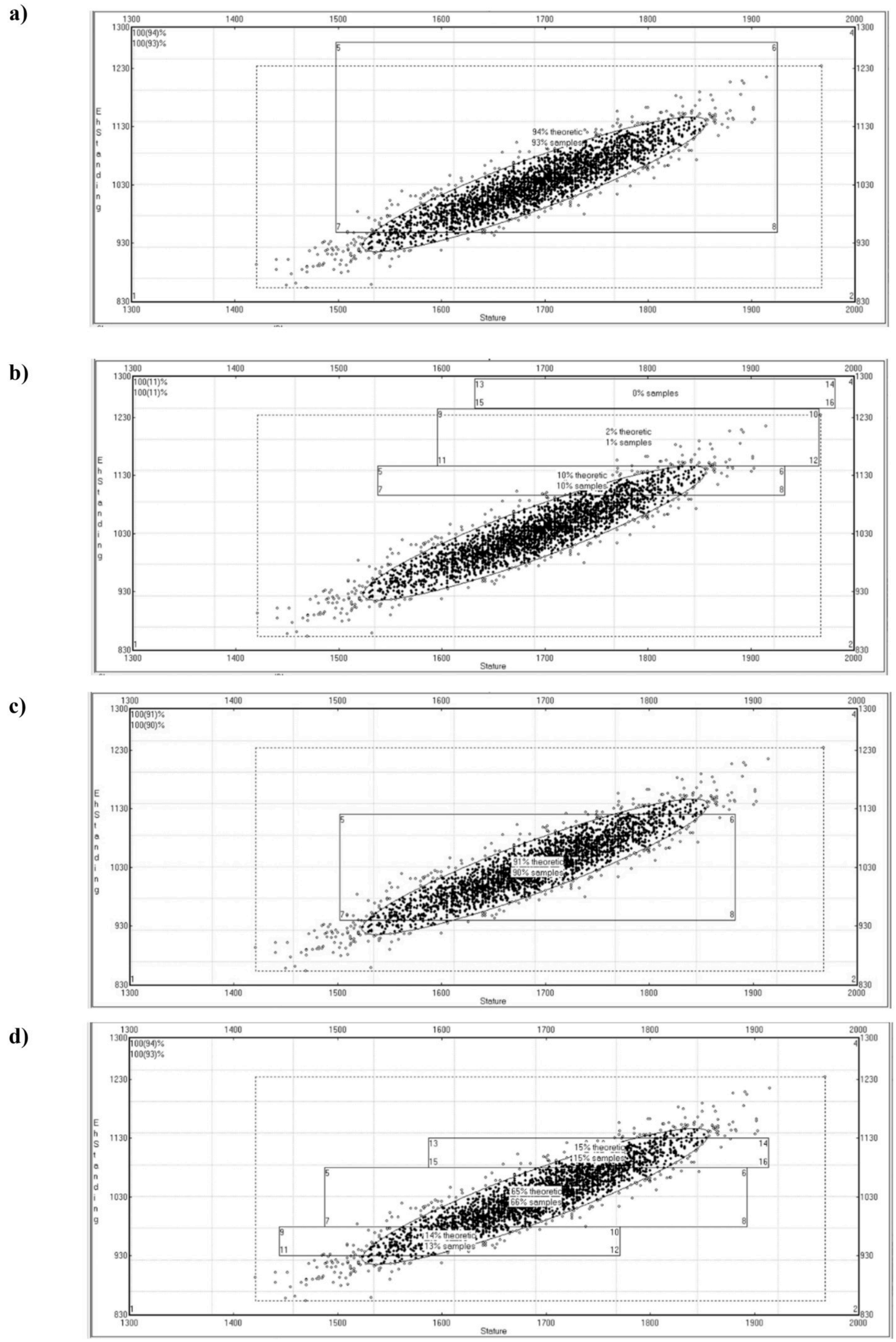

Fig. 2. Working height match levels (%) for tasks with high force requirements a) ISO adjustable (867–1105 mm range). B) ISO non-adjustable (1075 mm) c) adjustable proposal (770–1050 mm). d) non-adjustable proposal (910 mm).

accommodate the remaining 7% of users to attain adequate matching levels, as shown in Figs. 3e and 4e. Another option can be the use of an additional size (grading). It is noteworthy that even though only EHStand is used, this limit behaves as a bivariate, since it is two-way (upper and lower limits).

