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Application of mismatch equations in dynamic seating designs

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ABSTRACT

Anthropometry is critical for product and workplace design. Highly prevalent, office work is associated with sedentarism and physical discomfort due to prolonged sitting. Dynamic seating (alternating across sitting, perching, and standing) has been suggested as an alternative to overcome those problems. The current study tested a large sample of anthropometric data for mismatch levels against national and international office furniture standards using dynamic seating as a framework with traditional and perching mismatch equations, applied to three recommended dynamic seating components. Dimensions present in the standards used did not match the majority of the sample. For sitting, seat width and depth individually presented the lowest levels of match, as well as under cumulative fit of all office furniture dimensions. However, these were alleviated when incorporating adjustability. Perching was shown to be generally impeded given commercially-available chair height options. Limitations in state-of-the-art perching equations are discussed, and two new models are proposed as design alternatives. Further research should focus on testing the criteria presented in this research through discomfort and objective measures.

1. Introduction

Anthropometric dimensions are common in designing products and workspaces across highly heterogeneous settings and users, from fire fighters (Hsiao et al., 2014) to highly specific sports equipment for people with disabilities (Bragança et al., 2018). Despite the many unsolved issues still present today, ergonomic standards – which have largely remained unchanged since the 1970's – enjoy more consensus regarding basic product design and user interface principles than ever before (Woo et al., 2016). Unequivocally, every design should focus on the end users, their optimal match, safety, better performance in products and workplaces (Pheasant and Haslegrave, 2006), and overall sustainability (Nadadur and Parkinson, 2013).

Technological advancements have gradually reduced physical labor; this, however, has contributed to sedentary office work. In conjunction with a modern lifestyle, problems associated with sedentary habits are more commonplace. Across greater postural and cardiovascular risks (Brownson et al., 2005; Parry and Straker, 2013; Sowah et al., 2018), spending large portions of the day sitting is associated with cardiovascular ill-health and musculoskeletal disorders, specifically low back pain (LBP) (Corlett, 2008; Kirk and Rhodes, 2011; Parry and Straker, 2013), where workers with especially static sitting behaviors appear more likely to experience chronic LBP compared to their pain-free counterparts (Bontrup et al., 2019).

In preventing low back pain, conventional seating models and standard office chairs generally encourage an upright sitting posture, maintaining right angles at the ankles, knees, hips and elbows; however, working in the same posture or sitting still for prolonged periods may not be healthy or feasible (Woo et al., 2016). Particularly, Zemp et al. (2016) indicated that subjects who suffer from acute low back pain tend to have more static sitting behaviors. Aiming to increase movement and posture alternation while working, office settings have instituted health interventions at the level of individuals (e.g. incidental walking promotion), organizations (e.g. policies for encouraging more movement), and physical workspaces (e.g. treadmill desks, sit to stand workstations, etc.) (Parry et al., 2017).

