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Three-dimensional head and face dimensions of Chilean versus US CAESAR 3D data: Differences and implications for personal protective equipment design

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Abstract

Background: Personal Protective Equipment (PPE) is crucial for minimizing workplace hazards, and its effectiveness relies on adapting to diverse anthropometric features.

Objective: To establish the first 3D anthropometry database of Chilean workers. Also, this study compares 18 dimensions with the North American CAESAR three-dimensional anthropometrical scan database.

Methods: The research utilized three-dimensional data collected from 348 Chilean individuals, ages ranging between 19 and 68 years old. Measurements were captured with a 3D face scanner (3dMD®) following ISO/TS 16976-2 and ISO 15535 guidelines to maintain rigorous standards.

Results: Noticeable sexual dimorphism: Chilean males exhibit larger facial dimensions than females, such as Nose breadth and Face length, which emphasize the need for gender-specific PPE designs. Furthermore, comparisons with the CAESAR dataset revealed significant disparities among Chilean and other populations, emphasizing the importance of ethnic tailoring PPE. The implications for respiratory PPE design are substantial; variations in dimensions like Face length and Face width highlight the need for adjustable or size-specific respirators.

Conclusions: The study underlines the importance of considering not only gender-specific differences but also ethnic variations in PPE design. The findings emphasize the critical role of anthropometric data in developing tailored respiratory protection devices, ensuring effective workplace safety across diverse populations. The study recommends further research to validate the findings in other populations and to advocate for inclusive design practices in occupational safety.

Keywords

anthropometry, masks, body size, three-dimensional image, ergonomics, respiratory protective devices

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Introduction

Personal protective equipment (PPE) refers to equipment worn to minimize exposure to hazards that may cause serious workplace injuries and illnesses, resulting from contact with chemical, radiological, physical, electrical, mechanical, or other workplace hazards.[1] Therefore, PPE is commonly used in occupational settings that involve exposure to these dangers, such as the military, protective services (police, firefighting, security), skilled trades (electrical, plumbing, carpentry), healthcare, and aerospace/aviation, among other industries.[2] PPE includes a wide range of items, such as gloves, safety glasses and shoes, earplugs or muffs, hard hats, respirators, coveralls, vests, and full-body suits.

PPE is essential in many occupational domains and must comply with safety and protection standards. PPE Fit, associated with anthropometric dimensions and recommended size, plays a critical role and is a key factor in functional and operational performance detriments related to PPE use.[3,4] A mismatch may occur when the product does not suit the human body, specifically when the anthropometric dimensions are either below the minimum or above the maximum limits of the product dimensions.[5] To avoid this issue, anthropometric studies are constantly conducted to develop and continually update working populations databases worldwide, with applications in various industrial settings, hand tools, vehicle design, and PPE, among several other fields.[3]

In this regard, anthropometry employs conventional manual methods of collecting body measurements, such as anthropometers, calipers, and measuring tapes, which are low-cost and easy-to-use tools. However, there are several limitations in using direct manual measurements, including training, workers in various static and dynamic conditions, long application times, variations related to tape application or body posture, and misidentification of reference points.[6–10]

Currently, in an attempt to overcome those limitations, professionals use advanced anthropometric measurement systems utilizing three-dimensional scanners,[9] in areas like garment design, head wearable products, clothing, and craniofacial surface morphology applications.[11–14] Three-dimensional scanning technology may be used to calculate and measure complex human body dimensions, such as curves, surface shapes, area, and volume, as well as to determine simple dimensions such as length and width.[15] In regard to calculations and measurements, 3D anthropometry may be key to the automation and facilitation of tedious and time-consuming processes of traditional manual anthropometric measurement.[14] Another benefit of 3D anthropometry is that the evaluator is able to objectively quantify changes in three dimensions, thus capturing differences in volume and spatial positioning of soft tissues based on their actual shape.[16] Also, 3D anthropometry data is used to study shape variation among people, helping to understand anatomical differences in people from different ethnic groups or geographic locations.[17] One of the largest anthropometric databases, CAESAR[18] has accounted for both gender and ethnic differences in 3D facial anthropometrics, highlighting the importance of using specific databases for design, especially designing PPE.[19–22] Ethnic and gender differences are factors to be considered in any design, and PPE is no exception. Other studies have documented the differences in facial dimensions in ethnic groups[23] and the implications in respirator fit. In the case of Chile, these databases are quite recent. The Chilean economy is mainly based on commodities, with a small share of the Gross Domestic Product (GDP) from manufacturing. Therefore, virtually all the machinery and equipment, including PPE, is manufactured overseas. Today, all the respirators available in the national market have been designed and manufactured using foreign regulations. For example, roughly 66% of half-face and full-face respirators are certified by NIOSH (United States), and 34.4% by other certification entities (that is, Europe).[24] Considering that the first 3D facial anthropometry database is available, it is relevant to establish differences with other frequently used databases and theoretically test respirator anthropometric match.

This study aims to present a set of anthropometric dimensions of the human head and face calculated from three-dimensional data from Chilean workers for PPE design purposes to establish the first 3D anthropometry database of Chilean workers up to this date. This study also compares 18 dimensions with the North American CAESAR three-dimensional anthropometrical scan data extracted by Lee et al.,[15] which has also considered the same dimensions.