Finally, tasks with high force requirements match the 94% of the sample when cumulative match for both acceptable (high and low) and optimal heights is considered.

3.2.1. Tasks with high force requirements

Fig. 2 shows the ellipse analysis for tasks with high force requirements. Note from Fig. 2a and c that ISO standard achieves higher matching levels (94%) than the proposal (90%) when an adjustable design is used. Therefore, if adjustability is used, a range considering the proposal range should be used at least, ranging from 770 to 1050 mm.

As it can be seen in Fig. 2b and d, using the single height of 910 mm in the proposal will ensure a 93% cumulative match for the sample when acceptable (high and low) and optimal levels are considered.

3.2.2. Tasks requiring moderate level of force and precision

Fig. 3 shows the matching levels for tasks requiring moderate level of force and precision considering a mixed population (women and men). Note from Fig. 3a and c, that the matching levels using adjustability are adequate only with the proposal (90%), when using a range between 870 and 1100 mm, since the range in the ISO standard of 960–1225 mm only accommodates 84% of the sample.

Note from Fig. 3b and d that the ISO fixed dimension has no matches in the sample, while cumulative fit that the proposal contemplates provides an 83% match, considering acceptable (high and low) and optimal heights when a unique height of 985 mm is used. Adding up a 50 mm platform, so that smaller workers can stand, will increase the matching percentage by 7%, obtaining a 90% match (see Fig. 3e). As additional benefit, the 23% of the workers will fall on optimal range if the same design is used.

3.2.1. Tasks with high visual and/or precision requirements

Fig. 4 shows the use of ellipses (bivariate) analysis for tasks with high visual and/or precision requirements. Note from Fig. 4a and c that ISO provides higher matching level (97%) than the proposal (90%) when adjustable height is considered. If adjustability is an option, heights that range between at least 1020–1250 mm should be used.

From Fig. 4b and d, it can be observed that the best scenario is the scenario suggested in the proposal, with a single size of 1135 mm, since the ISO recommended dimension only matches 2% of the sample. Fig. 4d shows that when both acceptable (high and low) and optimal heights are considered, 83% of the sample will be matched with the fixed proposal. Adding up a 50 mm platform, so that smaller workers can stand, will increase the matching percentage by 7%, obtaining a 90% match (see Fig. 4e). As additional benefit, the 23% of the workers will fall on optimal range if the same design is used.

3.3. Ideal manual material handling height and depth

Fig. 5a shows the dimensions used graphically, were brackets represent acceptable (blue) and ideal (green) height. Similarly, pointed arrows represent horizontal or depth. Note the horizontal (depth) distances for manual handling are determined by the 5th percentile for females (shortest) of Elbow grip length (green) and Grip reach (blue), since if the person with the shortest reach is matched so are the users with the longest reach. Therefore, a depth between 341 mm (5th female Elbow grip length) and 749 mm (5th female Grip reach) will ensure that most of the sample performs manual handling safely when depth is considered.

Fig. 5b shows the match results for ideal manual handling selecting higher and upper limits using both smaller (i.e. 5th percentile EHStand female: 902 mm) and larger percentiles (i.e. 95th percentile KnuH male: 824 mm). Generally, a wider percentage of the population will be matched than just the 90%, reflecting in those scenarios where there are no conflicting measures, including both the smallest and the biggest users, which causes a matching percentage increase (Robinette, 2012). On the other hand, Fig. 5c shows that the matching percentage for ideal manual handling height using the same principles with the combined data of the entire sample (5th percentile: 939.6 and 95th percentile: 818.5; 90% match) produces lower matching levels. The reader may question the necessity of using combined data if match levels are lower. The answer is developed in section 3.4; however, in summary, the combined data allows to know/calculate more easily the percentage of total users (both genders) that match when there is a design's dimension.