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The traditional sitting posture is based on a 19th century proposal from Staffel, a German doctor, whose “cubist approach” called for hip, knee, and ankle joints to maintain a 90° angle (Dainoff et al., 1994). Since that time, studies have shown that this posture can generate several problems, such as tilting the pelvis backwards (retroversion), rectification of the lumbar spine (Keegan, 1953), increase in intradiscal spinal pressure in the lumbar region (Andersson et al., 1974), overall decreased movement capacity of the spine, and reduced circulation in the legs due to lack of muscular activity (Stranden, 2000). More modern seating posture proposals, like that of Mandal (1982), are based on spinal biomechanics, and recommend an angle between the thighs and trunk closer to 130°; without losing verticality, these proposal has come to be known as astronaut or perching postures. This position presents several advantages over Staffel’s, such as tilting the pelvis forwards (anteversion), maintaining lumbar lordosis, and decreasing intradiscal pressure (Noro et al., 2012). Common ergonomic designs that promote these beneficial postures – as well as alternation and movement - have used higher chairs with forward slopes, saddle chairs, and adjustable height desks (Mandal, 1991; Roossien et al., 2017; Kuster et al., 2018; Noguchi et al., 2019; Chambers et al., 2019; Vaucher et al., 2015; Johnston et al., 2019). Demonstrated across different populations - from dentists (Gouvêa et al., 2018) to school children (Castellucci et al., 2016a,b) - hybrid sitting interventions incorporate furniture and equipment that allow users to modify their sitting posture according to their preference, work-related use, and comfort. Moreover, they have been shown to be more effective than any single static posture (Noguchi et al., 2019). Based on the above, “new” fundamental design principles to bear under the framework of Dynamic Sitting, i.e., posture changes among sitting, standing, and half-standing positions, also known as semi-sitting or perching, should be included in office settings (Bendix and Bridger, 2004). Several documented principles have addressed Dynamic Sitting, and conclude that height-adjustable desks, a high saddle chair or tilting seat pans, all of them allowing the feet to be placed on the floor, promote higher user comfort levels (Fettweis et al., 2017; Mandal, 1994a). While the design of chair and desk sitting equipment generally imposes specific criteria, these are often extracted from laboratory settings; as such, the resulting sitting design testing equations used to test or match a specific design to an intended population do not generally take posture variability into account (Nadadur and Parkinson, 2013; Pheasant and Haslegrave, 2006). This creates a challenge in defining standards aimed at larger populations (Dainoff et al., 1994).

In accommodating larger populations, there is a tendency toward either stratified fixed designs, or adjustable designs (Underwood and Sims, 2019). On one side, even when adjustable designs are used, economic constraints from final production costs may jeopardize product viability. On the other side, accommodating less than 90% of the population can have an impact on sustainability and users’ safety (Nadadur and Parkinson, 2013; Pheasant and Haslegrave, 2006). Therefore, there is as yet no consensus among ergonomics specialists in recommending “proper” sitting designs that fit the majority of a given population, especially when considering office furniture that allows sitting, standing, and perching postures. The aim of the current paper is thus to assess sitting, perching and standing design equations using a recent anthropometric database of Chilean workers on the level of mismatch using available standards and products for three common sitting designs: a) traditional seating, with fixed desk and adjustable chair; b) traditional seating, with adjustable chair and desk; and c) hybrid sitting, with adjustable chair and desk. Additionally, the paper discusses hybrid sitting criteria and presents novel equations that can be applied in order to design and test accommodation in any population.

2. THEORY/CALCULATION

Though heavily cited by the ergonomics field, the “upright posture” (hips, knees and ankles at right angles) has been associated with several issues: it cannot be sustained more than 1–2 min (Mandal, 1981), and can cause biomechanical problems by changing the lumbar curve from lordosis (standing position) to kyphosis (sitting position) (Zacharkow, 1987; Mandal, 1994a). Indeed, X-ray examinations of 25 people sitting upright found an average 60° hip flexion and 30° lumbar flexion (Schoberth, cited by Mandal, 1981). Time spent in poor postures can significantly increase low back issues in seated workers (Bendix, 1994), especially exacerbated by the current sedentary job context that requires being seated for longer periods (Coenen et al., 2017).

Not only has the cubist approach been shown to have issues, so too has lumbar support. Mandal (1982), in summarizing the four fallacious design principles of upright sitting, argued against lumbar support. Users often prefer seated postures with less flexion of the spine as afforded by higher desks and seats, with either tilting seat pans or saddle chairs (Mandal, 1994a). Additionally, a backrest or lumbar support will only have a beneficial effect with a negative or backwards-sloping seat angle (Mandal, 1994a); here lumbar support may maintain lordosis while seated, but users tend in practice to lean forward and not use the backrest at all (Bendix, 1994; Bendix and Bridger, 2004), especially when sitting at higher office furniture with greater trunk/thigh angles (Mandal, 1994a).

