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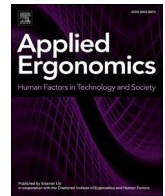
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## Secular trends in facial anthropometry among Chilean workers: Implications for ergonomic respirator design and fit panel adaptation

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### ABSTRACT

The ergonomic fit of respiratory protective equipment (RPE) is critical for ensuring both protection and long-term usability in occupational settings. However, most respirators are designed based on outdated or foreign anthropometric data that may not represent local populations. In Chile, as in many countries without updated national databases, this mismatch can compromise comfort, effectiveness, and user compliance. This study evaluated temporal changes in facial dimensions among Chilean workers and assessed the applicability of four widely used respirator fit test panels. Two representative datasets collected a decade apart were analyzed: Dataset A (n = 474; 2013) with manual measurements, and Dataset B (n = 2016; 2024) using 3D facial scanning. Eleven facial dimensions recommended by ISO standards were examined against the LANL half- and full-facepiece panels and the NIOSH/ISO bivariate and PCA panels. Results showed significant increases in facial size, particularly among men, and a general shift toward larger facial morphologies. The NIOSH/ISO bivariate panel provided the highest coverage, while the LANL full-facepiece panel showed the poorest fit, especially among recent male participants. Gender-based differences in fit were consistent across both datasets. These findings underscore the need for updated, population-specific anthropometric references and the ergonomic redesign of respirators and fit panels. Although centered on Chile, the study has global relevance for countries that import RPE without validating fit locally. The methodology offers a scalable approach for aligning protective equipment with evolving worker characteristics, supporting international efforts to improve comfort, safety, and usability through data-informed design. These declining match rates suggest that respirator fit panels may become increasingly outdated, potentially compromising worker safety if they are not updated to reflect current population characteristics.

### 1. Introduction

Ergonomic design and proper fit of respiratory protective equipment (RPE) are essential for optimizing protection and usability in occupational settings, particularly in high-risk environments such as industrial and healthcare settings. For example, there are reports of fitting issues with RPE, which are shown to affect more than 50 % of clinical personnel (Caggiari et al., 2022). Current fit-testing procedures prioritize achieving a tight seal to prevent particle leakage; however,

incorporating an assessment of comfort into these protocols is increasingly recommended to improve compliance and usability (Locatelli et al., 2014). Discomfort not only deters consistent use but also compounds over time, as healthcare workers report escalating discomfort with prolonged respirator wear across different models (Shenal et al., 2012). Recent findings show that discomfort can interfere with task performance and contribute to inconsistent respirator use, even among fit-tested users (Hackett et al., 2024). Psychometric research has also confirmed that comfort, fit, and ease of donning are critical usability

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factors that influence consistent use of respiratory protection (Suen et al., 2024). Additionally, studies have shown that respirators may lose fit during physical tasks, and that breathability, thermal sensation, and facial pressure significantly affect their usability (Suen et al., 2020). Evidence from a large clinical trial further demonstrated that adherence to N95 respirators was suboptimal and not significantly different from that of medical masks, suggesting that improving comfort and usability is essential to achieve consistent use in real-world settings (Radonovich et al., 2019). These findings reinforce that while achieving an adequate geometric fit through representative anthropometric data is essential, it must be supported by user-centered design considerations to ensure sustained and effective respirator use in real work environments.

This interplay between geometric fit and usability highlights the need for user-centered design based on anthropometric data that accurately represents diverse worker populations (Samet et al., 2022). Factors such as face shape, sex, age, and the presence of facial hair all influence the effectiveness of a respirator's seal. Furthermore, the growing awareness among workers of the importance of proper fit has driven demand for better-fitting devices tailored to varied anthropometric profiles (Makowski, 2022). To meet this demand, researchers emphasize the need for design modifications and testing protocols that account for the devices' ease of assembly, compatibility with P3 class filters (high-efficiency particulate filters rated to capture at least 99.95 % of airborne particles according to EN 143 standards (2000)), and their representation of commonly used workplace equipment (Makowski, 2022).

Anthropometric studies provide the foundation for evidence-based ergonomic design, ensuring compatibility between facial anthropometry and product design. Historically, the National Institute for Occupational Safety and Health (NIOSH) recognized the need to accommodate a wide range of facial shapes and sizes. In collaboration with Los Alamos National Laboratory (LANL), they developed facial panels representing 95 % of the U.S. working population based on key facial measurements such as face length and face width for a full-piece mask panel, and face length and lip length for a half-piece mask panel (Hack and McConville, 1978). However, these panels were calculated using military personnel for the most part, and concern was raised about their applicability to the workforce worldwide. As such, Zhuang et al. (2007) confirmed a low representation among workers for the LANL panels and presented updated panels considering a bivariate analysis of linear facial dimensions, along with an analysis of Principal Components Analysis (PCA) based on the 10 most representative facial dimensions (Rodríguez et al., 2020).

As an example, Chile is one of the countries that import most of their protective equipment from overseas, primarily from China and Europe, which are mostly based on foreign databases. For instance, Bradtmiller et al. (2004) describe an anthropometric survey conducted by NIOSH among U.S. respirator users aged 18 to 66, which serves as a key reference for respirator design in many countries. However, this dataset reflects the facial characteristics of the U.S. workforce and may not adequately represent the anthropometric profile of Chilean workers. This situation likely results in a suboptimal fit between imported respirators and local users. Rodríguez et al. (2020) measured eleven key facial anthropometric dimensions on 474 subjects and tested them against bivariate fit test panels proposed by LANL and those developed by NIOSH and considered by ISO/TS 16976-2 (bivariate and PCA), hereafter referred to as NIOSH/ISO panels. Their results show a total of 88.2 % match for the LANL half-facepiece panel, 79 % for the LANL full-piece panel, 95.4 % match for the bivariate NIOSH/ISO panel, and 95.6 % match for the 8-cell category PCA NIOSH/ISO panel, whereas NIOSH/ISO recommends that these panels should cover at least 95 % of the working population.

Although Rodríguez et al. (2020) provided the first evaluation of the applicability of international respirator fit test panels to the Chilean workforce, their data were collected nearly a decade ago. Since then, Chile has undergone substantial demographic and anthropometric

changes, including increased ethnic diversity due to immigration and documented secular trends in body dimensions (Castellucci et al., 2021). These changes may compromise the continued relevance of earlier findings. Therefore, this study aimed to assess the applicability of international respirator fit test panels to the current Chilean workforce by comparing newly collected anthropometric data from over 2000 actively employed workers (2023–2024) with previously published data collected between 2013 and 2016 (Rodríguez et al., 2020). By significantly increasing the sample size, including workers from diverse economic sectors and age groups up to 85 years, and incorporating advanced 3D scanning technology, this study enables a temporal analysis of facial dimension changes and their implications for respirator fit.