Table 4 shows ideal height for a mixed, female and male population. Note from Table 4 that the ideal height range for manual handling is an inferior limit for mixed population of 818.5 mm (95th percentile KnuH) and upper limit of 939.6 (5th percentile elbow height standing).

When only summary tables are available, with male and female data, the procedure is different. For a bivariate application (ideal manual handling heights), the female P5 of EHStand and P95 knuckle height of male population are used. In that case, the results will cover a larger percentage (higher than 90%). Since raw data are not available to calculate the average or percentile of the mixed population, it is best to use the following equations to calculate the mean ($\bar{x}_T$) and standard deviations (S_T) when the size of the sample from female and male are not equal (example: KnuH dimension):

$$\bar{x}_T = \frac{n_m}{n_m + n_f} \times \bar{x}_m + \frac{n_f}{n_m + n_f} \times \bar{x}_f$$

Where a n_m (number of male) value of 2346 was considered, n_f (number of female) value of 600 and $\bar{x}_m$ (mean of male) was considered regarding the KnuH dimensions, value of 758.8 (mean of male) and $\bar{x}_f$ (mean of female) value of 711.4 (see Table 2).

$$\bar{x}_T = \frac{2346}{2346 + 600} \times 758.8 + \frac{600}{2346 + 600} \times 711.4$$

$$\bar{x}_T = 749.2$$

$$S_T = \sqrt{\frac{n_m}{n_m + n_f} \times S_m^2 + \frac{n_f}{n_m + n_f} \times S_f^2 + \frac{n_m \times n_f}{(n_m + n_f)^2} \times (\bar{x}_m - \bar{x}_f)^2}$$

Where a n_m (number of male) value of 2346 was considered, n_f (number of female) value of 600, S_m (Standard deviation of male) was considered regarding the KnuH dimensions, value of 38.3 (see Table 2) and S_m (Standard deviation of female) value of 34.8 and $\bar{x}_m$ (mean of male) was considered the KnuH dimensions, value of 758.8 (see Table 2) and $\bar{x}_f$ (mean of female) value of 711.4.

$$S_T = \sqrt{\frac{2346}{2346 + 600} \times 38.3^2 + \frac{600}{2346 + 600} \times 34.8^2 + \frac{2346 \times 600}{(2346 + 600)^2} \times (758.8 - 711.4)^2}$$