Fig. 1a shows traditional or conventional seating, upon which mismatch equations found in several standards and publications are based (Castellucci et al., 2015). Notably, there is little in the literature on perching design guidelines (Dainoff et al., 1994). The studies that do discuss it define perching as a trunk/thigh angle of at least 105° (Fig. 1b) to promote neutral pelvis and spine lumbar positions (Bendix and Bridger, 2004). Other authors have suggested an ideal trunk/thigh angle of 120° (Fig. 1c) (Mandal, 1991; Noro et al., 2012), while others consider perching at a trunk/thigh angle of at least 135° (Fig. 1d) (Keegan, 1953; Mandal, 1981; Noguchi et al., 2019; Rohlmann et al., 2011).

It is thus not trivial to question current standards. Office furniture that use larger dimensions than those recommended by traditional seating standards has been reported to reduce lumbar flexion and pain, and moreover increase users’ preference (Mandal, 1994a). Additionally, the positive seat angle (a forward sloping seat), based on the principle that most work activities require a forward leaning posture, dissuades backrest use (Lueder and Berg Rice, 2008); however, a backrest allows users to lean back and adopt an additional posture, thus contributing to dynamic seating (Bendix, 1994). Finally, Mandal (1994a)suggested that higher seating can be obtained using a seat height between 2 and 4 cm higher than popliteal height. In spite of advances in Dynamic Sitting guidelines, however, there are still design challenges. First, a fixed range as stated by Mandal regarding popliteal height, is proportionally very different for people of different dimensions; and secondly, perching is not often addressed in standards.

The current research will therefore take a novel approach to two essential components of dynamic seating, namely: standing (Fig. 1e) and perching. The following sections will discuss and build on current equations for calculating user match under traditional seating, perching, and standing.

2.1. Seat height equation

Depending on desired user posture, different seat height equations can be used. The sections below go into further detail for calculating seat height under a modality of traditional sitting only; or by sitting plus perching.

2.1.1. Traditional or conventional sitting

Widely used (Afzan et al., 2012; Agha, 2010; Castellucci et al., 2014; Dianat et al., 2013; Gouvali and Boudolos, 2006), the following equation has been used in estimating traditional sitting mismatch and for calculating seat height (SH):

