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Cross-country comparisons and insights for PPE design

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3D facial anthropometry of Chilean workers and migrants: Cross-country comparisons and insights for PPE design

Edgardo C. Silva [a], Héctor Ignacio Castellucci [a,*], Roberto Camberes [a], Josefina Lira [a], Jaime Marabolí [a], Carlos Viviani [b], Johan F.M. Molenbroek [c], Toon Huysmans [c], Ariel Rodríguez [d], Luis Alberto Caroca [e], Jaime Ibacache [e]

[a] Centro de Estudio del Trabajo y Factores Humanos, Escuela de Kinesiología, Facultad de Medicina, Universidad de Valparaíso. Viña del Mar, Chile
[b] Facultad de Ciencias, Pontificia Universidad Católica de Valparaíso, Escuela de Kinesiología. Valparaíso, Chile
[c] Faculty of Industrial Design Engineering Section Applied Ergonomics and Design, Delft University of Technology. Delft, the Netherlands
[d] Sección Elementos Protección Personal, Departamento Salud Ocupacional, Instituto de Salud Pública de Chile. Santiago, Chile
[e] Sección Ergonomía, Departamento Salud Ocupacional, Instituto de Salud Pública de Chile. Santiago, Chile

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ABSTRACT

This study aimed to collect and analyze three-dimensional (3D) anthropometric data of Chilean workers to support the design of personal protective equipment (PPE) tailored to their physical characteristics. A total of 2016 participants, including Chileans and migrant workers, were measured using advanced 3D scanning technology. Significant sex-based and nationality-related differences were identified, with males exhibiting larger dimensions across most measurements. Comparisons with international datasets, including CAESAR, revealed unique anthropometric features among Chilean workers, highlighting substantial deviations in head and facial dimensions. These findings underscore the need for sex-specific and population-specific PPE designs, particularly given Chile's increasing workforce diversity. The results have practical implications for improving PPE fit, comfort, and safety in the workplace. This study provides a robust 3D anthropometric database that serves as a critical resource for manufacturers and safety professionals aiming to enhance occupational safety and equipment performance.

1. Introduction

Anthropometrics is a critical branch of human sciences dedicated to enhancing product comfort, optimal fit, and usability through comprehensive human body measurements. As Nadadur and Parkinson (2013) explained, this field analyzes size, weight, and proportions to provide essential insights for designing products and workplace environments across various sectors, including industrial settings, hand tool development, vehicle design, and personal protective equipment (PPE).

PPE represents the final line of defense for workers in high-risk environments such as mining, heavy industry, and hazardous material handling. Safety equipment like helmets, face protectors, and respiratory protective equipment (RPE) are designed to shield workers from a variety of workplace hazards. Hsiao (2013) and Hsiao et al. (2014) highlighted that the effectiveness of such equipment critically depends on its anthropometric compatibility with the user.

A significant challenge in PPE design is addressing the anthropometric mismatch, where equipment dimensions do not adequately correspond to the user's physical characteristics. Castellucci et al. (2016) noted that this mismatch can potentially reduce protective capabilities or create a false sense of security, potentially increasing workplace risks.

The present study is particularly significant in the context of Chile's recent substantial migration influx, which has potentially altered the anthropometric characteristics of the working population (Rodríguez et al., 2022). This demographic shift introduces additional complexity to understanding the physical dimensions of workers and the design of protective equipment.

Traditionally, anthropometric measurements relied on manual methods using tools like anthropometers, calipers, and measuring tapes. Beaumont et al. (2017) and Bravo et al. (2018) pointed out significant limitations in these approaches, including measurement variability,

* Corresponding author.
E-mail address: ignacio.castellucci@uv.cl (H.I. Castellucci).

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potential human error, and challenges in capturing complex body geometries.

Contemporary research has increasingly shifted towards advanced three-dimensional scanning technologies. Lee et al. (2018) demonstrated that 3D anthropometry enables precise measurement of complex body dimensions, including curves, surface shapes, areas, and volumes. This technological advancement facilitates more objective and comprehensive body measurement, particularly in specialized domains like garment design and craniofacial morphology studies.

The significance of 3D anthropometry extends beyond measurement precision. Shah and Luximon (2017) highlighted its importance in providing critical insights into anatomical variations across different ethnic groups and geographical locations. Robinette et al. (2002) and Yang et al. (2007) demonstrated the crucial role of considering sex and ethnic differences in personal protective equipment design.

In the Chilean context, the manufacturing sector represents a small portion of the national economy, with most machinery and equipment being manufactured overseas. According to ISP (2020) approximately 66 % of respirators in the national market are certified by NIOSH (United States), with the remaining 34.4 % certified by other international entities. This international sourcing underscores the necessity of regional anthropometric studies to ensure appropriate equipment fit and effectiveness.

Rodríguez et al. (2020) conducted a comprehensive survey based solely on manual anthropometric measurements. Their findings revealed considerable variability in respirator size compatibility depending on the reference standards applied, underscoring the dynamic nature of population anthropometric characteristics.

The continuous evolution of workforce demographics, technological advancements, and migration patterns necessitates ongoing anthropometric research. By understanding the physical characteristics of specific populations, researchers and designers can develop more ergonomically accurate, safer, and more comfortable products that protect and support workers across various industries.

Considering the previous information, the goal of the current study was to collect and describe three-dimensional anthropometric dimensions of the head and face of Chilean workers to support the improvement of products used by this population and thus help prevent health and safety issues. Additionally, our results were compared against four other similar databases in a cross-country comparison, using consistent measurement procedures.

2. Methods

2.1. Sample

The target sample was Chilean workers, but open to workers of any nationality in Chile, who were users or potentially users of personal protective equipment (PPE) and respiratory protective equipment (RPE), men and women.