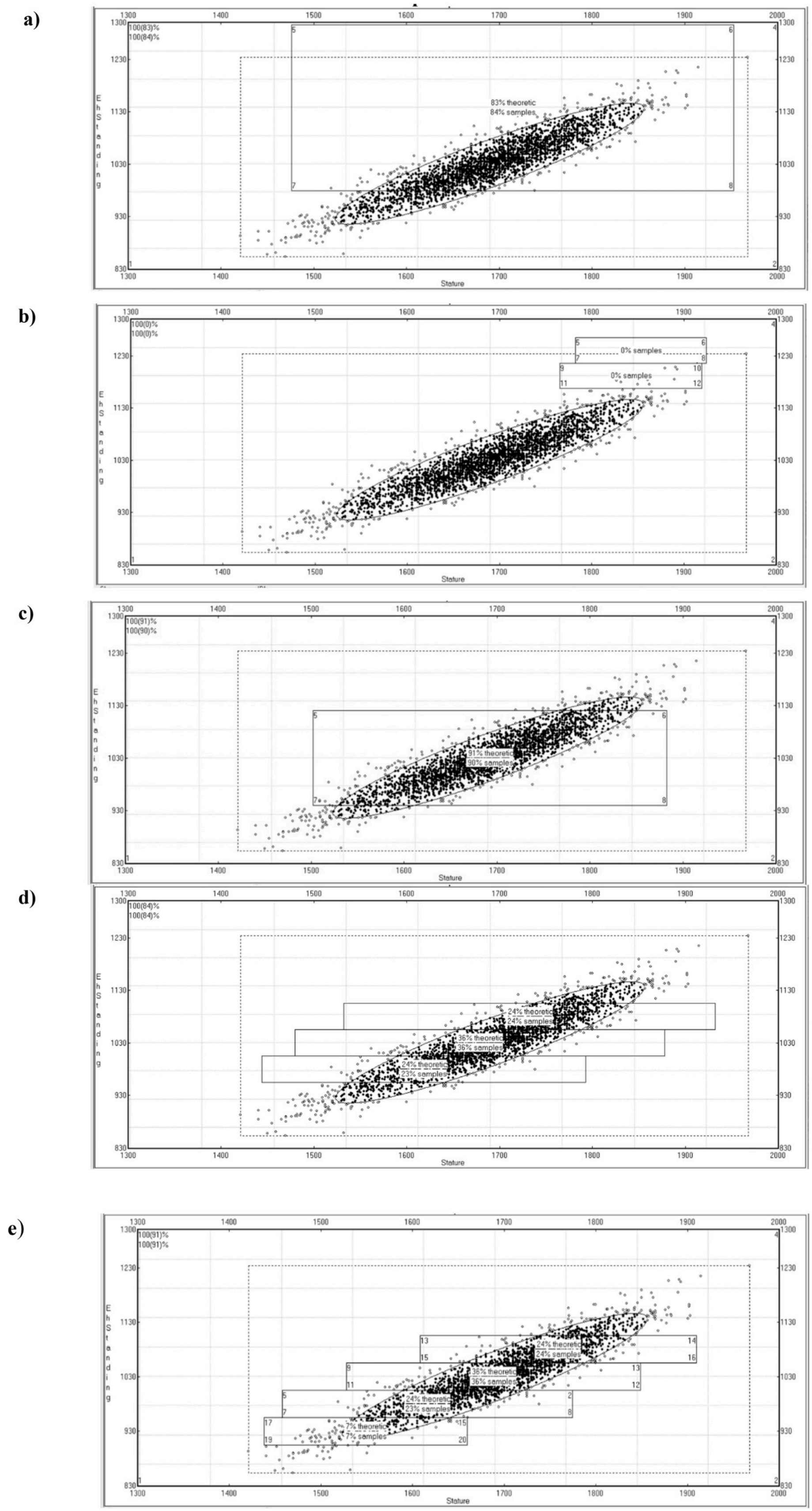

Fig. 3. Working height matching levels (%) for tasks requiring moderate level of force and precision. A) ISO adjustable (960–1225 mm range). B) ISO non-adjustable (1195 mm) c) Adjustable proposal (870–1100 mm). d) non-adjustable proposal (985 mm) e) match increase of 7% with a 50 mm platform.

a)
b)
c)
d)
e)