Methods and procedure

Sample

The sample size was calculated following the ISO 15535 recommendations, using the coefficient of variation.[25] The standard proposes that the sample size is estimated to be sufficient for technological design. As such, the minimum random sampling, N, required to ensure that the database's 5th and 95th percentiles account for the actual population's 5th and 95th percentiles with 95% confidence.

The exclusion criteria were having any facial malformation, a physical impediment for performing a quantitative fitting or having an abundant beard.

The Committee of Ethics of the Chilean Public Health Institute (Instituto de Salud Pública de Chile) approved the data collection process, and prior to the measurement procedure, the workers provided their written consent.

Table 1. Landmarks considered in this study. (From ISO/TS 16976-2[27] and NIOSH[28]).

Landmark	Definition
Menton	The inferior point of the mandible in the midsagittal plane.
Promentale	The protruding point on the bottom edge of the chin, along the jaw line
Subnasale	The point of the intersection of the philtrum (groove of the upper lip) with the inferior surface of the nose, in the midsagittal plane.
Pronasale	The point of the anterior projection of the tip of the nose.
Sellion	The point of the deepest depression of the nasal bones at the top of the nose.
Glabella	The anterior point on the frontal bone midway between the bony brow ridges.
Gonion, left and right	The lateral point on the posterior angle of the mandible.
Cheilion, left and right	The lateral point of the juncture of the fleshy tissue of the lips with the facial skin at the corner of the mouth.
Alare, left and right	The lateral point on the flare of the nose.
Zygion, left and right	Most lateral points of the face, that is, outermost points of the outside contours of the zygomatic arches
Tragion, left and right	The superior point on the juncture of the cartilaginous flap of the ear with the head.
Infraorbitale, left and right	The lowest point on the anterior border of the bony eye socket.
Nasal Root, left and right	The most depressed, superior part of the nose along the nasal ridge.
Zygofrontale, left and right	The lateral point of the frontal bone on its zygomatic process.
Frontotemporale, left and right	The point of deepest indentation of the temporal crest of the frontal bone above the brow ridges.

Data collection

Landmarking. To identify and mark the anthropometrical face landmarks, a single evaluator was trained by a specialist in ergonomics and anthropometrics for a one-week period, during which the measurer was focused on identifying head and nose reference points and mastering measurement procedures. The training centered on landmarking techniques, to avoid measurement errors.[7,8] Then, the evaluator went on to mark a group of volunteer workers after the training period. Subsequently, the evaluator marked the workers with a dermographic pencil. To minimize measurement errors, which are a significant source of anthropometric inaccuracies and may be exacerbated due to multiple measurers, the team members maintained consistent roles throughout the entire evaluation process.[8,26] ICC values were checked, which proved to be within the good to excellent range (>0.75 ICC).[26]

Then, the evaluator manually proceeded to identify a set of 24 facial and cranial landmarks, following ISO/TS[27] recommendations for human body measurement and landmarks and NIOSH recommendations for landmarking facial dimensions[28] (Table 1 and Figure 1).

Data capture. The capture of three-dimensional meshes was performed with the workers sitting in an erect posture on a height-adjustable chair placed on a flat surface, with the head in cervical extension within a range of 0 to 15°, legs flexed to a 90° angle, and feet placed flat on the ground, using an adjustable footrest. Workers wore regular shoes and clothes, except for those with long hair, who were asked to wear a swimming cap to improve capture of the scalp surface. All workers underwent manual landmarking for the 24 landmarks using a dermographic pen (Figure 1).

Three-dimensional measurements were recorded using a 3D face scanner (3dMD®), composed of two modular units of six machine vision cameras and an industrial-grade flash system synchronized in a single capture, generating a continuous three-dimensional polygon surface mesh from all synchronized stereo modular units.

Measurements calculations points. To determine the desired anthropometric measures, one of the researchers was responsible for the virtual pinpoint based on the physical landmarking of the anthropometric reference. Afterward, the following anthropometric measures were calculated according to the ISO/TS 16976-2 (2015) (Table 2 and Figure 2). All calculations were made by a custom Python algorithm involving geometrical and vectorial calculations. To ensure the measurement accuracy, for each virtual pinpoint marked on the 3D scan, a number and a name were assigned (See Table 2). Once all landmarks were identified and marked, data was exported into a JavaScript Object Notation (JSON) file. Using Visualization Toolkit (VTK) libraries, researchers checked that only points located near the reference point for each measurement were taken into the calculations. Moreover, the name of each marker has proven that only the target marker was used in each calculation. It is important to note that before any calculation, the 3D scans were manually oriented in terms of the x, y, and z axis using a reference object. This procedure allowed the scans and markers to be in the same plane during the calculations, avoiding the need for transformations such as rotation or translation, as the 3D scans were already in a common reference plane.