$$(PH + SC)\cos 30^{\circ} \leq SH\ (PH + SC)\cos 5^{\circ}$$

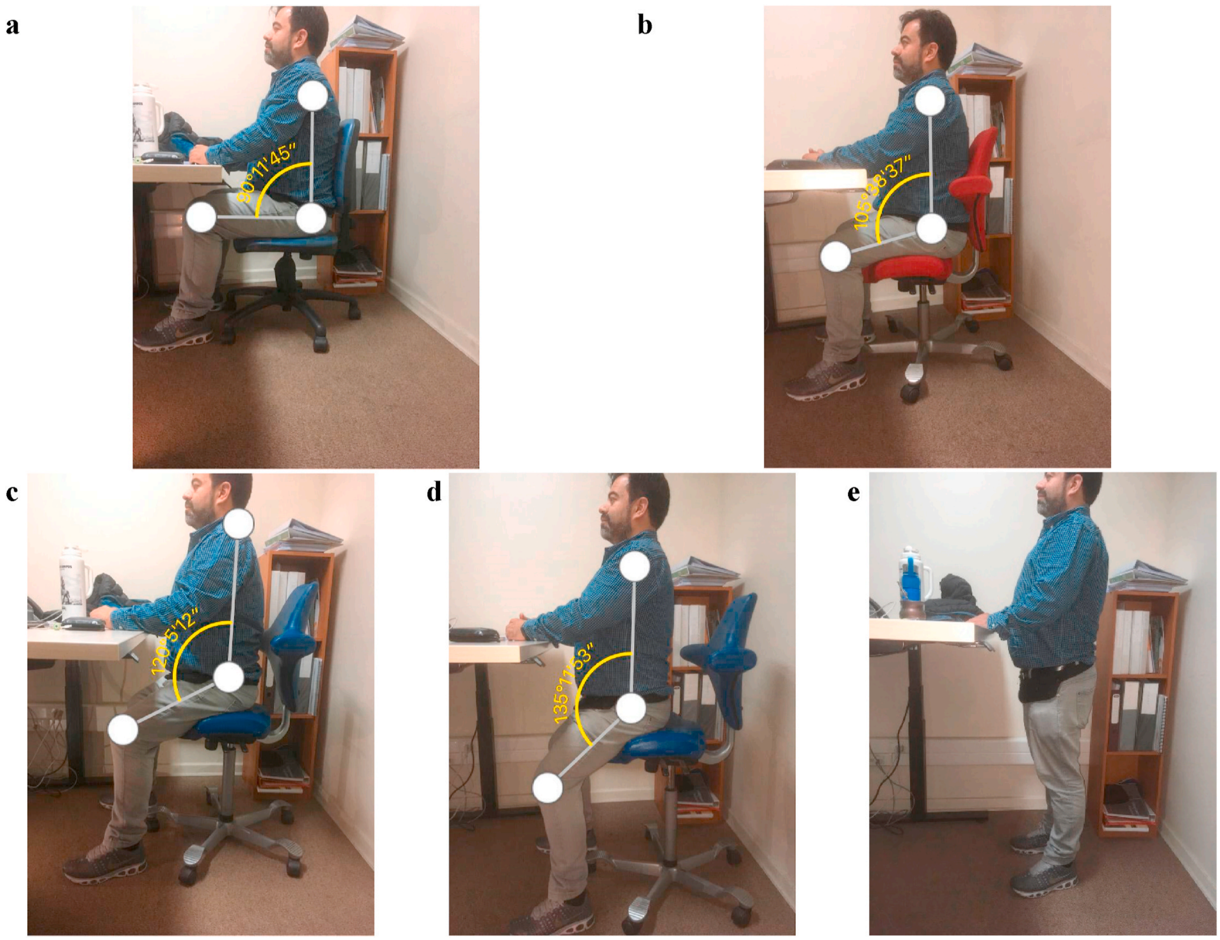


Fig. 1. Hybrid sitting postures. a) Traditional sitting with 90° trunk/thigh angle; b) perching with 105° trunk/thigh angle; c) perching with 120° trunk/thigh angle; d) perching with 135° trunk/thigh angle; and e) standing.

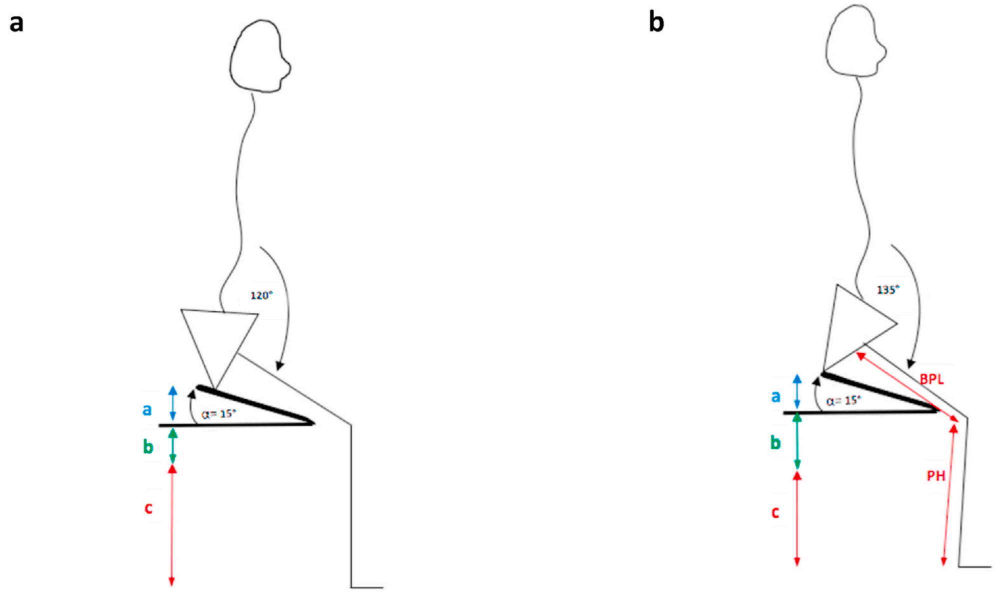


Fig. 2. Comparison of perching postures with slope and height. a) CEN (2015) standard; b) proposed forward slope alternative. PH: Popliteal height. BPL: Buttock-Popliteal length.