The sample size was calculated following the principles of ISO 15535: 2012 (2012), which has been widely used by authors regarding RPE (Du et al., 2008; Lee et al., 2013; Zhuang and Bradtmiller, 2005), and in anthropometrics in general (Castellucci et al., 2016; Syuaib, 2015). This study used stratified sampling to reliably use the 5th and the 95th percentiles, where the strata were determined by two factors: sex (2: female and male), and age range (3: 18–35, 36–53, 54–85 years old). It is worth noting that the third age group is above the theoretical age for retirement (65 in males, 60 in females), this was because Chile has the third-highest effective retirement age among countries in the Organization for Economic Co-operation and Development (OECD), with 67.7- and 71.3 years for women and men, respectively (OECD, 2017). Thus, the minimum number of randomly sampled subjects, N (Eq. (1)), needed to ensure that the database's 5th and 95th percentiles represented the true population's 5th and 95th percentiles with 95 % confidence (1.96). Furthermore, the sampling technique considered the desired percentage of relative accuracy (α) and the highest Coefficient of Variation (CV), which in this type of study considers the CV of the Menton-sellion length (face length).

$$N = \left(\frac{1.96 \times CV}{\alpha}\right)^2 \times 1.534^2 \qquad \text{Equation 1}$$

The CV using in this study was 5.3 (Zhuang and Bradtmiller, 2005), Also, the α (desired percentage of relative accuracy) was set to 1 %. Finally, after applying equation (2), the total sample size for each cluster was 254 workers (Table 1)

$$N = \left(\frac{1.96 \times 5.3}{1}\right)^2 \times 1.534^2 = 254 \qquad \text{Equation 2}$$

The final sample comprised 2016 participants, including 1057 females and 959 males (see Table 1). To comprehensively measure the anthropometric dimensions of the workforce in Chile, individuals of other nationalities were also invited to participate, as detailed in Table 2.

2.2. Data collection

The data collection process was approved by the Ethics Committee of Mutual de Seguridad of the Chilean Chamber of Construction on April 5, 2022. Written consent was obtained from the workers before the three-dimensional data were captured. Data were collected between November 2023 and March 2024 in Santiago, Chile.

Prior to three-dimensional data collection, height, weight, neck perimeter, and head circumference were manually measured for each subject following ISO 16976-2 (2015), and subjects were asked to answer a short survey regarding their age and nationality. While some literature has questioned the direct relevance of traditional anthropometric measurements to certain aspects of PPE design (Oestenstad and Perkins, 1992; Yu et al., 2024), particularly respirator fit, our methodology addresses these concerns in several ways. First, the ISO 16976-2 (2015) standard we followed was developed for respiratory protective devices, establishing the anthropometric measurements most relevant to PPE design. Second, our use of advanced 3D scanning technology allows for more precise capture of facial contours and surface geometries that are critical for respirators sealing surfaces. Bannister et al. (2020) demonstrated how 3D facial scanning enables more accurate landmarking and measurement of facial morphology relevant to product design. Third, the 15 anthropometric dimensions we calculated include key measurements (face length, face width, nose breadth, and inter-landmark distances) that have been demonstrated in the literature to influence respirator fit and comfort (Zhuang et al., 2010; Kim et al., 2003). Roberge et al. (2010) specifically investigated how facial dimensions affect the physiological impact of N95 respirators, confirming the relevance of these measurements to PPE design. By capturing these measurements through 3D scanning rather than traditional manual methods, we obtain more accurate representations of the complex surface geometries that interact with various types of PPE, particularly respirators, helmets, and eyewear.

The three-dimensional meshes were captured with participants seated in an upright posture on a height-adjustable chair positioned on a flat surface. All participants wore nylon wig caps to ensure accurate

Table 1
Estimated sample size and real sample size.

Age group	Estimated sample (1524)		Real sample (2016)	
	Female	Male	Female	Male
18–35	254	254	409	386
36–53	254	254	405	334
54–85	254	254	243	239
TOTAL	762	762	1057	959

Table 2
Sample.

Nationality	n	Female	Male	Age (mean)	Height (mean)	Weight (mean)
Argentina	4	2	2	34.96	1642.5	76.63
Bolivian	5	2	3	38.49	1666.0	76.6
Brazilian	1	1	0	21.45	1680.0	60.00
Chilean	1790	941	849	42.73	1639.5	79.89
Colombian	32	14	18	39.62	1657.8	80.60
Cuban	2	1	1	43.61	1715.0	79.75
Dominican	4	4	0	38.09	1652.5	84.38
Ecuadorian	9	4	5	39.60	1625.0	69.91
Haitian	3	1	2	37.21	1600.0	70.70
Nicaraguan	1	0	1	31.24	1685.5	76.75
Mexican	2	0	2	39.23	1585.0	69.60
Peruvian	45	24	21	41.75	1605.0	76.80
Venezuelan	118	63	55	37.91	1652.8	79.28
Other[a]	226	116	110	36.93	1642.9	78.33

[a] Consider nationalities other than Chilean.

capture of the scalp surface. For those with long hair, it was gathered into a bun positioned at the top-back of the head to maintain consistency in the procedure. They were instructed to maintain the Frankfurt plane, keep their mouths closed, and look straight ahead. Participants wore shoes and regular clothing during the process. To ease the calculations for virtual measurements on the 3D objects, 24 facial landmarks were marked manually on all subjects using a set of adhesive labels. These set of landmarks are generally, although not always, skeletal points that are usually marked on the skin overlying the point, thus easily to locate after the proper training (ISO, 2015).

Three-dimensional measurements were recorded using a 3D face scanner (3dMD®), which is composed of four modular units of three machine vision cameras each, two of them for depth estimation, and one for color registration plus one speckle pattern projector, an industrial-grade flash system synchronized in a single capture, generating a continuous three-dimensional polygon surface mesh from all synchronized stereo modular units. The 3DMDface system (3dMD®) was used in this study because it is well-known for its high accuracy. According to Hong et al. (2017), the system has a geometry accuracy of 0.2 mm root mean square (RMS), which ensures precise scanning results. Before each session of data collection, the modular camera system was calibrated using the calibration tool provided by the manufacturer.