## 2. Methods

This study compared two facial anthropometric datasets collected a decade apart to evaluate secular changes in facial dimensions and their implications for respirator fit. Dataset A ( $n = 474$ ) was collected between 2013 and 2016 using manual measurements and has been previously published (Rodríguez et al., 2020), while Dataset B ( $n = 2016$ ) was collected between 2023 and 2024 using 3D facial scanning. Both datasets included working adults aged 18–85 years from multiple economic sectors in Chile. Eleven key facial dimensions were extracted from each dataset and analyzed for differences over time and between sexes. Subsequently, the compatibility of both datasets with four international respirator fit test panels (LANL half- and full-facepiece panels, and NIOSH/ISO bivariate and PCA panels) was assessed. The methodology is described in four subsections: sample characteristics, data acquisition procedures, selected anthropometric dimensions, and respirator panel matching and statistical analysis.

### 2.1. Chilean database

The target sample was Chilean workers, but open to workers of any nationality in Chile, who were users or potentially users of PPE, both males and females.

Both samples consisted of a representative group of workers aged 18–85 years, drawn from various sectors of economic activity, including Mining, Manufacturing, Electricity, Construction, Transport and Communications, Financial Services, and Communal and Personal Services. Although the inclusion of workers up to 85 years old exceeds the legal retirement age in Chile (60 for women and 65 for men), all participants in the study were actively employed at the time of data collection. This reflects the national reality, as Chile ranks third among OECD (2017) countries in terms of effective retirement age, with workers retiring on average at 67.7 years for women and 71.3 years for men (OECD, 2017).

The sample size was calculated following the principles of ISO 15535: 2012 (ISO, 2012). Both studies used stratified sampling to reliably use the 5th and the 95th percentiles, where the strata were determined by two factors, gender and age range.

The first set of data, hereafter referred to as Dataset A, was originally collected between 2013 and 2016 and has been previously published in Rodríguez et al. (2020). It estimated a sample size of 440 workers, with

**Table 1**  
Dataset A and B.

	Nationality	n	Female	Male	Height (mean)	Weight (mean)
Dataset A	Chilean	474	229	245	1653.1	76.0
Dataset B	Chilean	1790	941	849	1639.0	79.8
	Other Latin American nationalities	226	116	110	1642.5	75.1
	Total	2016	1057	959	1642.2	75.5

110 participants from each cluster (4 clusters), resulting in a real sample of 474 workers: 229 women and 245 men (Table 1). The second dataset, hereafter referred to as Dataset B, estimated a sample size of 1,524, with 254 subjects for each cluster (6 clusters), leading to a real sample of 2016 subjects: 1057 women and 959 men (Table 1).

As shown, 88.8 % of the participants in Dataset B were of Chilean nationality, ensuring that the findings primarily reflect the Chilean workforce, while also acknowledging the increasing presence of immigrant workers in the labor market.

## 2.2. Data capture

Dataset A was gathered through manual measurements taken by a trained team who detected and marked the anthropometric reference points on each subject. Measurements were collected using a sliding caliper (GPM® Switzerland) following ISO (2015). The measurement team consisted of a marker, a measurer, and a data recorder, all trained by an ergonomics expert for one week in the identification of anthropometric landmarks and measurement procedures. To ensure consistency and minimize errors, team members maintained fixed roles throughout the entire data collection period. The measurement process adhered to ISO 15535 and 16976-2 standards and complied with maximum allowable errors established by NIOSH. The measurement process adhered to ISO 15535 and 16976-2 standards and complied with maximum allowable errors established by NIOSH. The data were collected between September 2013 and May 2016 as part of a study approved by the Ethics Committee of the Chilean Public Health Institute.

Dataset B, in turn, was captured using the 3dMDhead® system (3dMD®), which consists of four modular units with three machine vision cameras each: two for depth estimation and one for color registration, plus a speckle pattern projector and an industrial-grade flash system. All components are synchronized to capture a single image and generate a continuous three-dimensional polygon surface mesh. During scanning, participants were seated upright, wore regular clothing and shoes, and used swimming caps to facilitate accurate capture of the scalp surface. They were instructed to maintain their head in the Frankfurt plane, keeping their mouths closed and eyes looking straight ahead to ensure standardized posture and head orientation.

To support the calculation of virtual measurements on the 3D objects, 24 facial landmarks were manually marked on all participants using adhesive labels (Fig. 1). These landmarks are generally, although not always, skeletal points that are marked on the overlying skin, which makes them easier to locate with proper training (ISO, 2015). Data were

collected from November 2023 to March 2024. The use of physical adhesive markers before scanning improves methodological accuracy by ensuring consistent landmark placement. Although fully digital landmarking protocols have shown high reliability, Hobbs-Murphy et al. (2024) reported good to excellent intra- and inter-rater reliability using digital landmarks. Our protocol strengthens consistency and minimizes measurement errors by providing visible anatomical references during scan acquisition.

It is important to note that Dataset A and Dataset B were obtained using different measurement techniques: the first used manual anthropometry with calipers, and the second employed high-resolution 3D facial scanning. Manual measurements are standard and reliable but may introduce soft tissue compression and inter-rater variability. In contrast, 3D scanning captures dense surface geometry without contact and enables shape-based analysis. Previous research has shown that 3D methods can achieve sub-millimeter precision and offer advantages in reproducibility and multivariate analysis of facial morphology (Hobbs-Murphy et al., 2024; Joe et al., 2012; YU et al., 2021). While both techniques are valid and widely used, the implications of using different protocols are addressed further in the Limitations section.

## 2.3. Measurements

Eleven key anthropometric dimensions were selected for this study from the available dimensions of each database, listed in Table 2 and presented in Fig. 2. These dimensions were selected as they are recommended for defining fit panels for respirators, such as face length, face width, and lip length. Additionally, they were selected since are part of the multivariate analysis as they are relevant to respirator fit, and have a good correlation with other excluded dimensions (Zhuang et al., 2007).

## 2.4. Bivariate panels

The LANL respirator fit test panels were developed to represent the facial dimensions of 95 % of the U.S. working population. These panels include both full-piece and half-piece respirator panels, structured using a bivariate distribution of key facial dimensions. For full-piece masks, the axes represent face length (y-axis) and face width (x-axis), while for half-piece masks, the axes are face length (y-axis) and lip length (x-axis) (Hack and McConville, 1978; Zhuang et al., 2007).

Each panel is divided into 10 cells. This 10-cell configuration originates from the original LANL panel methodology, which first divided the panels into more categories (12 or 16 cells), but removed those with



Fig. 1. 3D facial images captured with 3dMDhead® system showing manually placed adhesive markers at key anatomical landmarks for virtual anthropometric measurements.