Where PH is popliteal height; SC, shoe correction; and SH, seat height.

2.1.2. Perching

As mentioned previously in sections 1 and 2, guidelines for perching suggest furniture height increases and angles between 120° and 135°, provided by either a taller seat with a forward slope, or a saddle chair. The criteria used by the European Committee for Normalization Standard for School Chairs - the only one that mentions perching (CEN, 2015) is given below:

$$\text{CEN criteria}: \cdot \text{SH (conventional sitting)} + \text{SD} \times 2Tan\alpha \, (\alpha = 15^\circ)$$

Where SH is seat height; and SD, seat depth.

This criterion provides for a 120° trunk/thigh user angle under two rationales. First, the standard is based not on the adjustability, but on the scalability/grading, therefore it uses seat depth dimensions as a basis to calculate seat height increases. It is worth noting that seat height (SH) represents a baseline obtained previously and recommended in the CEN standard, which is used similarly as a basis for the calculation, since as mentioned previously, it is based in grading. Secondly, under traditional seating, it provides the 90° trunk/thigh angle plus an additional 30° obtained through its resultant vertical height of 2*Tan α. Fig. 2a illustrates the CEN (2015) equation, where heights "a" and "b" are equal, given by the function described previously; height "c" is obtained from conventional seating; and total seat height is obtained adding heights a, b, and c.

Designers and ergonomic specialists may consider higher-angle perching (135°) by means of a forward slope; however, slope as the only factor would be too high (45°) and result in the buttocks sliding forward, transferring weight to the feet and increasing lower limb demands (Noguchi et al., 2019). A maximum forward slope angle of 15° has been previously discussed (Corlett and Gregg, 1994) and adopted by the CEN standard. In that sense, if a designer wishes to use a 15° forward sloped seat, seat height needs to be calculated increasing height. Fig. 2b shows a seat sloped forward by only 15° to avoid this sliding effect and weight transfer to the feet, which is calculated by the following equation:

$$\text{Forward slope } (15^\circ) \text{ criteria}: \cdot ((PH + 2.5) \cdot * \cdot \cos 5^\circ) + (BPL \cdot * \cdot \sin 30^\circ) + (BPL \cdot * \cdot \sin 15^\circ)$$

Where PH is popliteal height; and BPL, buttock-popliteal length.

In comparison, Fig. 2b illustrates a 135° perching angle, while also with a forward slope of 15°, implements the remaining 30° slope by increasing chair height. This is reflected in the first part of the criteria, with buttock-popliteal length (BPL*sin30°), represented by height "b" in green; popliteal height (PH * cos5°), represented by height "c" in red; a shoe correction of 2.5 cm; and chair height, with a 15° slope using BPL (height "a" in blue). Both criteria assume that the forward slopes maintain user weight mainly on the front part of the seat, with no need to use the backrest or carry more weight on the feet, following literature recommendations (Mandal, 1994b, 1994a, 1991). Here there is a novel utilization of buttock-popliteal length compared to the traditional seating criteria.

Building on the above, the perching criteria proposed and used throughout this paper blends an increased angle between the use of a saddle chair and an adjustable seat height. Given the nature of the present study, the raw data do not have a previously established seat depth dimension (as does CEN, 2015); as such, we fix BPL at sin 45° for a 135° thigh-trunk angle. The same criteria may be applied to achieve a 120° thigh-trunk angle using sin 30°; and a 105° thigh-trunk angle, with sin 15°.

$$\text{Saddle chair criteria}: \cdot (PH + 2.5) \cdot * \cos 5^\circ \cdot + \cdot BPL \cdot * \cdot \sin 45^\circ$$

Where PH is popliteal height; and BPL, buttock-popliteal length.