2.3. Measurements calculations

To determine the desired anthropometric measures, one of the researchers was responsible for the virtual pinpointing the landmark locations on the 3D mesh based on the physical landmarking of each subject, following the adhesive labels manually marked, adding 4 more virtual landmarks (marker 25 to marker 28) to a total of 28 virtual landmarks (Fig. 1).

Once the three-dimensional data were captured, the head of each subject was post-processed using FaceForm Wrap (Faceform LLC, 2024) which allowed the use of a reference template to fill in any missing data in the three-dimensional point mesh, orient the object, and reduce the amount of unnecessary data, such as clothing, accessories, and hair, presented in the subjects' head. Afterward, a resampling technique was utilized to normalize the distance between each vertex of the 3D points, this was done to prepare the mesh data for further 3D processing such as statistical shape modeling, effectively requiring a uniform distribution of points across the surface.

In addition to the accuracy of the scanning process, we also evaluated the accuracy of the post-processing steps, including the digital pinpointing of landmarks. To do this, we repeated the entire post-processing procedure several times using the same scan and measured the variation in the results. The variation between these repeated measurements was 1.3 mm, demonstrating that the post-processing steps are consistent and reliable.

Finally, once the surface of the target volunteer subject is normalized, 15 anthropometric dimensions were calculated following ISO 16976-2 (2015), reported in Table 3. Calculations were based on vector mathematics. (See Fig. 2).

2.4. Other databases for comparison

For the purpose of this study, a comparison dataset was established based on the CAESAR database from Robinette et al. (2002), which includes subjects from the United States (US), the Netherlands (NL), and Italy (IT). The dataset comprises 408 Italian males, 497 Dutch males, and 1122 US males, alongside 384 Italian females, 606 Dutch females, and 1262 US females. The dataset utilized the 3D A-pose body scans from the CAESAR database, supplemented by the locations of nine physically marked and digitized head and face landmarks: nuchale, left and right gonion, left and right tragion, left and right infraorbitale, supramenton, and sellion.

A uniformly sampled template mesh, equipped with the 28 landmarks from Fig. 1, was prepared. Correspondence between the template mesh and each subject in the CAESAR database was achieved through non-rigid deformation of the template to align with the geometry of each individual, with explicit enforcement of the matching of the nine head landmarks present in the CAESAR database. The registration process employed Wrap (Faceform LLC, n.d.). Subsequently, measurements for each subject were calculated based on the matched template and 28 corresponding landmark locations, following ISO 16976-2 guidelines. The same codebase was used to compute measurements for all subjects from The Netherlands, Italy, US, and Chile.

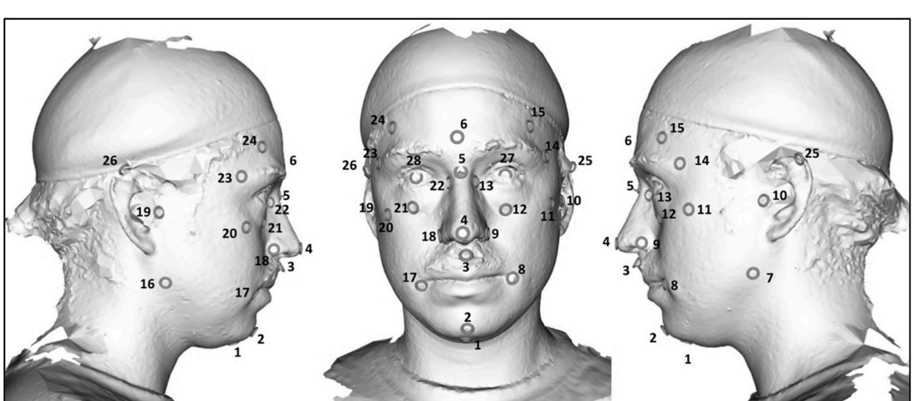

Fig. 1. Landmarks for anthropometric measurements.

Table 3
Measurements.

Dimension (mm)	Definition
Bigonial breadth	The straight-line distance between the gonion left and right landmarks is calculated as the norm (nonnegative number) of the difference between both gonion landmarks.
Bitragion chin arc	The surface distance between the right and left tragion landmarks across the anterior point of the chin, measured as the distance between tragion landmarks and menton landmark along a section of a curve (arc length).
Bitragion frontal arc	The surface distance between the right and left tragion landmarks across the forehead just above the ridges of the eyebrows (supraorbital ridges), calculated as the arc length from tragion landmarks and frontotemporal landmark.
Bitragion subnasale arc	The surface distance between the right and left tragion landmarks across the subnasale landmark at the bottom of the nose is calculated as the arc length from tragion landmarks and subnasale landmark.
Face length	The distance in the midsagittal plane between the menton landmark at the bottom of the chin and the sellion landmark at the deepest point of the nasal root depression. Measured as the norm of the difference between the sellion landmark and the menton landmark.
Face width	Maximum horizontal breadth of the face is measured as the norm difference between zygion landmarks from right to left.
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.
Maximum frontal breadth	The straight-line distance between the right and left zygofrontale landmarks at the upper margin of each bony eye socket. Calculated as the norm difference between the right and left zygofrontale landmarks.
Minimum frontal breadth	The straight-line distance between the right and left frontotemporal landmarks on the temporal crest on each side of the forehead is calculated as the norm difference between the right and left frontotemporal landmarks.
Nasal root breadth	The horizontal breadth of the nose at the level of the deepest depression in the root (sellion landmark) and at a depth equal to half the distance from the bridge of the nose to the eyes is measured as the distance between nasal root landmarks from right to left.
Nose breadth	Straight-line distance, calculated as the distance between the right and left alare landmarks.
Nose protrusion	The straight-line distance between the pronasale landmark at the tip of the nose and the subnasale landmark under the nose.
Subnasale-sellion length	Straight-line distance, calculated as the norm difference between the subnasale landmark and the sellion landmark.
Interpupillary distance	Straight-line distance calculated 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.