**Table 2**  
Anthropometric dimensions to consider in this study, taken from ISO TS 16976-2 (2015).

Dimension (mm)	Definition
Minimum frontal breadth	The straight-line distance between the right and left frontotemporal on the temporal crest on each side of the forehead.
Face width	The maximum horizontal breadth of the face is measured as the difference between the zygion from right to left.
Bigonial breadth	The straight-line distance between the gonion left and right.
Face length	The distance in the midsagittal plane between the menton at the bottom of the chin and the sellion at the deepest point of the nasal root depression.
Interpupillary distance	Straight-line distance between the center of the right and the center of the left pupil.
Head breadth	Maximum horizontal breadth of the head measured as a straight-line distance above the ears.
Nose protrusion	The straight-line distance between the pronasale at the tip of the nose and the subnasale under the nose.
Nose breadth	The straight-line distance between the right and left alare.
Nasal root breadth	The horizontal breadth of the nose at the level of the deepest depression in the root and at a depth equal to half the distance from the bridge of the nose to the eyes is measured as the distance between the nasal root from right to left.
Subnasale-sellion length	Straight-line distance between the subnasale and the sellion.
Lip length	The straight-line distance between the right and left cheilion landmarks at the corners of the closed mouth is measured as the norm difference between both cheilion landmarks right to left.

negligible population representation (<1 %), resulting in a simplified 10-cell layout that still covers approximately 95 % of the target population. The decision to use 10 cells was a compromise to balance population coverage, measurement precision, and the practical constraints of respirator testing procedures (Zhuang et al., 2007).

For the full-facepiece panel, face length values range from 98.5 mm to 138.5 mm in 10 mm increments, while face width values range from 120.5 mm to 158.5 mm in 9 mm increments. For the half-facepiece panel, the same face length range is used, while lip length values range from 34.5 mm to 51.5 mm, also in 9 mm increments. This standardization enables consistent categorization and facilitates analysis of panel fit across various populations.

The NIOSH bivariate panel, adopted by ISO 16976-2, follows a similar 10-cell structure using face length and face width as axes. The axes range from 98.5 mm to 128.5 mm for face length and from 120.5 mm to 146.5 mm for face width, both increasing by 10 mm intervals.

This approach provides a simplified yet effective classification system for fit testing that can be replicated across diverse populations.

### 2.5. Principal component analysis panels

The layout of the PCA panel is different from the bivariate panels above. The PCA panel is structured using elliptical boundaries that capture 95 % and 50 % of the target population based on multivariate analysis of key facial dimensions. This design enables a more comprehensive classification of facial morphology for fit testing purposes. The rationale for the rest of the PCA configuration is to have uniform distributions for each cell. Thus, two lines were used to divide the two ellipses into four quadrants resulting in eight cells. The population is then uniformly distributed among the 8-cell categories.

Each key dimension is weighed by a factor defined by ISO (2015). Principal Component 1 (PC1) is plotted on the x-axis against the Principal Component 2 (PC2), where x-axis limits are 246.8 mm and 316.4 mm, and y-axis limits are 14.8 mm and 43.2 mm.

PCA coordinates were derived following ISO 16976-2, enabling classification into elliptical fit zones representing 95 % of the population (PC1 and PC2), calculated following Table 3. Where each measurement is weighed against values of W for PC1 and values of V for PC2 (ISO, 2015; Zhuang et al., 2007), as described in Equations (1) and (2).

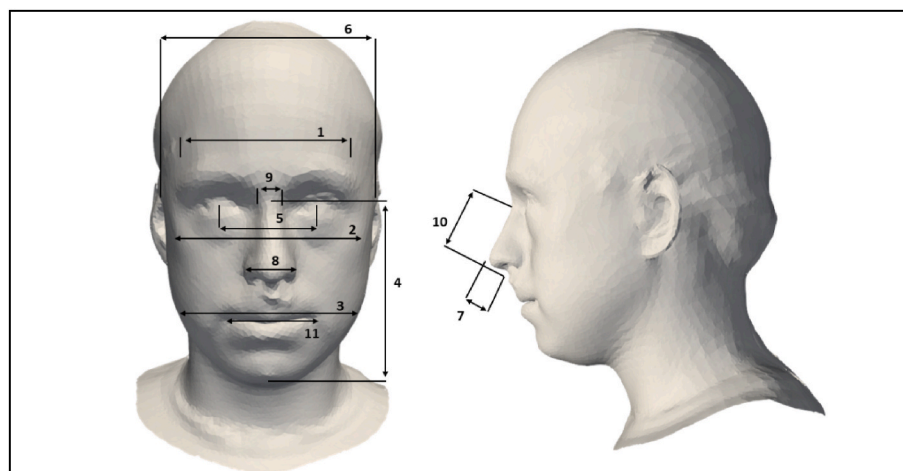
Equation 1. Principal Component 1. Summation of measurements M (1–10) multiplied by factor W (1–10).

$$PC1 = \sum_{n=1}^{10} W_n M_n$$

Equation 2 Principal Component 1. Summation of measurements M

**Table 3**  
Principal Components factors W and V to calculate PC1 and PC2.

Measurement	PC1	PC2
Minimum frontal breadth	W1 0,343264	V1 -0,152951
Face width	W2 0,426498	V2 -0,039087
Bigonial breadth	W3 0,372717	V3 -0,093279
Face length	W4 0,329648	V4 0,359799
Interpupillary distance	W5 0,363474	V5 -0,173099
Head breadth	W6 0,372241	V6 0,013306
Nose protrusion	W7 0,113578	V7 0,551842
Nose breadth	W8 0,301125	V8 -0,210833
Nasal root breadth	W9 0,202311	V9 -0,341235
Subnasale-sellion length	W10 0,19365	V10 0,584261



**Fig. 2. Eleven facial anthropometric dimensions used for respirator fit analysis**

1. Minimum frontal breadth, 2. Face width, 3. Bigonial breadth, 4. Face length, 5. Interpupillary distance, 6. Head breadth, 7. Nose protrusion, 8. Nose breadth, 9. Nasal root breadth, 10. Subnasale-sellion length, 11. Lip length.

(1–10) multiplied by factor V (1–10).

$$PC2 = \sum_{n=1}^{10} V_n M_n$$

After PC1 and PC2 are calculated, the algorithm presented in ISO TS 16796-2 can be applied to determine the cell on which each subject can be located.

### 2.6. Statistical analysis

The distribution of the samples was tested using D’Agostino and Pearson’s tests (R. B. D’Agostino, 1971; R. D’Agostino and Pearson, 1973) and given the non-gaussian distribution of the samples, Wilcoxon rank-sum statistic test was performed to compare the data from both datasets for females and males. All calculations and statistical tests were performed using the Scipy Python library (Virtanen et al., 2020).