Other samples and database

Chosen by the number of dimensions available and the similarities with this Chilean sample, this study used a

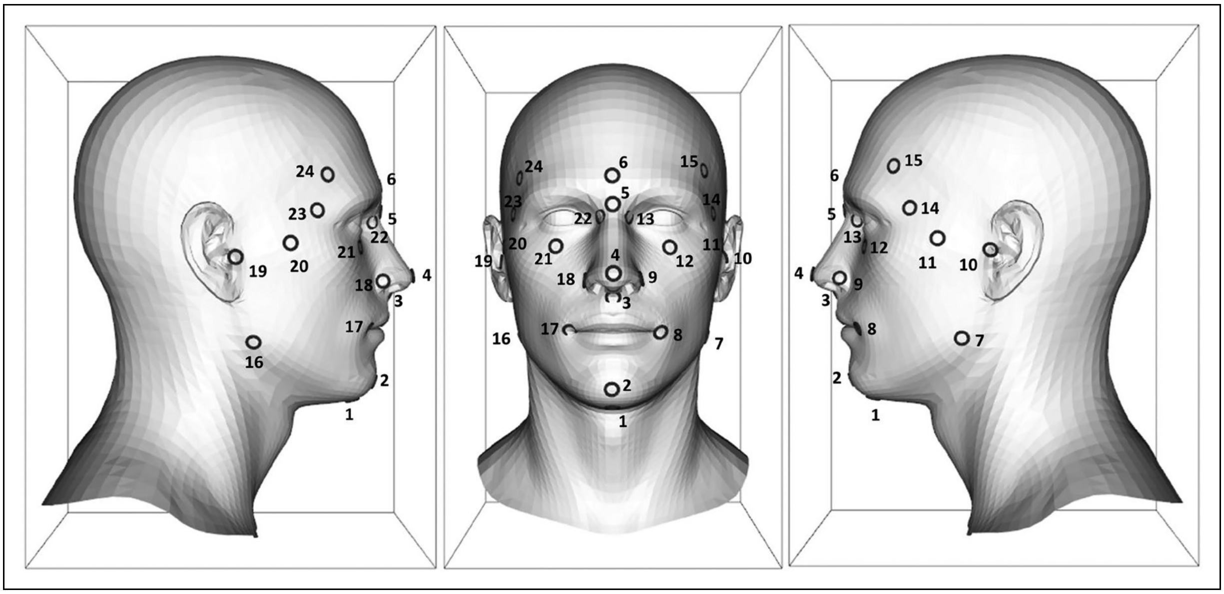

Figure 1. Landmarks as markers.
(1) Menton, (2) Promentale, (3) Subnasale, (4) Pronasale, (5) Sellion, (6) Glabella, (7) right Gonion, (8) right Cheilion, (9) right Alare, (10) right Tragion, (11) right Zygion (11), (12) right Infraorbitale, (13) right Nasal Root, (14) right Zygofrontale, (15) right Frontotemporale, (16) left Gonion, (17) left Cheilion, (18) left Alare, (19) left Tragion. (20) left Zygion, (21) left Infraorbitale, (22) left Nasal Root, (23) left Zygofrontale, and (24) left Frontotemporale.

subset of the Civilian American and European Surface Anthropometry Resource (CAESAR).[15] The study of Lee et al.[15] database consisted of 2299 North American participants separated by gender (male and female) and ethnicity (Caucasian, African American, Asian, and Hispanic). The Hispanics were not considered due to the small sample size (31 males and 18 females).

Statistical analysis

All anthropometric data was analyzed using STATA (StataCorp, 2021). A Variance-comparison test was performed in the Chilean sample, which resulted in a difference in variances between genders, leading to the use of a modified *t-test*, the Welch t-test for unequal variances, with a 95% confidence interval, to examine the difference in measurements between genders in the Chilean sample. Also, absolute and relative differences between genders were calculated. Significance values were set at a minimum of $p < 0.05$.

The other non-Chilean samples provided size, average and standard deviations, and percentiles, thus neither normality nor variance could be determined.[15] Therefore, a non-equal variance *t-test* was performed to determine the difference between the Chilean and CAESAR samples. The CAESAR sample had 30 anthropometric measurements, from which it was possible to compare 10 of the 13 matching measurements from the Chilean data.

Finally, to verify the level of mismatch, the anthropometric key dimensions of the face were contrasted with the Los Alamos National Laboratory (LANL)[29] (half-facepiece: face length and lip length; full-facepiece: face length and face width) and the NIOSH (Bivariate: face length and face width) fit test panels established by ISO[27] based on the NIOSH studies.[22]

Results

The Chilean sample size was 348 workers (Female: 163, Male: 185) from different industrial sectors from two central regions of Chile (Region Metropolitana and Libertador General Bernardo O'Higgins). The results will be presented first by analyzing gender differences within the Chilean sample, and in the subsequent sections, comparisons with CAESAR databases are shown. The third subsection provides match levels between ISO and LANL panels.

Anthropometrical dimensions of Chilean subjects

The calculated dimensions of both male and female Chilean workers are presented in Table 3. These results indicate that males have significantly bigger dimensions than females. The highest percentual differences were for Nose breadth (10.9%), Bitragion chin arc (9.1%), Bigonial breadth (8.4%), Lip length (8.1%), Face length (7.8%), Bitragion subnasale arc (6.9%), Subnasale-sellion length (5.5%), Bitragion frontal arc (5.3%), and Face width (4.8%). In the discussion section, we will analyze and explain these findings in detail.

Table 2. Anthropometric dimensions considered in this study (From ISO/TS 16976-2[27] and NIOSH[28]).