2.5. Statistical analysis

The distribution of all anthropometric data were evaluated through the Shapiro–Francia test given the sample size of the data. We compared the Chilean data by two categories: sex (Female – Male) and nationality (Chilean – other). Comparisons were made using the Wilcoxon rank-sum test given the non-normal distribution of data, and within-group comparisons for nationality by sex were performed as well using the same Wilcoxon rank-sum test. Additionally, an independent *t*-test was performed to compare the differences between the Chilean anthropometric data and data from the CAESAR, seventeen measurements were compared using this method of the available nineteen measurements presented in the other databases. All statistical calculations were made using STATA 18 statistical software (StataCorp, 2021).

3. Results

The collected sample size was 2016 workers (Female: 1057, Male: 959) belonging to different industrial sectors, of which 11.26 % were migrant workers in Chile. Results are presented first by sex differences and then nationality, all within the Chilean sample. Furthermore, results are presented to highlight the differences in measurements from Chilean data against CAESAR data. Subsequently, these results will be discussed in depth.

3.1. Measurements by sex

Table 4 presents the comparisons made by sex, where males have significantly bigger dimensions than females. Of the 15 three-dimensional anthropometric measurements calculated, the highest percentual differences were for nose breadth (9.5 %), bigonial breadth (9,2 %), head breadth (8.8 %), bitragion chin arc (8.2 %), and face length (7.4 %).

3.2. Measurements by nationality

As for workers in Chile from different nationalities, Table 5 shows the comparisons that were made between Chileans against other nationalities. It is noteworthy to mention that the highest foreign populations represented in the sample are Venezuelan (5.85 %), Peruvian (2.32 %), and Colombian (1.58 %).

Regarding the three-dimensional anthropometric measurements, significant differences were found for 7 of the 15 calculated measurements, with the highest percentual differences for nose breadth (4.5 %), nose protrusion (3.17 %), nasal root breadth (2.23 %), subnasale sellion length (1.87 %), and face length (1.26 %).

3.3. Comparisons against other databases

Chilean data were compared against data from CAESAR, from Italy, the Netherlands, and the US. If any anthropometric dimensions were not present in the given databases, it was coded with a dashed line and skipped from the analysis. Data are presented for males (Table 6) and females (Table 7).

When comparisons are made for males from Chilean data are made against the Italian population, all but two measurements, minimum frontal breadth and nasal root breadth, present statistically significant differences. All $p < 0.001$ except lip length ($p = 0{,}018$). The same can be said about comparisons against the Netherlands database, for which all but two measurements, lip length and neck perimeter, are statistically significantly different, with all p-values <0.001, apart from the head perimeter ($p = 0{,}001$). Finally, for the US database, all measurements are significantly different from the Chilean database, with all p-values <0.001, except for lip length ($p = 0.033$).

Comparing female Chilean data against Italian data, all measurements are statistically significantly different, (all $p < 0.001$). Meanwhile, when comparisons were made against the Netherlands female population, all but three measurements, lip length, neck perimeter, and nose protrusion, were statistically significantly different, with all $p < 0.001$ except for maximum frontal breadth ($p = 0.046$). Lastly, Chilean data against the US database shows that all measurements are statistically significantly different, except for Minimum frontal breadth, and all p-values are below 0.001, apart from head breadth ($p = 0.041$).

4. Discussion

4.1. Sexual dimorphism and basic anthropometric characteristics

Our three-dimensional anthropometric study of Chilean workers revealed significant insights into the population's facial characteristics and their implications for PPE design. The findings demonstrate clear sexual dimorphism across all measured dimensions, with male workers consistently showing larger measurements than their female counterparts. The most pronounced differences were observed in nose breadth (9.5 %), bigonial breadth (9.2 %), and head breadth (8.8 %). These sex-

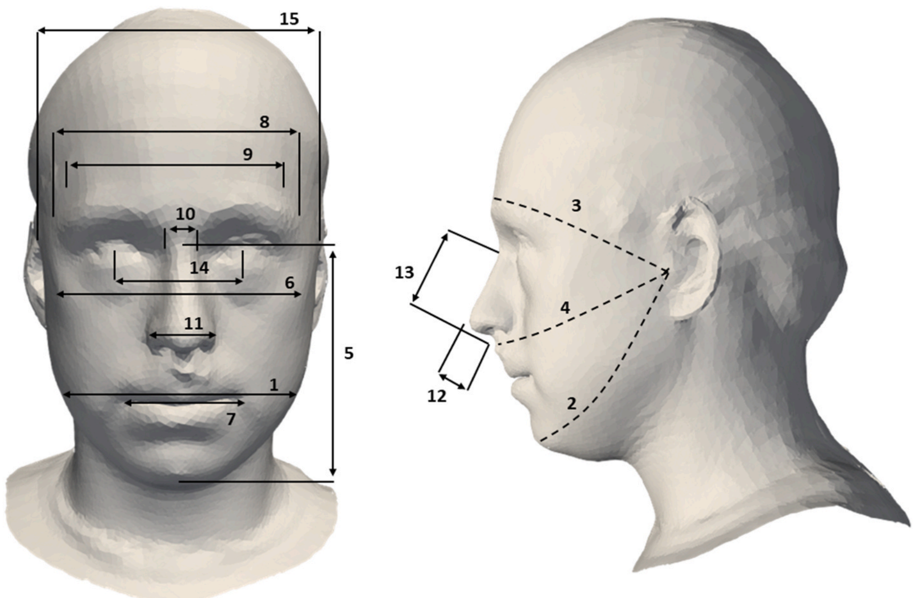

Fig. 2. Anthropometric measurements.

Table 4
Chilean three-dimensional anthropometric data in mm, compared by sex.