Finally, all the key facial anthropometric dimensions were used to assign participants to cell categories within the bivariate and PCA panels from LANL and NIOSH/ISO, allowing comparison of population distributions across datasets.

## 3. Results

### 3.1. Descriptive statistics of facial dimensions

Tables 4 and 5 summarize the key facial anthropometric measurements for female and male participants, respectively, across both datasets.

Table 4 presents the descriptive statistics of the eleven facial anthropometric dimensions for female participants in Dataset A and Dataset B. Across all dimensions, statistically significant differences were observed between the two samples ( $p < 0.001$ ), with Dataset B showing notably larger values in most measurements, such as bigonial breadth and interpupillary distance. These results suggest important secular changes in the facial morphology of Chilean women over the past decade.

Table 5 summarizes the same eleven facial dimensions for male participants in both datasets. Similar to the female group, significant increases were found in most dimensions in Dataset B compared to Dataset A ( $p < 0.001$ ), particularly in head breadth and nose protrusion. Interestingly, face width was the only measurement without a significant difference between the two samples ( $p = 0.802$ ), indicating a potential stabilization of this particular facial feature among men.

**Table 4**  
Key anthropometric dimensions used in this study, females only.

Anthropometric dimensions (mm)	Dataset A (n = 229)		Dataset B (n = 1057)		Difference	
	mean	sd	mean	sd	significant	p-value
Minimum frontal breadth	95.61	5.56	110.18	7.22	***	0.000
Face width	132.74	5.31	135.23	8.16	***	0.000
Bigonial breadth	103.31	6.47	125.00	10.08	***	0.000
Face length	116.52	5.66	119.93	5.83	***	0.000
Interpupillary distance	60.03	2.80	64.61	3.30	***	0.000
Head breadth	147.45	5.20	160.62	16.01	***	0.000
Nose protrusion	17.24	2.35	21.36	2.01	***	0.000
Lip length	52.78	3.77	50.78	4.21	***	0.000
Nose breadth	33.9	2.7	34.83	3.20	***	0.000
Nasal root breadth	18.2	2.2	17.63	2.17	***	0.000
Subnasale-sellion length	51.2	3.4	55.43	3.67	***	0.000

\*\*\* Statistically significant difference between datasets ( $p < 0.001$ ).

**Table 5**  
Key anthropometric dimensions used in this study, males only.

Anthropometric dimensions (mm)	Dataset A (n = 245)		Dataset B (n = 959)		Difference	
	mean	sd	mean	sd	significant	p-value
Minimum frontal breadth	100.44	5.10	116.12	8.91	***	0.000
Face width	142.37	6.60	141.72	8.31	ns	0.802
Bigonial breadth	109.89	7.09	137.76	12.23	***	0.000
Face length	127.20	6.56	129.48	7.30	***	0.000
Interpupillary distance	61.00	3.11	67.12	3.43	***	0.000
Head breadth	154.58	5.77	176.20	15.00	***	0.000
Nose protrusion	19.11	2.51	22.61	2.22	***	0.000
Lip length	55.75	4.13	53.88	4.32	***	0.000
Nose breadth	38.3	3.2	38.49	3.52	***	0.000
Nasal root breadth	18.9	2.4	17.87	2.15	***	0.000
Subnasale-sellion length	55.2	4.1	59.05	4.22	***	0.000

\*\*\* Statistically significant difference between datasets ( $p < 0.001$ ).

### 3.2. Respirator fit panel performance

The LANL and NIOSH/ISO panels and the distribution of Dataset A and Dataset B for each of the cell categories for women and men, respectively, are presented below.

Table 6 shows the distribution of females from both datasets among the cell categories of the panels for half-piece and full-piece masks, bivariate and principal component analysis. Data is presented in percentage of the population and number of subjects for each cell, including the total amount of matches and mismatches for all cell categories.

Dataset A shows an overall better fit within all panels than Dataset B, where the highest level of match is presented for both NIOSH/ISO panels, with 98.6 % of the population fitting within the PCA panel, followed by 98.2 % of the subjects fitting within the Bivariate panel. LANL panels also present high levels of match for Dataset A, with 96.9 % and 85.6 % of matched populations for Half- and Full-piece mask panels respectively. On the other hand, Dataset B shows the highest match for the LANL half-piece mask panel with 97.5 % followed by the NIOSH/ISO Bivariate panel with 95.9 % and the PCA panel with 94.2 %. The lowest fit for Dataset B is presented for the LANL full-piece mask panel, with a 77.4 % match for the female population.

It is also important to note that the distribution of both samples among the cell categories, where the highest match within cells is marked with an \* to ease the interpretation of the results. For instance, the LANL panels of the half-piece mask present the highest match of subjects on cell 8 for Dataset A, with 58 subjects (25.4 %), and on cell 7 for Dataset B, with 425 subjects (40.2 %). Percentages are shown in parentheses throughout the table. Full-piece mask has the highest match of subjects within cell 6 for both Dataset A, with 73 subjects (31.9 %), and Dataset B, with 227 subjects (21.5 %). Furthermore, NIOSH/ISO panels present a more differentiated distribution of subjects among the cells of each panel. Dataset A presents the highest number of subjects on cell 3 of the Bivariate panel, with 70 subjects (30.1 %). A similar finding was obtained for Dataset B, but on cell 6, with 229 subjects (21.7 %). Regarding the PCA panel, Dataset A fits subjects mostly in cell 1, with 85 subjects (37.1 %), while the highest number of subjects from Dataset B can be found in cell 8, with 284 subjects (26.9 %).