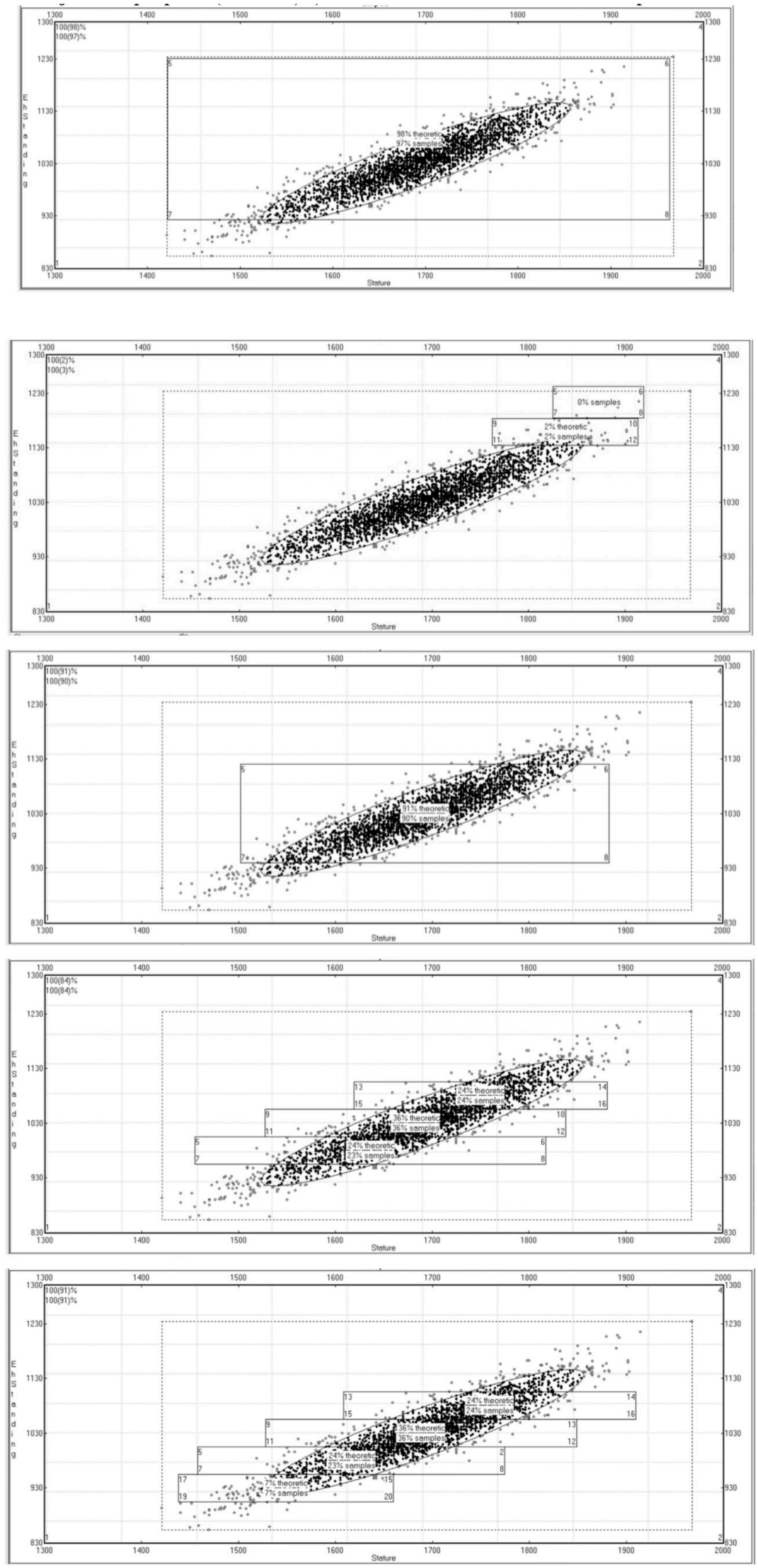

Fig. 4. Working height match levels (%) for tasks with high visual and/or precision requirements. A) ISO adjustable b) ISO non-adjustable. C) adjustable proposal (range 1020–1250 mm). d) non-adjustable proposal (1135 mm) e) match increase of 7% with a 50 mm platform.