The application of buttock-popliteal length in this design criteria is necessary; seat depth is affected by a higher perching seat height. Indeed, it is likely that the user will use the front part of the seat, and so buttock-popliteal length - and not seat depth – will dictate behavior. Fig. 2 compares the two models under each rationale, where the former considers seat depth only (straight horizontal black line) and not the actual orientation of buttock-popliteal length in space. Rather, the seat height criteria under both sitting and perching are as follows:

$$Sitting: \cdot low \cdot \text{lim}it \cdot SHr \cdot \leq \cdot (PH + 2.5) \cdot * \cos 5^\circ \cdot \leq \cdot upper \cdot \text{lim}it \cdot SHr$$

$$Perching: \cdot low \cdot \text{lim}it \cdot SHr \cdot \leq \cdot (PH + 2.5) \cdot * \cos 5^\circ \cdot + \cdot BPL \cdot * \sin 45^\circ \cdot \leq \cdot upper \cdot \text{lim}it \cdot SHr$$

Where SHr is seat height range, PH is popliteal height; and BPL, buttock-popliteal length.

Since adjustable seats are used, it implies that there is a range with an upper and lower limit in order to sit and perch. If the resulting calculation for sitting is between the low and upper limit it means that the user will be able to sit. Oppositely, if the calculation is lower than the seat height lower limit, the user will be unable to sit, where the chair is too high for sitting. In the other hand, if the calculation is higher than the seat height upper limit, the user will be unable to sit, where the chair is too low for sitting. The same principles apply to the perching calculation. Furthermore, if both upper and lower limits of the adjustability range are inadequate for both calculations, the user will not be able to neither sit nor perch. In order to further explain the calculations and why this specific hybrid sitting section is done differently, is due to the fact than an actual range of commercially available hybrid chairs should accommodate both the upper and lower ranges in sitting and perching. For example, in section 4.2.1, it can be seen that the Hag Capisco Chair small lift has an adjustability range between 400 and 650 mm. In that case, as in all calculations aimed at testing hybrid sitting, the seat had to match upper and lower ranges for both sitting and perching together, since there could be the case where a seat has high mismatch % in lower and/or higher ends for sitting and not perching or vice versa. Therefore, match cumulative for both postures need to be tested using the formulae presented here. More details are provided in section 4. Results.

2.2. Desk height equation

Desk height was calculated with minimum and maximal adjustable heights. Equations test matches in a combination of seat height and desk height for traditionally seated, perching, and standing users. Standing equations follow Chaffin and Anderson (1991).

$$Low \cdot Limit \cdot (sitting): \cdot (PH \cdot + \cdot SC) \cdot \cos30^{\circ} \cdot + \cdot EHSit \leq \cdot DH \cdot \leq (PH \cdot + \cdot SC) \cdot \cos5^{\circ} \cdot + \cdot EHSit * 0.8517 + SHSit * 0.1483$$

$$High \cdot Limit \cdot (sitting): \cdot EHS\tan ding \cdot \leq \cdot DH \cdot \leq \cdot EHS\tan ding \cdot * 0.8517 + \cdot SHS\tan ding * 0.1483$$

Where PH is popliteal height; SC is shoe correction; EHSit, elbow height sitting; DH, desk height; and SHSit, shoulder height sitting.

2.3. Legroom depth equation

Calculations for legroom depth under conventional seating models, following Molenbroek et al. (2003), is given by:

$$\mathrm{Legroom \cdot depth \cdot traditional \cdot equation: \cdot BPL + PH \cdot \times \cdot \sin30^{\circ} + FL \cdot < \cdot LD}$$

Where BPL is buttock-popliteal length; PH, popliteal height; FL, foot length and LD, legroom depth.