The fit of males of each dataset is presented in Table 7. Following the trend of females in Table 6, Dataset A shows an overall better fit for all panels. The highest level of match was observed in the NIOSH/ISO Bivariate panel, with 227 subjects (92.7 %), and in the PCA panel, with 227 subjects (92.7 %) fitting within the respective cell categories. LANL panels for half- and full-piece masks reported matches of 196 subjects (80.0 %) and 179 subjects (73.0 %), respectively. Dataset B, in turn, shows the highest match for the NIOSH/ISO Bivariate panel, with 833

**Table 6**  
Distribution of female participants from Datasets A and B across the LANL and NIOSH/ISO fit panels.

Cell	LANL								NIOSH/ISO							
	Half-piece mask				Full-piece mask				Bivariate				PCA			
	Dataset A		Dataset B		Dataset A		Dataset B		Dataset A		Dataset B		Dataset A		Dataset B	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
1	0	(0)	0	(0)	0	(0)	0	(0)	9	(3.9)	11	(1.0)	85 <sup>a</sup>	(37.1) <sup>a</sup>	19	(1.8)
2	2	(0.8)	1	(0.1)	3	(1.3)	1	(0.1)	3	(1.3)	11	(1.0)	63	(27.5)	57	(5.4)
3	0	(0)	3	(0.3)	9	(3.9)	26	(2.5)	70 <sup>a</sup>	(30.1) <sup>a</sup>	159	(15.0)	6	(2.6)	45	(4.3)
4	35	(15.3)	104	(9.8)	42	(18.3)	60	(5.7)	61	(26.6)	190	(18.0)	17	(7.4)	70	(6.6)
5	22	(9.6)	41	(3.8)	9	(3.9)	55	(5.2)	1	(0.4)	31	(2.9)	27	(11.8)	150	(14.2)
6	1	(0.4)	14	(1.3)	73 <sup>a</sup>	(31.9) <sup>a</sup>	227 <sup>a</sup>	(21.5) <sup>a</sup>	43	(18.8)	229 <sup>a</sup>	(21.7) <sup>a</sup>	24	(10.5)	168	(15.9)
7	57	(24.9)	425 <sup>a</sup>	(40.2) <sup>a</sup>	47	(20.5)	224	(21.2)	36	(15.7)	279	(26.4)	4	(1.7)	203	(19.2)
8	58 <sup>a</sup>	(25.4) <sup>a</sup>	168	(15.9)	1	(0.4)	71	(6.7)	0	(0)	55	(5.2)	0	(0)	284 <sup>a</sup>	(26.9) <sup>a</sup>
9	11	(4.8)	180	(17.0)	12	(5.2)	110	(10.4)	2	(2.6)	36	(3.4)	N/A	N/A	N/A	N/A
10	36	(15.7)	94	(8.9)	0	(0)	44	(4.2)	0	(0)	13	(1.2)	N/A	N/A	N/A	N/A
Match	222	(96.9)	1030	(97.5)	196	(85.6)	818	(77.4)	225	(98.2)	1014	(95.9)	226	(98.6)	996	(94.2)
Mismatch	7	(3.1)	27	(2.5)	33	(14.4)	239	(22.6)	4	(1.8)	43	(4.1)	3	(1.4)	61	(5.8)

Values represent the number of individuals (N) and corresponding percentage (%) of the total female sample assigned to each cell of the panel.

<sup>a</sup> Cells with the highest match.

**Table 7**  
Distribution of male participants from Datasets A and B across the LANL and NIOSH/ISO fit panels.

Cell	LANL								NIOSH/ISO							
	Half-piece mask				Full-piece mask				Bivariate				PCA			
	Dataset A		Dataset B		Dataset A		Dataset B		Dataset A		Dataset B		Dataset A		Dataset B	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
1	0	(0)	0	(0)	0	(0)	0	(0)	0	(0)	0	(0)	2	(0.8)	1	(0.1)
2	0	(0)	0	(0)	0	(0)	0	(0)	0	(0)	1	(0.1)	10	(4.1)	1	(0.1)
3	0	(0)	0	(0)	0	(0)	2	(0.2)	2	(0.8)	12	(1.3)	1	(0.4)	1	(0.1)
4	2	(0.8)	8	(0.8)	2	(0.8)	3	(0.3)	11	(4.5)	25	(2.6)	13	(5.3)	7	(0.7)
5	9	(3.7)	4	(0.4)	3	(1.2)	2	(0.2)	4	(1.6)	16	(1.7)	51	(20.8)	15	(1.6)
6	0	(0)	1	(0.1)	11	(4.5)	31	(3.2)	22	(9)	138	(14.4)	88 <sup>a</sup>	(35.9) <sup>a</sup>	63	(6.6)
7	8	(3.3)	75	(7.8)	29	(11.8)	77	(8.0)	83 <sup>a</sup>	(33.9) <sup>a</sup>	199	(20.8)	45	(18.4)	29	(3.0)
8	66	(26.8)	96	(10.0)	19	(7.8)	46	(4.8)	32	(13.1)	90	(9.4)	17	(6.9)	296 <sup>a</sup>	(30.9) <sup>a</sup>
9	31	(12.7)	209	(21.8)	67 <sup>a</sup>	(27.3) <sup>a</sup>	226 <sup>a</sup>	(23.67) <sup>a</sup>	51	(20.8)	239 <sup>a</sup>	(24.9) <sup>a</sup>	N/A	N/A	N/A	N/A
10	80 <sup>a</sup>	(32.7) <sup>a</sup>	294 <sup>a</sup>	(30.7) <sup>a</sup>	48	(19.6)	158	(16.5)	22	(9)	113	(11.7)	N/A	N/A	N/A	N/A
Match	196	(80.0)	687	(71.6)	179	(73.1)	545	(56.8)	227	(92.7)	833	(86.9)	227	(92.7)	413	(43.1)
Mismatch	49	(20.00)	272	(28.4)	66	(26.9)	414	(43.2)	18	(7.3)	126	(13.1)	18	(7.3)	546	(56.9)

Values represent the number of individuals (N) and corresponding percentage (%) of the total female sample assigned to each cell of the panel.

<sup>a</sup> Cells with the highest match.

subjects (86.9 %), followed by the LANL half-mask panel, with 687 subjects (71.6 %). The LANL full-piece mask panel showed a match of 545 subjects (56.8 %), while the PCA panel had the lowest performance, with only 413 subjects (43.1 %) of the male population fitting within the panel configuration.

On a closer look at each panel, all males tend to fit in the cells associated with larger sizes. For example, both Dataset A and B reported the highest number of subjects on cell 10 of the half-piece panel, with 80 subjects (32.7 %) for Dataset A and 294 subjects (30.7 %) for Dataset B. Similarly, cell 9 of the full-piece panel had the highest concentration of subjects, with 67 subjects (27.3 %) for Dataset A and 226 subjects (23.6 %) for Dataset B. For the NIOSH/ISO panels, the highest number of subjects in the bivariate panel were found in cell 7 for Dataset A, with 83 subjects (33.9 %), and in cell 9 for Dataset B, with 239 subjects (24.9 %). Regarding the PCA panel, the greatest number of subjects were located in cell 6 for Dataset A, with 88 subjects (35.9 %), and in cell 8 for Dataset B, with 296 subjects (30.9 %).

### 3.3. Gender and temporal fit trends

Further analysis of the data revealed consistent gender-based differences in fit performance and a temporal shift toward larger facial dimensions, particularly among males.

Figs. 3–6 present the distribution of male and female participants from Dataset A and Dataset B across four respirator fit test panels: LANL half-facepiece (Fig. 3), LANL full-facepiece (Fig. 4), NIOSH/ISO bivariate (Fig. 5), and NIOSH/ISO PCA panel (Fig. 6). These visualizations display the classification of individuals into cell categories based on key facial measurements, with women shown on the left and men on the right in each figure.