Anthropometric dimensions	Female (n = 1057)				Male (n = 959)				Difference			
	Mean	SD	P5	P95	Mean	SD	P5	P95	significant	p-value	AV	%
Weight (kg)°	75.0	16.4	53.5	102.8	84.9	15.6	62.5	111.0	***	0.000	9.8	11.6
Height°	1581.5	63.2	1479.5	1690.0	1704.3	68.9	1590.0	1820.0	***	0.000	122.8	7.2
Body mass index°	29.9	6.2	21.9	40.4	29.2	5.0	21.9	37.9	*	0.027	0.7	2.6
Neck perimeter°	350.1	33.6	304.8	405.0	400.5	32.1	353.0	460.0	***	0.000	50.4	12.6
Head perimeter °	559.2	23.0	530.0	590.0	574.6	18.3	547.0	603.0	***	0.000	15.4	2.7
Bigonial breadth	125.0	10.1	109.4	143.9	137.7	12.2	117.9	158.0	***	0.000	12.7	9.2
Bitragion chin arc	290.2	14.1	268.0	313.7	316.1	16.3	290.8	344.0	***	0.000	26.0	8.2
Bitragion frontal arc	304.7	11.3	286.9	324.2	315.4	12.0	295.5	335.6	***	0.000	10.8	3.4
Bitragion subnasale arc	268.9	13.1	249.3	289.8	283.0	12.7	262.5	303.8	***	0.000	14.1	5.0
Face length	119.9	5.8	110.3	129.5	129.5	7.3	117.8	142.5	***	0.000	9.5	7.4
Face width	135.2	8.2	121.2	148.2	141.8	8.3	126.8	154.3	***	0.000	6.5	4.6
Lip length	50.8	4.2	44.5	57.2	53.9	4.3	47.1	61.3	***	0.000	3.1	5.8
Maximum frontal breadth	120.4	6.8	109.0	132.4	126.7	7.1	116.0	139.0	***	0.000	6.3	5.0
Minimum frontal breadth	110.1	7.2	98.2	121.4	116.1	8.9	101.2	129.4	***	0.000	5.9	5.1
Nasal root breadth	17.6	2.2	14.4	21.5	17.9	2.1	14.5	21.5	**	0.002	0.3	1.4
Nose breadth	34.8	3.2	29.9	40.3	38.5	3.5	33.0	44.5	***	0.000	3.7	9.5
Nose protrusion	21.4	2.0	18.2	24.8	22.6	2.2	19.0	26.3	***	0.000	1.2	5.5
Subnasale-sellion length	55.4	3.7	49.1	61.6	59.0	4.2	52.4	66.0	***	0.000	3.6	6.1
Interpupillary distance	64.6	3.3	59.7	69.8	67.1	3.4	61.5	73.0	***	0.000	2.5	3.8
Head breadth	160.6	16.0	128.2	181.0	176.2	15.0	147.3	196.4	***	0.000	15.6	8.8

°Manual data. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

based variations align with previous studies of facial anthropometry across different populations and can be attributed to intrinsic size differences influenced by genetics, hormones, and environmental factors (H. I. H. Castellucci et al., 2021; Junqueira Junior et al., 2016). Several studies have documented similar sex-related face anthropometry patterns across various populations (Monteiro et al., 2023; Zhuang et al., 2010).

4.2. Workforce diversity and demographic considerations

An important finding was the presence of significant differences between Chilean nationals (88.74 %) and migrant workers (11.26 %, predominantly Venezuelan, Peruvian, and Colombian) in 7 of the 16 calculated measurements. The most notable differences were in nose breadth (4.5 %), nose protrusion (3.17 %), nasal root breadth (2.23 %), subnasale-sellion length (1.87 %), and face length (1.26 %). These variations highlight the importance of considering demographic diversity in PPE design, particularly considering increasing workforce migration. This is a very new finding since Chilean population was relatively homogeneous in its genetic makeup, with studies showing composition of 51 % European, 44 % Amerindian, 3 % African (Chilegenomico, 2015). However, it is very common in other countries that all databases are stratified by ethnicity within the population (Oestenstad and Bartolucci, 2010; Zhuang et al., 2010).

4.3. Cross-country comparisons and population-specific features

When examining our data against international databases, we found distinctive characteristics in the Chilean population. When comparing our findings with the CAESAR databases, we discovered revealing patterns that highlight the uniqueness of Chilean facial characteristics. Our male participants showed notable differences from their Italian, Dutch, and US counterparts across most dimensions measured. Interestingly, when compared with Italian males, only two measurements - minimum

Table 5
Chilean three-dimensional anthropometric data in mm, compared by nationality.