Dimension	Definition	Marker	
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.	Gonion left Gonion right	marker 7 marker 16
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)	Tragion left Tragion right Menton	marker 10 marker 19 marker 1
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 frontotemporale landmark.	Tragion left Tragion right Frontotemporale left Frontotemporale right	marker 10 marker 19 marker 15 marker 24
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	Tragion left Tragion right Subnasale	marker 10 marker 19 marker 3
Face length (menton-sellion 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.	Menton Sellion	marker 1 marker 5
Face width	Maximum horizontal breadth of the face is measured as the norm difference between zygion landmarks from right to left.	Zygion left Zygion right	marker 11 marker 20
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.	Cheilion left Cheilion right	marker 8 marker 17
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.	Zygofrontale left Zygofrontale right	marker 14 marker 23
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.	Frontotemporale left Frontotemporale right	marker 15 marker 24
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.	Nasal Root left Nasal Root right	marker 13 marker 22
Nose breadth	Straight-line distance, calculated as the distance between the right and left alare landmarks.	Alare left Alare right	marker 9 marker 18
Nose protrusion	The straight-line distance between the pronasale landmark at the tip of the nose and the subnasale landmark under the nose.	Subnasale Pronasale	marker 3 marker 4
Subnasale-sellion length	Straight-line distance, calculated as the norm difference between the subnasale landmark and the sellion landmark.	Subnasale Sellion	marker 4 marker 5

Comparison with anthropometrical dimensions from CAESAR

Tables 4 and 5 present the comparisons with the CAESAR available data, for males and females, respectively. The comparison data from CAESAR is presented for Caucasian, African American, and Asian participants. If an anthropometric dimension was not presented in that database, it was coded with a dashed line.

Note that, both female and male Chilean populations show statistically significant differences with all other populations in the following dimensions: Face width, Maximum frontal breadth, Nose protrusion, and Subnasale sellion length. Additionally, only males exhibited significant differences in Face length compared with other populations, while females showed important differences in Bigonial breadth and Nasal root breadth.

The results from Table 4 show that most of the Chilean male facial dimensions were larger than the facial dimensions of Caucasian, African American, and Asian populations. Chilean sample Bigonal breadth and Bitragion frontal arc were significantly larger than Caucasian and Asian samples. Face length, Face width, Maximum frontal breadth, Nose protrusion, and Subnasale-sellion length of the Chilean male population were all significantly larger than the other sample populations. Asian Nasal root breadth, although also larger than the Chilean male population, did not show a significant difference.