The figures reveal important temporal and gender-related shifts in the distribution of the population across panel cells. Figs. 3 and 4 show a concentration of subjects in upper-right cells for the LANL panels, which are associated with larger face dimensions, especially in Dataset B. This suggests a morphological shift toward larger facial structures in the more recent sample.

Figs. 5 and 6, corresponding to the NIOSH/ISO panels, demonstrate a more even distribution across the cells, indicating greater adaptability to facial diversity. In Fig. 5 (bivariate panel), both datasets show clustering around mid-to-larger face dimensions, though Dataset B tends to occupy higher-numbered cells more frequently, especially among males. Fig. 6 (PCA panel) emphasizes this trend more clearly: subjects from Dataset B, particularly men, are noticeably displaced toward cells associated with higher values in Principal Component 1 (PC1), which reflects overall facial size.

These graphical comparisons support the statistical findings,

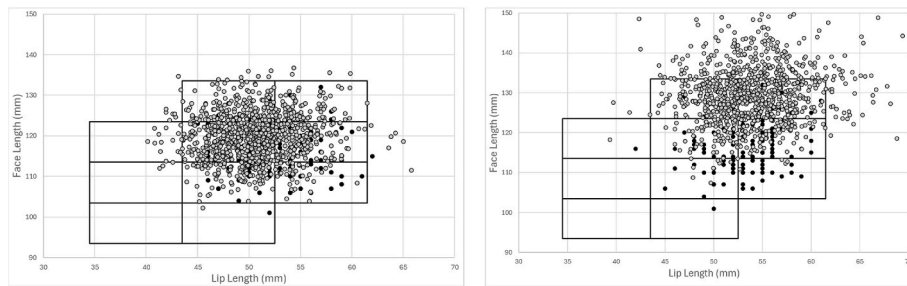


Fig. 3. Distribution of female (left) and male (right) participants from Datasets A and B in the LANL half-piece mask panel. Dataset A is represented in (●), and Dataset B in (○).

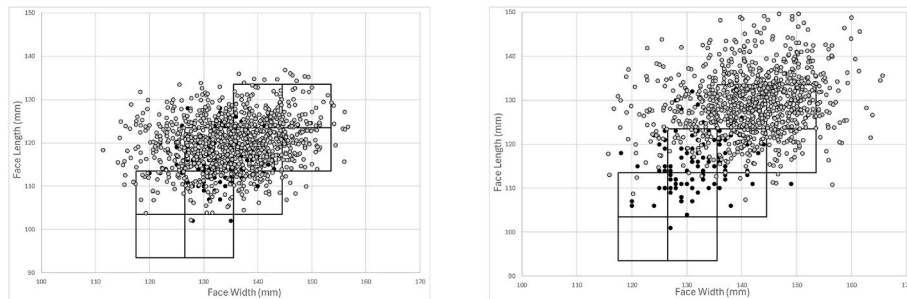


Fig. 4. Distribution of female (left) and male (right) participants from Datasets A and B in the LANL Full-piece mask panel. Dataset A is represented in (●), and Dataset B in (○).

indicating that facial dimensions have changed over the past decade, particularly among male workers, and that current respirator fit panels, especially those based on LANL, may no longer adequately represent the facial profiles of the Chilean workforce.

#### 4. Discussion

##### 4.1. Temporal anthropometric changes

The findings from this study demonstrate significant differences between the two datasets (A and B) across most facial anthropometric

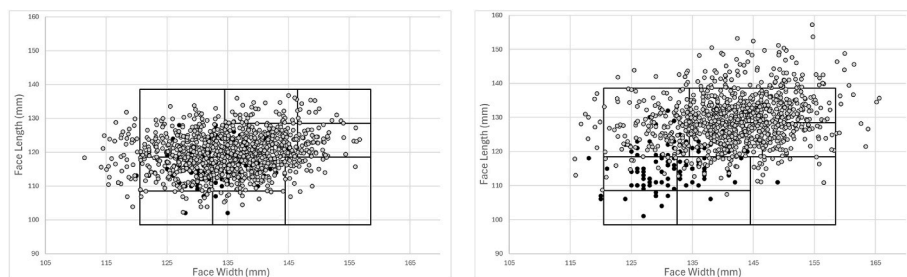


Fig. 5. Distribution of female (left) and male (right) participants from Datasets A and B in the NIOSH/ISO Bivariate panel. Dataset A is represented in (●), and Dataset B in (○).

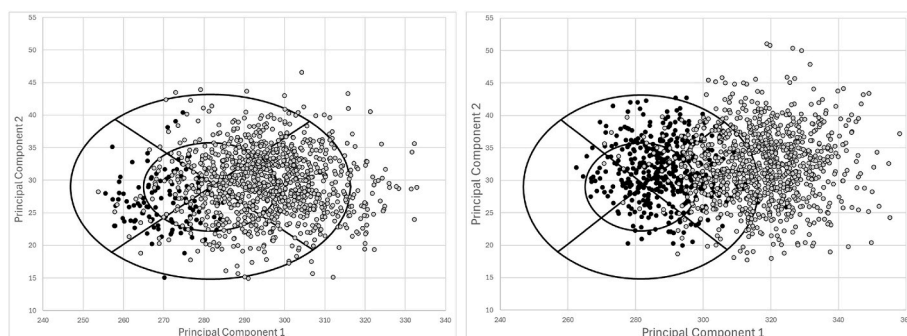


Fig. 6. Distribution of female (left) and male (right) participants from Datasets A and B in the NIOSH/ISO PCA panel. Dataset A is represented in (●), and Dataset B in (○).

dimensions (Tables 4 and 5), which could be attributed to the secular changes in Chilean population dimensions as noted by Castellucci et al. (2021). This trend aligns with previous research showing anthropometric variations over time in different populations (Viviani et al., 2020). Additionally, the composition of the two datasets allows us to establish a baseline proxy for demographic changes in the Chilean working population. Dataset A included only Chilean-born individuals, who were, at the time of collection, considered to be relatively genetically homogeneous (Chilegenomico, 2015), while Dataset B includes nearly 10 % immigrant participants, reflecting the more diverse demographic and ethnic makeup of the current workforce (Instituto Nacional de Estadísticas de Chile (INE), 2023).