Anthropometric dimensions	Chilean (n = 1790)				Other (n = 226)				Difference			
	Mean	SD	P5	P95	Mean	SD	P5	P95	summary	p-value	AV	%
Weight (kg)°	79.90	16.78	56.7	108.5	78.33	16.65	53.0	109.0	ns	0.113	1.58	2.01
Height°	1639.5	90.44	1500.0	1792.8	1642.9	87.37	1510.0	1780.0	ns	0.510	3.44	0.21
Body mass index°	29.70	5.70	22.0	39.5	28.96	5.55	21.1	39.2	*	0.044	0.74	2.54
Neck perimeter°	374.08	41.17	311.5	444.0	374.23	43.75	312.4	445.3	ns	0.949	0.15	0.04
Head perimeter°	566.77	21.42	535.0	598.0	564.39	28.45	535.0	598.7	ns	0.407	2.38	0.42
Bigonial breadth	131.11	12.87	111.6	154.1	130.78	12.61	111.8	151.8	ns	0.751	0.33	0.25
Bitragion chin arc	302.47	20.08	272.6	336.6	303.07	18.91	268.9	334.8	ns	0.347	0.60	0.20
Bitragion frontal arc	310.03	12.78	289.8	331.8	307.67	12.87	289.3	330.4	**	0.005	2.36	0.77
Bitragion subnasale arc	275.59	14.75	253.1	300.0	275.91	14.57	251.1	300.1	ns	0.501	0.32	0.12
Face length	124.64	8.07	110.5	136.9	123.09	8.36	107.7	136.2	*	0.013	1.55	1.26
Face width	138.32	8.75	123.2	151.9	138.26	9.55	120.9	152.9	ns	0.999	0.06	0.04
Lip length	52.20	4.54	45.4	59.4	52.65	4.47	45.6	61.1	ns	0.190	0.44	0.84
Maximum frontal breadth	123.39	7.59	112.8	137.1	123.47	8.14	111.2	137.0	ns	0.568	0.08	0.07
Minimum frontal breadth	113.05	8.62	104.2	123.2	112.65	8.43	104.1	123.5	ns	0.418	0.40	0.36
Nasal root breadth	17.70	2.15	14.4	21.4	18.10	2.22	15.0	22.3	*	0.019	0.40	2.23
Nose breadth	36.38	3.76	30.4	42.8	38.10	4.01	31.8	45.0	***	0.000	1.72	4.51
Nose protrusion	22.03	2.20	18.6	25.6	21.35	2.16	18.1	25.3	***	0.000	0.68	3.17
Subnasale-sellion length	57.27	4.31	50.2	64.5	56.22	4.38	48.9	62.8	***	0.001	1.05	1.87
Interpupillary distance	65.75	3.58	60.2	71.8	66.26	3.67	60.2	72.4	*	0.027	0.51	0.77
Head breadth	168.05	17.44	137.2	163.3	167.92	16.86	134.5	162.3	ns	0.872	0.13	0.08

°Manual data. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

Table 6
Three-dimensional data anthropometric data, cross-country comparisons, only males.

Anthropometric dimensions	Chile (n = 959)		Italy (n = 408)				Netherlands (n = 497)				US = (1122)			
	Mean	SD	Mean	SD	p-value		Mean	SD	p-value		Mean	SD	p-value	
Weight°	84.9	15.6	72.62	10.99	***	0.000	84.16	16.03	ns	0.406	86.24	18.03	ns	0.070
Height°	1704.3	68.9	1735.4	67.3	***	0.000	1817.1	87.0	***	0.000	1777.5	79.3	***	0.000
Body Mass Index (BMI) °	29.2	5.0	24.06	3.61	***	0.000	25.46	4.96	ns	0.82	27.21	4.93	***	0.000
Neck perimeter°	400.5	32.1	384.73	26.67	***	0.000	397.15	36.18	ns	0.069	408.32	38.70	***	0.000
Head perimeter°	574.6	18.3	589.44	17.80	***	0.000	584.84	24.26	**	0.001	598.06	18.17	***	0.000
Bigonial breadth	137.7	12.2	119.05	9.05	***	0.000	126.08	10.38	***	0.000	125.67	11.85	***	0.000
Bitragion chin arc	316.1	16.3	323.15	16.43	***	0.000	334.87	19.51	***	0.000	332.94	19.40	***	0.000
Bitragion frontal arc	315.4	12.0	310.49	12.29	***	0.000	308.64	18.36	***	0.000	310.15	13.75	***	0.000
Bitragion subnasale arc	283.0	12.7	288.55	13.37	***	0.000	293.52	14.20	***	0.000	292.46	15.29	***	0.000
Face length	129.5	7.3	120.05	5.93	***	0.000	123.64	7.04	***	0.000	123.83	6.75	***	0.000
Face width	141.8	8.3	125.12	5.27	***	0.000	127.31	5.66	***	0.000	128.18	6.05	***	0.000
Lip length	53.9	4.3	53.33	2.93	*	0.018	54.16	3.07	ns	0.202	54.26	3.72	*	0.033
Maximum frontal breadth	126.7	7.1	124.6	4.42	***	0.000	126	5.13	***	0.000	125.4	5.4	***	0.000
Minimum frontal breadth	116.1	8.9	116.8	4.11	ns	0.076	118.8	4.5	***	0.000	118.1	4.55	***	0.000
Nasal root breadth	17.9	2.1	17.85	1.80	ns	0.818	19.53	1.72	***	0.000	18.68	2.15	***	0.000
Nose breadth	38.5	3.5	35.59	2.63	***	0.000	37.55	2.90	***	0.000	37.74	3.59	***	0.000
Nose protrusion	22.6	2.2	23.72	1.51	***	0.000	23.30	1.76	***	0.000	23.33	1.86	***	0.000
Subnasale-sellion length	59.0	4.2	52.71	3.19	***	0.000	55.89	3.93	***	0.000	54.27	3.46	***	0.000
Interpupillary distance	67.1	3.4	60.16	3.17	***	0.000	62.21	3.35	***	0.000	61.79	3.34	***	0.000
Head breadth	176.2	15.0	166.23	6.50	***	0.000	164.79	6.68	***	0.000	167.65	7.12	***	0.000

°Manual data. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

frontal breadth and nasal root breadth - showed similarity, suggesting fundamentally different facial structures.

The pattern of differences was equally striking among female participants, though in somewhat different ways. When compared with Italian females, every single measurement showed significant differences, indicating a complete divergence in facial characteristics. These consistent patterns of difference across multiple populations and both sexes underscore a crucial finding: Chilean facial anthropometry presents distinct characteristics that set it apart from other well-studied populations (Rodríguez et al., 2022; Zhuang et al., 2013). The breadth and consistency of these differences strongly suggest that Chilean workers cannot be adequately served by PPE designed using anthropometric data from other populations, reinforcing the need for population-based approaches to protective equipment design (Yang et al., 2007).