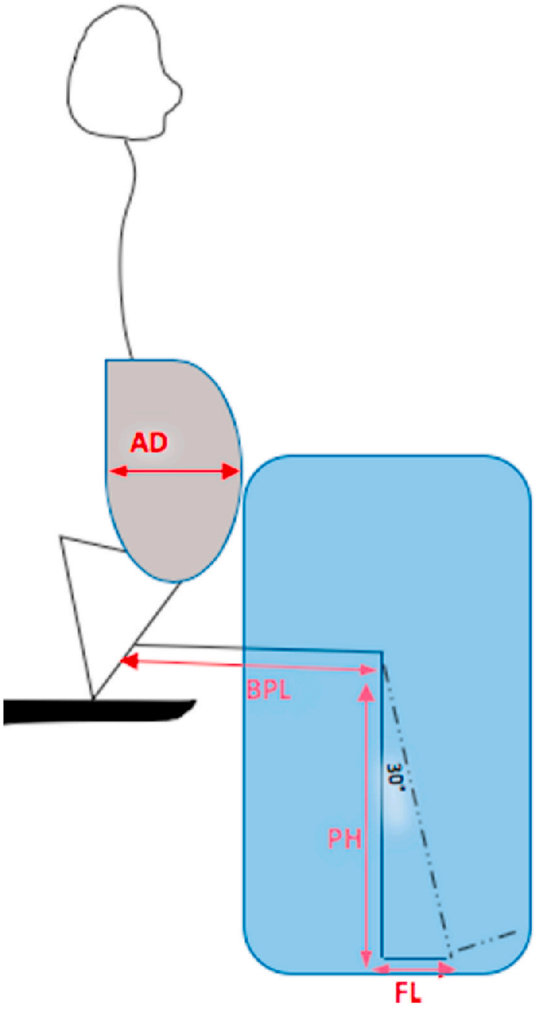


Fig. 3. Legroom depth equation considering abdominal depth.

The equation considers legroom depth for a knee extension of at least 30°; however, this calculation does not account for abdomen contact with the edge of the desk. Fig. 3 introduces abdominal depth (AD) to overcome the issue described above, given by:

$$\mathrm{Proposed \cdot equation \cdot for \cdot LD: \cdot (BPL \cdot + \cdot PH \cdot \sin30^{\circ} \cdot + \cdot FL) \cdot - \cdot AD \cdot < \cdot LD}$$

Where BPL is buttock-popliteal length; PH, popliteal height; FL, foot length; AD, abdominal depth and LD, legroom depth.

3. Materials and methods

3.1. Sample

As part of a larger 2016 research project, information was gathered on 32 distinct anthropometric dimensions by the authors of this article for N = 2946 workers (600 female and 2346 male) from the two most populous regions of Chile (Valparaíso and Metropolitana), distributed across nine economic sectors (Agriculture and Fishing; Mining; Manufacturing; Electricity; Construction; Commerce; Transport and Communications; Financial Services; and Communal and Personal Services). Details on sample, procedure, reliability, and results are available in Castellucci et al. (2019).

Measurements were collected manually by specialized teams of physiotherapists who underwent training and performed pilot studies to assess both inter- and intra-measurer reliability, ensuring high quality measurements (Viviani et al., 2018). The results for interrater reliability using ICC showed, according to Portney and Watkins (2008), strong

Table 1
Anthropometric dimensions used in the current research.

Anthropometric measurements	Definition
Shoulder height standing (SHstand)	vertical distance from the floor to the acromion.
Elbow height standing (EHstand)	taken with a 90° angle elbow flexion. as the vertical distance from the bottom of the tip of the elbow (olecranon) to the floor.
Shoulder height sitting (SHsit)	vertical distance from subject's seated surface to the acromion.
Elbow height sitting (EHsit)	taken with a 90° angle elbow flexion. as the vertical distance from the bottom of the tip of the elbow (olecranon) to the subject's seated surface.
Abdominal depth (AD)	maximum horizontal distance from the vertical reference plane to the standard sitting position.
Thigh thickness (TT)	vertical distance from the highest uncompressed point of thigh to the subject's seated surface.
Buttock-Popliteal Length (BPL)	horizontal distance from the popliteal surface to the rearmost point of the buttock.
Popliteal height (PH)	vertical distance from the floor or footrest and the posterior surface of the knee (popliteal surface).
Hip width (HW)	horizontal distance measured in the widest point of the hip in the sitting position
Foot length (FL)	Maximum distance from rear of the heel to of the longest (first or second) toe, measured parallel to the longitudinal axis of the foot.