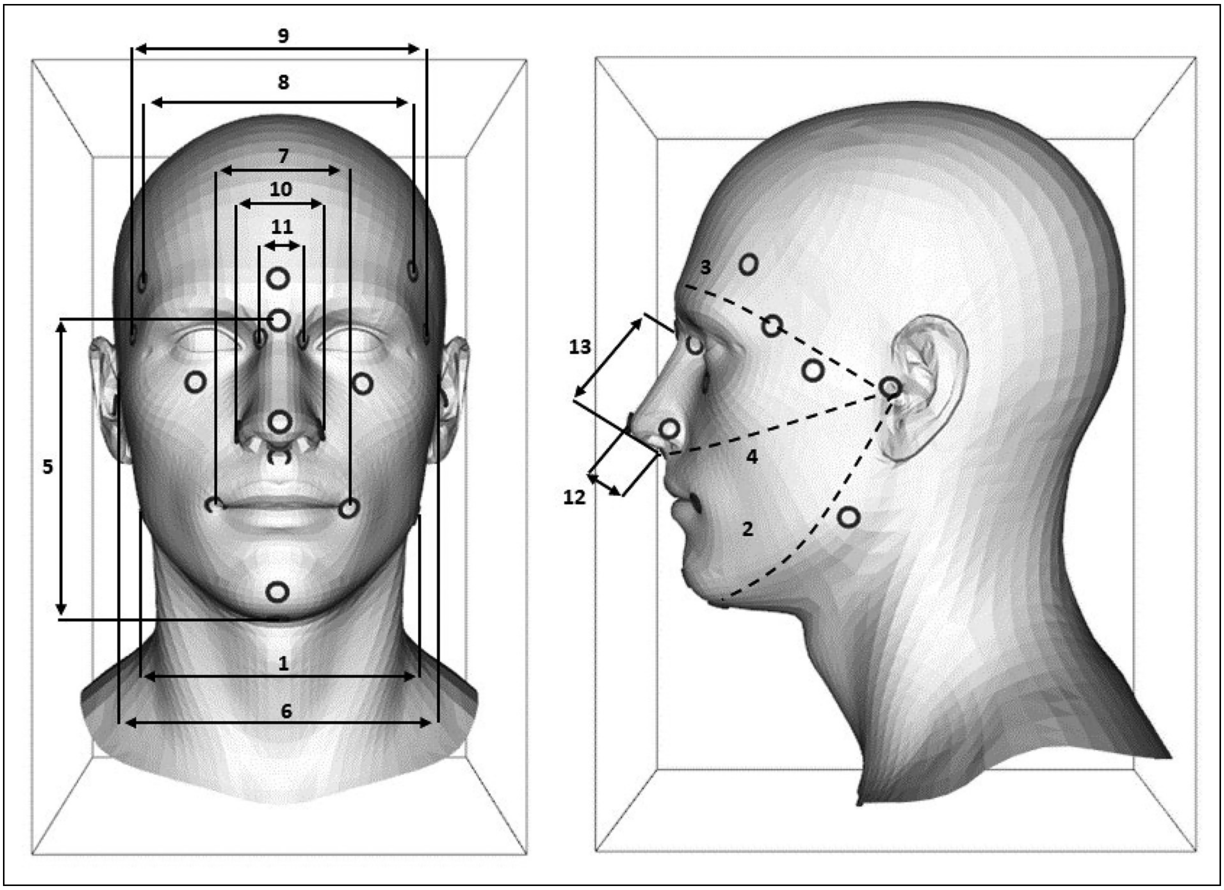

Figure 2. Anthropometric measurements gathered in this study.
1. Bigonial breadth, 2. Bitragion chin arc, 3. Bitragion frontal arc, 4. Bitragion subnasale arc,5. Face length, 6. Face width, 7. Lip length, 8. Minimum frontal breadth, 9. Maximum frontal breadth, 10. Nasal root breadth, 11. Nose breadth, 12. Nose protrusion, 13. Subnasale-sellion length.

Table 5 shows that Chilean females have, in general, smaller facial dimensions than Caucasian, African American, and Asian populations. The significantly smaller dimensions were the Bigonial breadth, Face width, Maximum frontal breadth, and Nasal root breadth. The only exceptions were seen in Nose protrusion and Subnasale-sellion length, which were larger than the dimensions seen in Caucasian, African American, and Asian populations.

Level of match for the respirator fit panels by the LANL and ISO

In Table 6 is stated that 11.44% of females and 46.49% of males remained without an assigned cell for half face-piece respirator size according to the LANL. The Chilean sample had larger key face dimensions (face length and lip length) than the military population on which the LANL panels are based.

Also, Table 6 shows that full face-piece respirator sizes from the LANL significantly vary. The cells with the highest number of people were 8 and 10, with 20.98% and 27.59%, respectively. Furthermore, females presented a higher match level (88.34%) than males (44.32%). These values reflect that female workers show smaller key face dimensions (face length and face width) than males (Table 3).

Finally, in Table 6, we observe that the bivariate fit test panels established by ISO presented the highest level of overall match with 94.81%. The analysis of specific gender differences showed a 99.39% match for females and a 90.81% match for males.

Discussion

Sexual dimorphism in the Chilean population

Sexual dimorphism in anthropometric dimensions is attributed to the intrinsic differences in sizes between males and females, which are associated with several factors,[30] including genetics, hormones, and environmental factors.[31,32] Additionally, environmental factors such as nutrition,

Table 3. Chilean three-dimensional anthropometric data.

Anthropometric dimensions (mm)	Female (N = 163)					Male (N = 185)					Difference		
	Mean	SD	P5	P50	P95	Mean	SD	P5	P50	P95	p-value	AV	%
bigonial breadth	113.86	7.84	100.84	113.36	128.77	123.50	9.27	108.60	123.74	138.57	***	9.64	8.46
bitragion chin arc	302.55	13.50	277.80	302.46	325.33	330.32	11.43	304.32	332.41	345.77	***	27.77	9.18
bitragion frontal arc	294.40	14.84	266.90	295.68	316.26	310.07	14.67	288.75	311.91	329.82	***	15.67	5.32
bitragion subnasale arc	281.25	11.67	261.29	280.68	298.79	300.67	11.29	281.56	301.03	317.85	***	19.42	6.90
face length	122.40	5.75	114.01	122.24	133.44	131.98	5.79	121.95	132.06	141.62	***	9.576	7.82
face width	139.43	5.44	130.87	139.53	148.19	146.18	5.81	137.03	146.56	155.33	***	6.757	4.84
lip length	54.31	4.95	45.75	54.44	62.55	58.72	4.39	50.41	58.48	66.72	***	4.411	8.12
maximum frontal breadth	107.69	4.48	98.75	107.37	115.73	112.00	5.01	104.94	111.88	120.54	***	4.307	3.99
minimum frontal breadth	103.58	4.75	96.53	103.90	111.81	107.25	5.31	98.83	107.55	116.42	***	3.675	3.54
nasal root breadth	19.64	2.28	16.15	19.46	23.62	20.18	3.29	16.15	20.06	24.25		0.543	2.76
nose breadth	34.61	6.72	29.73	33.96	39.82	38.39	2.80	34.15	38.22	43.61	***	3.777	10.9
nose protrusion	19.49	2.11	15.76	19.48	23.17	19.92	2.26	16.62	19.69	23.95		0.426	2.18
subnasale-sellion length	54.76	3.51	49.83	54.52	60.88	57.81	3.86	51.57	57.61	64.07	***	3.052	5.57

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$; AV: Absolute value = mean values of males – mean values of females; % = ((mean values of males – mean values of females)/mean values of female)×100.

Table 4. Comparison of the Chilean male anthropometric data with other populations.