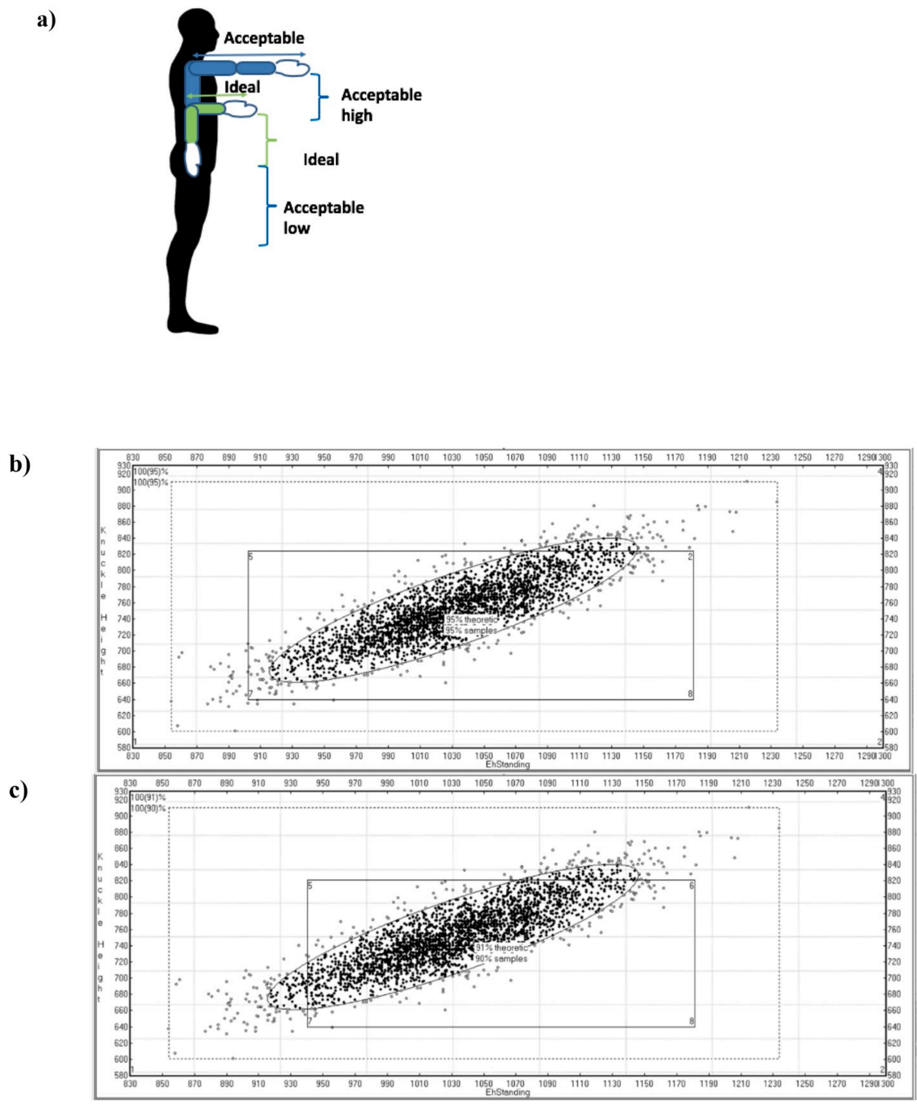

Fig. 5. Ideal manual handling height and depth a) acceptable (blue) and ideal (green) heights and depths b) Ideal manual handling height match using gender specific c) ideal manual handling height match using mixed population.

Table 4
Ideal manual handling of loads heights (mm).

Manual Handling Condition*	Population					
	Mixed		Female		Male	
	Inf. lim	Sup. lim	Inf. lim	Sup. lim	Inf. lim	Sup. lim
Acceptable high (between EhStand and ShStand)	1118.4	1278.8	105.3	122.1	112.3	132.0
Ideal (between KnuH and EhStand)	818.5	939.6	77.1	90.2	82.4	96.5
Acceptable low (between KH and KnuH)	563.7	680.1	52.4	65.6	56.7	69.9