4.4. Implications for PPE

The anthropometric variations we discovered have significant practical implications for the design and sizing of personal protective equipment. In the realm of respiratory protection, our findings indicate that Chilean workers present a unique combination of facial features, particularly in face length and nose dimensions, that differ markedly from other populations (Zhuang et al., 2007). These differences suggest that existing respirator designs may not provide optimal protection for Chilean workers. The specific measurements we identified as significantly different—face length, face width, and nose breadth—are critical determinants of respirator fit. For instance, face length and width directly influence the sealing surface of full-face respirators, while nose bridge dimensions affect the fit of filtering facepiece respirators. Earlier studies, such as Oestenstad and Perkins (1992), also highlighted the predictive value of basic facial dimensions like nose length and chin depth for respirator fit. Roberge et al. (2010) demonstrated that proper

Table 7
Three-dimensional data anthropometric data, cross-country comparisons, only females.

Anthropometric dimensions	Chile (n = 1057)		Italy (n = 384)				Netherlands (n = 606)				US = (1262)			
	Mean	SD	Mean	SD	p-value		Mean	SD	p-value		Mean	SD	p-value	
Weight°	75.0	16.4	57.59	9.03	***	0.000	72.95	15.21	*	0.010	68.86	17.60	***	0.000
Height°	1581.5	63.2	1611.3	62.0	***	0.000	1678.8	75.4	***	0.000	1640.0	72.8	***	0.000
Body Mass Index (BMI) °	29.9	6.2	22.18	3.33	***	0.000	25.93	5.39	***	0.000	25.58	6.19	***	0.000
Neck perimeter°	350.1	33.6	323.28	21.76	***	0.000	347.79	33.86	ns	0.176	343.47	36.61	***	0.000
Head perimeter°	559.2	23.0	567.72	15.47	***	0.000	562.98	22.39	***	0.000	578.74	24.34	***	0.000
Bigonial breadth	125.0	10.1	107.13	6.77	***	0.000	115.95	8.84	***	0.000	111.32	9.53	***	0.000
Bitragion chin arc	290.2	14.1	296.03	11.96	***	0.000	309.41	15.20	***	0.000	302.59	15.78	***	0.000
Bitragion frontal arc	304.7	11.3	297.62	11.76	***	0.000	297.53	13.06	***	0.000	299.72	12.22	***	0.000
Bitragion subnasale arc	268.9	13.1	272.72	10.66	***	0.000	279.35	12.70	***	0.000	275.74	14.83	***	0.000
Face length	119.9	5.8	110.94	4.97	***	0.000	113.94	6.05	***	0.000	112.89	5.70	***	0.000
Face width	135.2	8.2	119.85	4.65	***	0.000	123.25	5.36	***	0.000	122.44	6.06	***	0.000
Lip length	50.8	4.2	49.19	2.55	***	0.000	50.86	2.54	ns	0.644	49.46	3.20	***	0.000
Maximum frontal breadth	120.4	6.8	118.1	4.19	***	0.000	120.8	4.49	*	0.046	119	5.29	***	0.000
Minimum frontal breadth	110.1	7.2	110.6	3.79	***	0.001	113.5	4.22	***	0.000	112	4.82	ns	0.360
Nasal root breadth	17.6	2.2	16.93	1.61	***	0.000	19.40	1.67	***	0.000	18.17	2.25	***	0.000
Nose breadth	34.8	3.2	33.22	2.24	***	0.000	35.92	2.75	***	0.000	35.73	3.32	***	0.000
Nose protrusion	21.4	2.0	22.43	1.41	***	0.000	21.20	1.66	ns	0.092	21.77	1.85	***	0.000
Subnasale-sellion length	55.4	3.7	49.36	2.93	***	0.000	52.06	3.68	***	0.000	49.69	3.34	***	0.000
Interpupillary distance	64.6	3.3	57.46	2.66	***	0.000	59.66	3.07	***	0.000	59.64	3.45	***	0.000
Head breadth	160.6	16.0	158.65	5.99	***	0.000	158.85	7.29	***	0.000	160.67	7.40	*	0.041

°Manual data. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

respirator fit depends on the match between facial dimensions and respirator design, with implications for both protection and physiological burden on wearers. Manufacturers should utilize our detailed measurements to develop respirator sizing systems that specifically accommodate the larger face dimensions of Chilean workers compared to reference populations. Safety professionals should consider these population variations when selecting respirators, potentially prioritizing adjustable models that can accommodate the wider range of facial dimensions we observed between male and female Chilean workers. As demonstrated in previous studies, proper respirator fit is crucial, as ill-fitting equipment can not only fail to protect but may also create additional hazards through distorted vision or discomfort (Kim et al., 2003; Zhuang et al., 2010).

Head protection presents another area where our findings call for particular design considerations. The distinctive patterns we observed in head breadth and related measurements suggest that protective headgear designed for other populations may not adequately serve Chilean workers. Our data reveals that Chilean workers have significantly larger head breadth measurements than those in the CAESAR database, with male Chilean workers averaging 176.2 mm compared to 166.23 mm for Italian males. This 9.97 mm difference (approximately 6 %) is substantial enough to affect the fit and stability of helmets and other head protection. White et al. (2020) emphasized that such population-specific variations in craniofacial morphology have direct implications for products that interface with the head and face. Manufacturers should revise sizing charts for the Chilean market to accommodate these larger dimensions, potentially requiring the addition of larger size options or adjustments to existing sizing systems. Safety managers should be particularly attentive to proper sizing protocols when selecting head protection for diverse workforces that include both Chilean nationals and migrant workers. The substantial differences between male and female head measurements further indicate that a one-size-fits-all approach, even within the Chilean population, would be insufficient (Rodríguez et al., 2022).