Anthropometric dimensions (mm)	Chile			Caucasian				African American				Asian			
	N	Mean	SD	N	Mean	SD	p-value	N	Mean	SD	p-value	N	Mean	SD	p-value
bigonial breadth	185	123.50	9.27	859	117.40	12.20	***	110	117.50	13.40		80	116.90	11.60	***
bitragion chin arc	185	330.32	11.43	854	306.10	21.20		108	305.00	23.10		81	305.20	20.40	
bitragion frontal arc	185	310.07	14.67	862	300.60	14.70	***	111	295.90	14.90		80	299.20	16.50	*
bitragion subnasale arc	185	300.67	11.29	862	281.30	14.30		111	279.20	16.50		81	278.70	15.00	
face length	185	131.98	5.79	854	123.80	9.00	***	108	122.70	9.60	***	81	125.20	9.20	***
face width	185	146.18	5.81	862	144.30	8.80	**	111	143.20	8.80	***	81	143.60	9.30	**
lip length	185	58.72	4.39	-	-	-	-	-	-	-	-	-	-	-	-
maximum frontal breadth	185	112.00	5.01	857	110.60	6.90	**	110	109.80	6.40	**	80	109.40	7.30	***
minimum frontal breadth	185	107.25	5.31	-	-	-	-	-	-	-	-	-	-	-	-
nasal root breadth	185	20.18	3.29	860	21.20	2.80	***	110	20.90	2.50	*	81	20.70	3.10	
nose breadth	185	38.39	2.80	-	-	-	-	-	-	-	-	-	-	-	-
nose protrusion	185	19.92	2.26	862	16.10	2.80	***	111	15.70	2.50	***	81	15.80	2.50	***
subnasale-sellion length	185	57.81	3.86	862	53.00	4.10	***	111	52.40	4.40	***	81	53.20	4.20	***

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

Table 5. Comparison of the Chilean female anthropometric data with other populations.

	Chile			Caucasian				African American				Asian			
Anthropometric dimensions (mm)	N	Mean	SD	N	Mean	SD	p-value	N	Mean	SD	p-value	N	Mean	SD	p-value
bigonial breadth	163	113.86	7.84	951	117.40	12.40	***	146	117.40	11.20	**	91	118.70	11.80	***
bitragion chin arc	163	302.55	13.50	949	305.60	21.20		146	306.00	20.70		89	306.60	22.10	
bitragion frontal arc	163	294.40	14.84	955	299.90	14.90	***	147	297.10	14.70		92	297.10	14.50	
bitragion subnasale arc	163	281.25	11.67	956	280.80	14.40		147	279.30	14.20		92	279.40	16.50	
face length	163	122.40	5.75	949	123.50	9.10		146	123.40	8.40		89	124.20	9.20	
face width	163	139.43	5.44	956	144.20	8.80	***	147	143.10	8.00	***	92	143.80	8.20	***
lip length	163	54.31	4.95	-	-	-	-	-	-	-	-	-	-	-	-
maximum frontal breadth	163	107.69	4.48	950	110.30	6.90	***	147	111.20	6.20	***	91	110.20	6.50	***
minimum frontal breadth	163	103.58	4.75	-	-	-	-	-	-	-	-	-	-	-	-
nasal root breadth	163	19.64	2.28	954	21.10	2.80	***	146	21.10	2.50	***	92	20.90	2.60	***
nose breadth	163	34.61	6.72	-	-	-	-	-	-	-	-	-	-	-	-
nose protrusion	163	19.49	2.11	956	16.00	2.80	***	147	16.10	2.60	***	92	16.40	2.60	***
subnasale-sellion length	163	54.76	3.51	956	52.90	4.20	***	147	52.50	4.00	***	92	53.20	4.30	**

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

Table 6. Number and percentage of Chilean workers for the respirator fit panels by the LANL and ISO.

	LANL						ISO		
	Bivariate half-facepiece			Bivariate full-facepiece			Bivariate		
Cell	Female	Male	Total	Female	Male	Total	Female	Male	Total
1	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
2	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.61)	0 (0)	1 (0.29)
3	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (1.84)	1 (0.54)	4 (1.15)
4	1 (0.61)	0 (0)	1 (0.29)	4 (2.45)	0 (0)	4 (1.15)	39 (23.93)	1 (0.54)	40 (11.49)
5	4 (2.45)	0 (0)	4 (1.15)	2 (1.23)	0 (0)	2 (0.57)	1 (0.61)	0 (0)	1 (0.29)
6	26 (15.95)	2 (1.08)	28 (8.05)	1 (0.61)	0 (0)	1 (0.29)	16 (9.82)	3 (1.62)	19 (5.46)
7	56 (34.36)	4 (2.16)	60 (17.24)	25 (15.34)	3 (1.62)	28 (8.05)	66 (40.49)	24 (12.97)	90 (25.86)
8	12 (7.36)	6 (3.24)	18 (5.17)	63 (38.65)	10 (5.41)	73 (20.98)	11 (6.75)	19 (10.27)	30 (8.62)
9	35 (21.47)	40 (21.62)	75 (21.55)	16 (9.82)	6 (3.24)	22 (6.32)	22 (13.5)	58 (31.35)	80 (22.99)
10	11 (6.75)	47 (25.41)	58 (16.67)	33 (20.25)	63 (34.05)	96 (27.59)	3 (1.84)	62 (33.51)	65 (18.68)
Match	**145 (88.96)**	**99 (53.51)**	**244 (70.11)**	**144 (88.34)**	**82 (44.32)**	**226 (64.94)**	**162 (99.39)**	**168 (90.81)**	**330 (94.83)**
Mismatch	**18 (11.04)**	**86 (46.49)**	**104 (29.89)**	**19 (11.66)**	**103 (55.68)**	**122 (35.06)**	**1 (0.61)**	**17 (9.19)**	**18 (5.17)**

physical activity, education, gender equality, and exposure to certain chemicals may also affect anthropometric dimensions.[31,33–36] Also, we observe that the Chilean workers' anthropometric dimensions have significantly grown in the last 20 years, showing sexual dimorphism in most of them.[30] A recent study presented differences between Chilean male and Chilean female facial dimensions, as well.[3]