$S_T = 42.2$

3.4. Design practical implications and limitations

Alternatives using either a percentile/limit or bivariate procedures were used to successfully calculate the highest possible matching levels for the intended population. The bivariate approach was used, which is based on the use of percentiles, a widely used approach in research (Dianat et al., 2018). This approach considers the proper identification of critical dimensions for a particular design, since the use of a bivariate approach makes the assumption that if the boundary cases are matched by the design, so are all of those between the ellipse (Robinette, 2012). Although using ellipses (bivariate) is very accurate and can ensure higher matching levels, the entire raw data is needed for achieving those goals (Robinette, 2012). Another bivariate approach limitation occurs when the data distribution is highly scattered or it is used for clothing design or other gear with multivariate dimensions. In those cases, using proper grading (Robinette, 2012) or scalability (Castellucci et al., 2016) are recommended. In the case of this study, adding a 50 mm platform assured the desired matching percentage of 90% without an additional working height size or the application of scalability.

Although having anthropometric data summarized in tables has been a standard practice, it may be advisable to review it, since data is often presented separated exclusively for men and women. This may be useful for the design of gender specific products; however, to design workplaces used by both genders can be complicated, as the ones in the current study (Robinette, 2012). The inclusion of combined sample's dimensions (male and female) should be a standard practice when anthropometric data is used, especially for those applications similar to those in point 2.3.1.1, where the lack of the combined data makes the process more cumbersome, since the procedure for calculating a match from a pre-established dimensional design ('reverse engineer'), will need to be executed separately for both males and females, thus calculating the total match for an entire population results in a more complex task. In practice, matching percentages for females and males can be calculated, although it is much better the use of anthropometric tables with mixed dimensions, so that designers can be spared of first combining the data and/or calculating matching percentages separated by gender.

The non-adjustable values recommended in this study proved to match most of the population, where ISO dimensions accommodated none. Thus, the provided recommendations and their matching levels account for the differences in the populations that were used to create the ISO standards and highlights the importance of having specific population anthropometric data when compared against ISO. Up to this date, there were no practical recommendations available regarding design of common industrial solutions for Chilean workers.

The recommendations present in the current study aimed to fill the existing gap in that area, since previous information was vague. It is worth to mention that the research team presented their results in a simple and straightforward manner. This was done mainly because it is desired that designers aiming to solve/design most common issues (i.e. manual handling heights, production line height and depth) have the information they need. This has been shown to be of extremely high value by previous research, mainly because industrial designers work on their own and rarely consult an ergonomist (Ranger et al., 2019). The same authors have also shown that industrial designers have a hard time to identify what anthropometric measurements are needed to size a product and that they would appreciate to have data according to a specific geographical territory or a precise market. Moreover, industrial designers find standards more appealing and useful when they provide the "ready to use" dimensions, sparing them of complex calculations (Ranger et al., 2019). In that regard, the current research provides the information in that format, aiming at designers and decision makers, in order to be used in designs for Chilean workers. The lack of specific and concrete anthropometrics applications for designing has been identified as a barrier for preventive and successful recommendations and design (Dianat et al., 2018); therefore, this paper contributes in that aspect.

Additionally, through an application example, a common scenario was addressed showing how to determine a matching percentage of a population only having a specific design's dimensions and the anthropometric summary tables separated by gender. In those cases, the Z-score allows to determine how many persons are matched, by indicating the percentile value where a design lays and indicating the matching levels. It is important to remember that the percentile values considered for univariate methods (limits) only ensure a match when the dimensions do not interact between them, such as the case of manual handling depths. In those cases, were interaction occurs or a univariate dimension is used as a 'two-way limit' (working heights per task type), the bivariate analysis proves to be useful. For ideal manual handling heights, a bivariate method was used with depths as well, where the latter does not have conflicting dimensions with heights; therefore, a univariate 'one-way' limit approach, using the 5th percentile value of the shortest reach (female), can be selected with no issues. In those cases, where space, reach, and other similar situations, the matching % can be even greater, as it includes 90% of the females and more than 90% of the males.