#### 4.2. Fit panel performance across datasets

The analysis of respirator fit panels revealed varying levels of match between the Chilean female workers' facial dimensions and established standards (Table 6). For Dataset A, the LANL half-piece mask panel showed the highest match (98.6 %), followed by both NIOSH/ISO Bivariate panel (98.2 %). However, Dataset B demonstrated lower match percentages overall, with the LANL half-piece mask panel showing a 97.5 % match, followed by NIOSH/ISO Bivariate (95.9 %) and PCA panels (91.49 %). These findings are comparable to previous studies, such as Yang et al. (2007), who reported similar mismatch patterns in their analysis of Asian populations. These findings suggest that current respirator designs based on LANL panels may not provide adequate protection for a significant portion of the female Chilean workforce, particularly for more recent users (Dataset B).

The LANL full-piece mask panel demonstrated the lowest match rates for both datasets (85.6 % for Dataset A and 77.4 % for Dataset B) (Fig. 4), suggesting potential limitations in its applicability to the Chilean female population. This finding is consistent with Zhuang et al. (2007), who noted that LANL panels might not adequately represent diverse populations outside the original US military population used in their development. The declining match rates between Dataset A and B suggest that the mismatch problem is becoming more acute over time, potentially compromising worker safety if not addressed.

Despite the clear differences in dimensions between the women from samples A and B, this was not reflected in the fit adequacy levels of the different panels (Table 6). However, when analyzed by cell distribution, the impact of these differences becomes evident. In the case of the NIOSH/ISO bivariate panel, in cells 6 to 10, which represent the largest face length and width, 37.1 % of sample A is distributed, significantly less than the 57.9 % of sample B (Table 6 and Fig. 5). This is even more evident in the PCA panel, where all 10 dimensions are considered, and it is possible to observe that the highest percentage of female from sample A is distributed in cell 1, in contrast to the highest distribution in cell 8 for sample B. (Table 6 and Fig. 6). This clustering effect has important implications for respirator design specifications, suggesting that current sizing systems may need to be adjusted to better accommodate these demographic changes. These adjustments may include modifying the distribution and scaling of facial dimensions used in size grading, incorporating sex-specific design features, and accounting for emerging population subgroups such as immigrants, who may not be well represented in existing standards.

Interestingly, despite the general increase in most facial dimensions, lip length significantly decreased in the more recent female cohort (Dataset B). Given that lip length is a key axis in the LANL half-facepiece panel, this reduction may contribute to the observed shift in cell distributions, particularly toward cells representing shorter horizontal facial dimensions (Table 6 and Fig. 3). This finding highlights the importance of monitoring not only overall facial growth trends but also isolated dimensional changes that may disproportionately affect respirator fit, especially in panels that rely on specific measurements such as lip length.

#### 4.3. Gender differences in panel fit

When considering the males from samples A and B, it is important to note that they follow the same trend observed in female participants, as shown in Table 7. However, a significant difference was observed in the PCA panel (Fig. 6), largely due to Principal Component 1 (PC1), which is strongly influenced by three key facial dimensions: head breadth, face width, and bigonial breadth. While Principal Component Analysis (PCA) has been successfully applied in previous studies to explain over 90 % of head-and-face shape variability among U.S. civilian workers (Zhuang et al., 2013), the PCA panel in our study showed limited applicability for the male Chilean workforce. Specifically, only 43.07 % of men from Dataset B were classified within the panel's defined range.

This mismatch may reflect morphological differences not captured by the original PCA configuration. Notably, the bigonial breadth and head breadth of male participants in Dataset B were 17.4 mm and 23.2 mm larger, respectively, than those used in the development of the original fit panels (Zhuang and Bradtmiller, 2005). These two dimensions are major contributors to PC1, and their substantial increase helps explain the rightward shift of Dataset B males in Fig. 6. While both female and male workers exhibited a general shift toward larger facial dimensions over time, the reduction in panel match rates was more pronounced among males, particularly in the PCA panel. This finding reinforces the need to recalibrate PCA-based fit panels using updated, region-specific anthropometric data to ensure adequate protection for diverse worker populations.

Gender differences were notable in both datasets. Female subjects generally showed better-fit percentages across all panels compared to males, particularly in Dataset A. Lin and Chen (2017) documented significant sex-based differences in facial anthropometry among Taiwanese respirator users, which may contribute to variability in respirator fit. Although their study did not include fit testing, their findings support the need to consider sex-specific facial characteristics when designing fit test panels. The lower fit percentages for males, especially in Dataset B, indicate a critical need for manufacturers to reassess sizing strategies to improve fit and protection for the male Chilean workforce.

#### 4.4. Design and policy implications

For PPE selection in occupational settings, our findings indicate that respirators designed using NIOSH/ISO panels would be more appropriate for the Chilean workforce than those based on LANL panels. However, the decreasing match percentages in Dataset B suggest that even NIOSH/ISO-based designs may need updating to maintain their effectiveness for the current Chilean population.

The main contribution of this study lies in providing updated, large-scale facial anthropometric data for a Chilean working population using high-precision 3D scanning methods. This is one of the first studies to compare temporal anthropometric changes across a decade in Chilean workers and to assess the applicability of multiple international respirator fit test panels. The findings have direct implications for the design and selection of respiratory protective equipment in Chile and similar contexts where imported PPE is not necessarily suited to local populations. By identifying panel mismatch patterns and highlighting gender-specific fit issues, this research supports the development of locally adapted or region-specific fit panels. Furthermore, it contributes to the global discourse on updating international standards to reflect ongoing demographic and morphological changes. The methodology applied in this research can serve as a model for similar assessments in other countries that lack their own anthropometric databases for PPE design.

Nemeth et al. (2025) demonstrated the value of geometric morphometric analyses, which are statistical shape analyses based on landmark configurations from 3D meshes, for representing facial diversity across populations in the context of pediatric respirator design. Their findings showed that ancestry accounts for a significant proportion of facial

shape variance in children, particularly in features such as nasal projection and jaw protrusion that are critical for respirator fit. While the study focused on pediatric populations, the same principle applies to adult users: overlooking shape variability, beyond linear size, may compromise fit quality and perpetuate inequities in protection. This reinforces the importance of incorporating regionally relevant and demographically inclusive facial data into fit panel design. Recent studies on pediatric respirator design have demonstrated the value of geometric morphometric analyses using 3D meshes to represent facial diversity across populations.

#### 4.5. Organizational and contextual barriers to PPE effectiveness

Additionally, previous research highlights that although PPE has been developed to accommodate diverse facial and body dimensions, its effective use may be hindered by external barriers such as supply chain issues, insufficient product promotion, and restrictive organizational procurement policies that limit workers' access to appropriately sized PPE (Flynn et al., 2017). These factors might partly explain the mismatch issues identified in our study regarding the fit of international respirator panels to the Chilean workforce, suggesting that even available respirators might not effectively reach end-users due to operational and administrative challenges.