The current study found that Chilean males have significantly larger facial dimensions than Chilean females. The finding that males have larger anthropometric dimensions than females is consistent with previous studies that have found sexual dimorphism in facial dimensions across different populations.[21,37] In this study, the highest differences were observed in Nose breadth, Bitragion chin arc, Bigonial breadth, Lip length, Face length, Bitragion subnasale arc, Subnasale-sellion length, Bitragion frontal arc, and Face width. The regions where the differences were most significant are fairly similar to some of those presented in a study by Junqueira et al.[38] conducted in Brazilian males and Brazilian females, which found that Brazilian males had significantly larger facial dimensions than Brazilian females, in the mandibular and lower nasal regions. In the current study, and contrarily to the Brazilian population, as well as in the Chilean males' mid and upper-third dimensions of the face were bigger than the Chilean females' dimensions. Similarly to this study, gender-related face anthropometry has been documented in several other populations.[38–42]

The differences observed in some dimensions in this study are paramount. For example, the Bitragion chin arc, Bitragion frontal arc, and Bitragion subnasale arc showed gender differences ranging between 19 and 27 mm. These differences may have important implications in product design and workspaces, which need to accommodate both male and female workers.

Implications of sexual dimorphism in respiratory PPE

One of the most critical dimensions for PPE design is face length, as it determines the distance between the nose and chin, which affects the fit of respiratory protection devices such as respirators.[43] Facial dimensions are an essential factor in selecting and fitting respirators, and failure to account for such differences may result in inadequate protection. The face length difference observed in the Chilean population suggests that a different size range of respirators may be required to ensure a proper fit for both males and females (Table 6).

Another important dimension in PPE design is the Bigonial breadth, which is the distance between the two jaw angles. Bigonial breadth is one of the most significant facial dimensions to consider when designing respirators, as it directly affects the respirator's seal on the face.[21,44,45] The differences observed in Bigonial breadth between Chilean males and Chilean females suggest that different sizes of respirators or alternative designs may be required to adapt to different jaw angles.

Previous research has shown that lip dimensions affect the fit of half-mask respirators and face masks, and proper fitting of those devices is critical for effective respiratory protection.[38,39] This study found that males have significantly longer lip length than females. The differences observed in these dimensions in the Chilean population suggest that, especially for males, different sizes or designs of respirators may be required to ensure a proper fit for both males and females (Table 6). This could imply that half-mask respirators designed for Chilean males need to be adapted to longer lip dimensions to ensure an effective fit. This hypothesis should be tested in participants using other methods, such as a fitting trial, for empirical confirmation, as it has been done in other studies.

Additionally, dimensions like Subnasale-sellion length, Face width, Face length, Maximum frontal breadth, and Minimum frontal breadth are crucial in PPE design. Subnasale-sellion length and Face width may affect the size and shape of the respirator while Bitragion frontal arc, Maximum frontal breadth, and Minimum frontal breadth are important in determining the size of the respirator's filter and cover material.

In addition, the significant anthropometric differences observed in the Chilean population have important implications for the design of personal respiratory protection devices. It is essential to account for these differences in designing PPE to ensure adequate protection and prevention from exposure to hazardous airborne particles. Further research is necessary to explore the applicability of these findings to other populations and to develop PPE designs that may adapt to various facial dimensions.

Specific facial dimensions differences between populations and their contribution to respiratory PPE fit

The study also compared the facial dimensions of Chilean workers with those of Caucasian, African American, and Asian populations.

On the one hand, the results showed that Chilean males have larger facial dimensions than almost all the other populations, except for Nasal root breadth which was smaller than the Caucasian, Asian, and African American populations.

On the other hand, Chilean females, show smaller facial dimensions than almost all the other populations, except for Nose protrusion and Subnasale-sellion length, which were larger than the Caucasian, African American, and Asian populations. These findings are consistent with previous studies that have found significant variations in facial dimensions across different ethnic populations.[37,39,42,46]

The findings of this study are similar to studies involving the Chilean working population, specifically in major head and face dimensions.[3] For example, Chilean males' Face length was the largest among Chinese, South Korean, and US populations. Chilean Head length was longer than Chinese and South Korean Head length, but shorter than the US head length. Larger head dimensions in the referred study also showed that Chilean Head breadth was smaller than Chinese and South Korean Head breadth. Similarly, Chileans' Face width was smaller than the US and Chinese's.[3] These results are in some way similar to those obtained by Monteiro et al.[41] where Brazilian adults showed significant differences in facial dimensions related to ethnicity, specifically regarding the lower third (mouth/chin) facial dimensions.