The values regarding height need to be corrected with shoe heights used by the intended user population, as was presented in the current study. This approach is highly suggested since designers can customize production working and manual handling heights according to the specific garments used. This approach was taken further by Guan et al. (2012) were they measured truck drivers with and without shoes in order to quantify and typify the differences between the most commonly used shoes. Guan et al. (2012) also accounted for ethnic difference. In that regard, it is important to mention that the anthropometric dimensions that led to the recommended values, and that were presented in the current research, were measured using Chilean born subjects only. The first and only genetic national study found no differences regarding ethnicity in Chileans across the North, Center and South of the country (Chilegenomico, 2015). This can be interpreted as both a strength and a weakness: a strength, since the survey was conducted in 2016, right before a massive migration of Haitian people arrived in the country, which are of African ethnicity (Rojas and Silva, 2016). Therefore, the gathered data can be used as baseline to be used without the ethnicity component. This can also be interpreted as a weakness, and even although most migrant workers nowadays do work in informal jobs in non-industrial sectors such as agriculture, fishing, services, and construction (Díaz and Gálvez, 2015), they are not "anthropometrically" considered in the current recommendations, therefore, future studies should account for ethnic differences or complement the current information with dimensions of the most representative migrant groups, such as people from Venezuela, Colombia, and Perú, whom recently have surpassed the Haitian community (INE, 2018). Considering the ethnic variation was not an issue in Chile until recently; thus, considering ethnic variation is a must for future studies, as it was recognized as a priority as well in recently published papers (Deneau et al., 2018; Hartono, 2018). The comparison between the suggested ideal manual handling of loads and working heights of different task types, with the suggested workplace design guideline data from other ethnic groups, would be necessary (Rhie et al., 2017). Before applying the anthropometric data, it is important to considered the secular trend (Castellucci et al., 2015b) and it is recommended to gather anthropometric dimensions at least every decade in order to account for secular trends experienced by populations due to improvements or worsening in the quality of life (Cole, 2000, 2003; Gordon and Bradtmiller, 2012; Tanner, 1986).

Also, as suggested by Dianat et al. (2018), experimental trials with representative samples of users testing prototype versions of products/environments under controlled conditions seem to be necessary to evaluate the effectiveness of proposed designs. To consider this possibility, both objective (e.g. performance, time, error, etc.) and subjective assessments (e.g. user assessments such as preference, comfort/discomfort, usability, etc.) that provide valuable information about the design are recommended. Given the calculated results in working and ideal manual handling heights, a field validation study using the working heights suggested by this study would be very helpful for the practitioners. This field validation needs to be performed in a stakeholders' involvement in order to obtain the best results and feedback (Zare et al., 2020), considering task types as well, since additional research has shown different exposures according to each task; thus, total risk levels in jobs involving different manual handling tasks should account for that additive effect (Nogueira et al., 2018). It is suggested that the recommendations made in the current study are tested using fitting trials with real users accounting also for preference, since theoretical match does not necessarily correlates with preference (Bahrampour et al., 2019; Robinette, 2012).

4. Conclusion

The current research uses a recently published anthropometric database of Chilean workers to provide common industry design/preventive recommendations for that particular segment, and to show that the ISO non-adjustable dimensions presented low matching levels when applied to the sample. Different matching methods were used, contributing to the generation of specific recommendation for working height according to task type and safe manual handling height/depth. Most of the applications, showed high matching levels (at least 90%) with just a couple of options. Ethnic differences should be considered in future studies, together with the use of fitting trials that consider preference, to validate the recommendations presented in this study.

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.

CRediT authorship contribution statement

Héctor Castellucci: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing - original draft. **Carlos Viviani:** Conceptualization, Data curation, Funding acquisition, Writing - original draft. **Pedro Arezes:** Conceptualization, Methodology, Writing - review & editing. **Johan F. M. Molenbroek:** Formal analysis, Methodology, Writing - review & editing. **Marta Martínez:** Funding acquisition, Project administration. **Verónica Aparici:** Investigation, Resources. **I. Dianat:** Validation, Visualization, Writing - review & editing.

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Appendix A. Supplementary data

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