Recent research highlights that healthcare workers' psychological distress during high-demand scenarios, such as the COVID-19 pandemic, can be exacerbated by several organizational and interpersonal factors, including prolonged use of PPE, fear of infecting relatives, and perceived insufficient protection provided by PPE (Arias-ulloa et al., 2023). These findings underscore the importance of addressing not only the anthropometric fit of respirators but also broader psychological and organizational aspects to ensure the comprehensive safety and wellbeing of healthcare workers.

#### 4.6. Limitations and future research

A notable limitation of this study is the temporal gap between Dataset A and Dataset B collections, which involved a methodological change in measurement techniques (manual versus 3D scanning) that may affect comparability between the two datasets. Our findings align with previous research demonstrating both the advantages and limitations of 3D scanning compared to manual anthropometry. As highlighted by Joe et al. (2012), 3D scanning eliminates soft tissue compression errors inherent in manual measurements while providing more comprehensive facial data. However, its accuracy can be influenced by factors such as scanner resolution, landmark identification, and post-processing algorithms (YU et al., 2021). Hobbs-Murphy et al. (2024) showed that digital landmarking protocols can yield good to excellent reliability, and in our study, the use of physical markers further improved consistency. Although high-end scanners achieve sub-millimeter precision, lower-cost systems may introduce greater dimensional error, particularly in peripheral facial areas (Shan et al., 2021; YU et al., 2021). These considerations underscore the need for standardized protocols in future research. Despite this limitation, the dataset comparison provides valuable insights into secular changes in facial morphology, supporting previous findings on anthropometric trends in the Chilean workforce (Castellucci et al., 2021).

Although we acknowledge the possibility that differences between Dataset A and B may partly result from the change in measurement methodology, we believe that the observed secular trends are not fully attributable to methodological artifacts. First, the manual measurement team in Dataset A was trained under strict protocols and consistently applied standardized procedures using calibrated instruments, minimizing intra- and inter-observer error. Second, the differences between datasets are not uniform across all dimensions; for example, lip length decreased in Dataset B, which would not be expected under a systematic overestimation bias from manual measurements. Third, similar secular

increases in body dimensions have been documented in other Chilean studies (Castellucci et al., 2021), lending support to the hypothesis that genuine morphological changes are occurring. While a degree of methodological bias cannot be entirely ruled out, the pattern and directionality of the changes suggest a real anthropometric shift rather than a simple measurement artifact.

In addition, the cross-sectional nature of both datasets limits the ability to draw causal inferences and prevents the observation of changes at the individual level over time. The absence of complementary contextual variables related to work environments and task characteristics may also restrict the interpretation of some findings. Despite these limitations, this research provides valuable insights, as it represents one of the few large-scale facial anthropometry studies conducted in Latin America. In developing countries like Chile, logistical, geographic, and funding constraints often hinder the implementation of comprehensive ergonomic data collection efforts. For this reason, the successful execution of this study, with a large and diverse sample using advanced 3D scanning technology, constitutes a significant contribution to the regional evidence base for respirator design and fit panel adaptation. In developing countries like Chile, logistical, geographic, and funding constraints often hinder the implementation of comprehensive ergonomic data collection efforts. With a territory spanning nearly 4000 km from north to south, these challenges are amplified by geographical dispersion and access limitations. As a result, the sample may have been disproportionately drawn from large urban centers, where access is logistically simpler and where immigration is also more concentrated. This may have introduced a sampling bias that overrepresents facial morphologies influenced by recent demographic changes, particularly among foreign-born or second-generation participants. Future studies should aim to include more geographically diverse populations to ensure that national fit panels reflect the full range of regional anthropometric variation.

To address these limitations, future studies should aim to standardize measurement protocols by applying consistent 3D scanning methodologies across all data collection phases. Longitudinal designs would allow researchers to track individual-level changes over time and strengthen the evidence on temporal anthropometric trends. It would also be valuable to incorporate more detailed occupational datasets and exposure histories to better understand the factors driving changes in facial morphology. Finally, the mismatch patterns observed in this study, particularly among male workers, highlight the need to develop and validate updated respirator fit test panels based on recent data. These panels should reflect current population characteristics and ensure improved fit and protection across different segments of the workforce.

Given that many countries are experiencing demographic shifts due to increased immigration, it is plausible that similar secular changes in facial anthropometry could be occurring elsewhere. Populations in Latin America, Europe, and parts of Asia with growing ethnic diversity may face challenges related to respirator fit if protective equipment is not adapted to their evolving morphological profiles. In this context, the methodology presented in our study offers a transferable and scalable framework that can be applied in other regions to support the development of locally appropriate respirator fit panels and improve occupational health protection standards globally.

## 5. Conclusion

This study identifies secular changes in worker facial morphology with direct ergonomic implications for the design and selection of respiratory protection systems. The findings strongly indicate that respirators designed using NIOSH/ISO bivariate panels should be preferred over LANL specifications, though special attention must be paid to fit-testing for male workers who showed lower match rates in recent measurements. For manufacturers, these results suggest the need for modified size distributions that better reflect the observed PCA clustering patterns, potentially requiring gender-specific design approaches

and consideration of secular changes in facial dimensions.

Furthermore, regulatory bodies and standards organizations should consider implementing regular updates to anthropometric databases and fit test panels, while developing specific guidelines for the Chilean market that account for the observed characteristics. The study emphasizes that current international standards may not adequately serve the Chilean working population, particularly in industries requiring full-face respirators.

The declining match rates observed between Dataset A and Dataset B underscore that the mismatch issue is becoming more acute over time. If not addressed, this growing disconnect could undermine the effectiveness of respiratory protection programs and jeopardize worker safety.

Future research should focus on developing region-specific sizing systems that can better accommodate the facial characteristics of the Chilean workforce while maintaining the required protection factors for workplace safety.

### CRediT authorship contribution statement

**Edgardo C. Silva:** Writing – original draft, Visualization, Formal analysis, Data curation. **Héctor Ignacio Castellucci:** Funding acquisition, Formal analysis, Conceptualization, Writing – original draft, Project administration, Methodology. **Roberto Camberes:** Investigation. **Josefina Lira:** Investigation. **Jaime Marabolí:** Investigation. **Carlos Viviani:** Writing – original draft, Project administration, Methodology, Conceptualization. **Johan F.M. Molenbroek:** Writing – review & editing, Methodology, Conceptualization. **Toon Huysmans:** Writing – review & editing, Formal analysis, Validation, Software, Methodology. **Ariel Rodríguez:** Visualization, Funding acquisition, Investigation. **Luis Alberto Caroca:** Investigation, Resources, Funding acquisition. **Jaime Ibacache:** Resources, Funding acquisition, Conceptualization.

### Declaration of competing interest

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

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