The implications of these findings on the design of personal respiratory protection devices are significant. A one-size-fits-all approach may not be effective in ensuring a proper fit for individuals from different populations. Manufacturers of respiratory protection devices should consider the variations in facial dimensions across various populations and ethnic groups when designing these devices. Several studies have recommended the use of anthropometric data to develop facial templates that may be used to design respiratory protection devices that fit different populations.[21,47,48] The present study demonstrates that, for the Chilean sample, the ISO panels present a higher level of match than the LANL panels (Table 6). This ISO standard suggests that the bivariate panel based on face width and length should at least cover 95% of the population.[27] It also states that in the selected population, the panel covers 96.7% of males and 98.7% of females; however, in the Chilean sample, this panel includes 90.81% of males and 99.39% of females (Table 6). This result shows good compliance with the standard for Chilean females, but a 9.19% risk for the Chilean male population.

Nose protrusion and Subnasale-sellion length are other important dimensions that influence the fit of PPE devices.[27,44] The study found that both Chilean males and Chilean females have significantly larger Nose protrusion and Subnasale-sellion length than other populations. This implies that PPE devices designed for Chilean workers need to adapt to larger nose dimensions to ensure an effective fit. Previous studies have shown that nose dimensions affect the fit of half-mask respirators and face masks, and proper fitting of these devices is critical for effective respiratory protection.[44,45]

Bigonial breadth and Face width are important dimensions that determine the width of the lower face, which affects the fit of PPE devices, such as respirators and face shields.[48] When compared with other populations, the study found that Chilean males have significantly larger Bigonial breadth and Face width, while Chilean females have smaller Bigonial breadth and Face width. This implies that PPE devices designed for Chilean workers need to adapt for wider and narrower lower face dimensions, respectively. Previous research has shown that facial width affects the fit of respirators and face shields, and proper fitting of these devices is critical for effective respiratory protection.[43]

Face length and Subnasale-sellion length are dimensions that determine the height of the face, which also affects the fit of PPE devices. The study found that Chilean males have significantly longer Face length and Subnasale-sellion length than other populations. This implies that PPE devices designed for Chilean males need to adapt to larger faces to ensure an effective fit. Previous research has shown that facial height affects the fit of respirators and face masks, and proper fitting of these devices is critical for effective respiratory protection.[43–45]

Maximum frontal breadth and Minimum frontal breadth are dimensions that determine the width of the forehead, which affects the fit of PPE devices such as headgear and face shields. The study found that Chilean males have significantly larger Maximum frontal breadth, while the opposite happened with Chilean females. This implies that PPE devices designed for Chilean workers need to adapt for wider foreheads for males and narrower foreheads for females to ensure an effective fit. Previous research has shown that forehead width affects the fit of various PPE devices such as headgear and face shields, and a proper fit is crucial to ensure adequate respiratory protection.[43]

In addition to the forehead width, other dimensions such as Face length, Subnasale-sellion length, and Lip length may also affect the fit of PPE devices. For instance, studies have found that Face length and Subnasale-sellion length were significantly associated with respirator fit among a Korean sample using different brands of quarter-face respirators.[42,44] The dimensions influencing the fit were mainly menton subnasale length, biocular breadth, and bitragion subnasale arc.[42] In the case of Chilean males, the Bitragion subnasale arc was significantly larger than in other populations.

These findings highlight the importance of considering anthropometric differences when designing PPE devices, particularly respiratory protection devices. A proper fit of these devices is crucial to ensure effective protection against hazardous airborne particles and prevent occupational illnesses.

Limitations

Certain constraints of this study should be noted. While it involved a sizable participant pool, the findings are somewhat constrained as they are derived from an analysis of a specific area within Chile. Also, Chile is nearly 4000 kilometers long, which makes it quite a challenge to get representative and sizeable samples from all the country's regions. This is especially challenging in terms of obtaining funding for large sample projects in developing countries. Despite that, Chilean genetics at the time of data collection was quite homogeneous, according to the first large genetic study.[6,49] It is important to highlight that the measurements presented in this article were obtained from individuals born in Chile, prior to the significant migration influx that the country has recently experienced, thus possibly contributing to somehow mitigate the constraints. Future studies should try to recruit bigger samples and account for ethnic differences, if and when they occur.

Conclusion

This study provides valuable information on the differences in anthropometric dimensions between male and female Chilean workers. The results indicate that males have larger anthropometric dimensions than females in all dimensions measured. These findings have important implications in designing the products that need to suit both male and female workers. It is important to consider individual variations in anthropometric dimensions for designing products to ensure that these are appropriate for a wide range of users.

The findings in the studies emphasize the importance of designing personal respiratory protection devices suitable for both male and female workers. That may be achieved by using adjustable straps or the availability of different size devices. Additionally, the design of the sealing surface of the device should account for the variations in facial contours between males and females. Also, it is important to consider the variations in facial dimensions of the different populations when designing these devices.

The implications of this study extend beyond the design of personal respiratory protection devices. Workplace safety regulations should also consider the differences in anthropometric dimensions between males and females. For example, employers should provide personal respiratory protection devices suitable for both male and female workers.

Finally, the study found significant variations in facial dimensions between male and female Chilean workers and, among Chilean workers and other populations. These findings have important implications for the design of personal respiratory protection devices. Using anthropometric data to develop facial templates that adapt to different populations may help to ensure the proper fit and enhance the effectiveness of such devices.

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Statements and declarations

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Informed consent

Written informed consent was obtained from all participants.

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