Eye protection design must also account for the unique characteristics we observed in the Chilean population. The variations we found in interpupillary distance and facial width measurements have direct implications for the fit and effectiveness of protective eyewear. Our data show that Chilean workers have significantly wider interpupillary distances (males: 67.1 mm; females: 64.6 mm) compared to other populations in the CAESAR database (Italian: males: 60.16 mm, females: 57.46 mm; US: males: 61.79 mm, females: 59.64 mm). This difference of approximately 5–7 mm affects the optimal placement of lenses in safety glasses and impacts the bridge design needed for proper fit. Bannister et al. (2020) highlighted how such specific facial landmarks can be crucial for proper alignment of products that interface with the face. Manufacturers should adjust lens spacing and frame dimensions to accommodate these wider measurements. Additionally, the larger face width measurements we documented suggest that wider frame designs would better accommodate Chilean facial structures, reducing pressure points that can lead to discomfort and non-compliance. PPE testing protocols should incorporate these population-specific characteristics when evaluating equipment intended for use in Chile. These differences affect not only the basic dimensions of safety glasses and goggles but also their stability on the face and their ability to provide adequate protection (Du et al., 2008; Zhuang and Bradtmiller, 2005).

Previous studies have shown that respirator fit panels have varying levels of compatibility with the Chilean population. For example, while ISO panels showed good overall compatibility with a 94.81 % match rate, LANL panels demonstrated considerably lower match rates, particularly for male workers (Rodríguez et al., 2020). This discrepancy underscores the practical value of our dataset for developing more appropriate fit testing protocols. Specifically, certification bodies could use our anthropometric data to create Chilean-specific fit test panels that better represent the range of facial dimensions in this population. Fuentes et al. (2019) emphasized the importance of recognizing biological variation among human populations and its practical applications. The significant differences we found between Chilean and other populations (particularly in face length, face width, and nose dimensions) indicate that existing fit test protocols may not adequately evaluate respirator fit for Chilean workers. We recommend that regulators consider these population variations when developing testing standards, and that manufacturers use our comprehensive dataset to validate their designs against the actual dimensions of the target population. This discrepancy highlights the importance of considering population characteristics in PPE design to serve the Chilean workforce (Hack and McConville, 1978).

The practical applications of our findings extend to custom PPE design approaches as well. The detailed 3D data we've collected enables more sophisticated design methodologies beyond traditional linear measurements. Acka (2003) demonstrated how advanced 3D modeling techniques like Generalized Procrustes Analysis can be applied to create precise alignments of complex shapes—a method that could be valuable for analyzing the fit between facial morphology and PPE. Baken et al.

(2021) further showed how modern geometric morphometric methods can quantify and analyze complex shape variation, which could be applied to optimize the interface between facial structures and protective equipment. Manufacturers could utilize our dataset to create digital avatars representing the average Chilean worker's facial dimensions for virtual fit testing and prototyping. These virtual models would allow for rapid iteration of designs without costly physical prototyping, particularly beneficial for addressing the specific facial characteristics where we found significant differences from international populations (nose breadth, face length, and head breadth).

Recent advances also point towards the integration of 3D scanning data with machine learning algorithms to predict respirator fit outcomes automatically. Yu et al. (2024) demonstrated that combining specialized facial measurements with predictive models significantly improves fit prediction accuracy. Notably, their study identified specific facial features such as the mid-nose slope and upper ear height as stronger predictors of fit for Filtering Facepiece Respirators (FFR) than traditional anthropometric dimensions.

Although our current dataset includes conventional ISO-based measurements, the availability of 3D facial meshes opens the possibility of calculating additional facial variables relevant to FFR fit in future research. As suggested by Yu et al. (2024), developing such targeted facial metrics could optimize PPE design and validation processes. Transitioning from standard linear measurements towards fit-focused facial metrics would allow the creation of more precise predictive tools and design criteria tailored to the unique morphology of the Chilean workforce.

Additionally, our findings on sex-based differences provide strong justification for sex-specific PPE designs, particularly for respirators where the 7.4 % difference in face length and 9.5 % difference in nose breadth between males and females could significantly impact fit and protection factors.

4.5. Limitations and further studies

Several limitations should be considered when interpreting our findings. Our sample, though substantial (N = 2016), was primarily collected from central regions of Chile, which may not fully represent the anthropometric diversity across the country's extensive geography. Although we captured the beginning of demographic changes with 11.26 % of our sample being migrant workers, contemporary workforce diversity may be even greater (H.I Castellucci et al., 2021). Moreover, although the sample size is considerable, anthropometric studies often benefit from exceptionally large samples to fully capture the extremes and subtle variations within a population. Our sample size may have been influenced by factors such as participant availability, recruitment feasibility, and resource constraints, which should be considered when generalizing the findings.

Another limitation pertains to our comparison methodology. Although we adhered to standardized procedures when comparing our data with the CAESAR databases, some measurements were not consistently available across all datasets, which restricted certain comparative analyses. Furthermore, the temporal gap between our data collection and some reference databases must be considered when interpreting cross-population comparisons, as the CAESAR database is over 20 years old. Lastly, differences in equipment quality should be noted, with the 3dMD system used in our study offering superior precision compared to the equipment employed in the CAESAR database.

5. Conclusion

Our comprehensive three-dimensional anthropometric study of Chilean workers has revealed significant findings with important implications for occupational safety and PPE design. The study demonstrates that Chilean workers possess unique anthropometric characteristics that distinguish them from other populations, with clear patterns of sexual dimorphism and emerging workforce diversity.

The study revealed an emerging pattern of anthropometric diversity within the Chilean workforce itself, with significant differences between Chilean nationals and migrant workers. This finding is particularly important given Chile's historically homogeneous population and recent demographic changes, suggesting a need for more inclusive approaches to PPE design.

These findings have three main practical implications. First, the need for sex-based PPE design approaches, particularly in respiratory protection where fit is crucial for effectiveness. Second, the importance of developing population-adapted sizing systems that account for the unique characteristics of Chilean workers. Finally, the requirement to consider increasing workforce diversity in PPE design and testing.

In the context of evolving workplace safety requirements and increasing workforce diversity, these findings provide crucial guidance for improving occupational safety through better-fitting PPE. The database established through this study serves as a valuable resource for manufacturers, safety professionals, and regulatory bodies in developing and selecting appropriate PPE for Chilean workers.

CRediT authorship contribution statement

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

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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