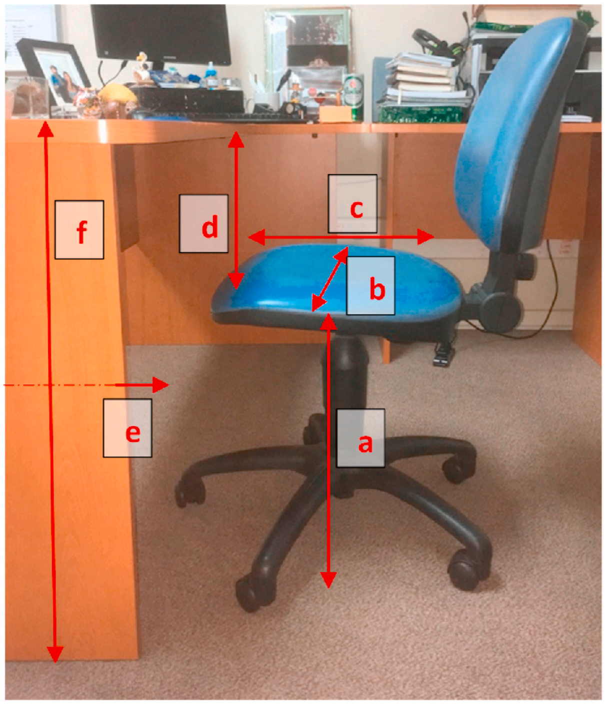


Fig. 4. Office furniture dimensions used. a) seat height; b) seat width; c) seat depth; d) seat to desk clearance; e) legroom depth; and f) desk height.

Table 2

European (CEN) and Chilean (ISP) recommended office furniture dimensions.

Furniture dimension	ISP (in mm)	CEN (in mm)
Seat Height (SH)	350–500	400–510
Seat Width (SW)	460	400
Seat Depth (SD)	400	400–420
[a]Seat to Desk Clearance (SDC)	200–350	180–290
^ Seat to Desk Clearance fully adjustable (SDCa)	50–350	90–400
Legroom Depth (LD)	790	800
Desk height adjustable (DHa)	600–750	650–850
Desk height fixed (DHf)	750	740

[a] SH adjustable and DH fixed; ^ both SH and DH adjustable; note: Desk top thickness 50 mm.

results for all the dimensions (Elbow height sitting: 0.793, Abdominal Depth: 0.942, Thigh Thickness: 0.879, Buttock Popliteal Length: 0.878, Popliteal height: 0.929, Hip Width: 0.784 and Foot length: 0.968). Shoulder height standing and Elbow height standing were derived from other dimensions, thus ICC results for these were not computed.

3.2. Anthropometric dimensions

Table 1 shows the dimension data categories in the current research, as commonly used in designing sitting postures (Castellucci et al., 2010; Pheasant and Steenbekkers, 2005).

3.3. Furniture dimensions

Furniture dimensions were seat height, seat width, seat depth, seat to desk clearance (seat height adjustable and desk height fixed), seat to desk clearance (fully adjustable), legroom depth, desk height (adjustable), and desk height (fixed). These dimensions are illustrated in Fig. 4, and summarized in Table 2.

Table 3

Mismatch equations for office furniture.

Furniture dimension	Mismatch equation
SH (sitting)	$(PH + SC)\cos 30^\circ \leq SH \leq (PH + SC)\cos 5^\circ$
*SH (sitting and perching)	Sitting: low limit SHr $\leq (PH+2.5) * \cos 5^\circ \leq$ upper limit SHr Perching: low limit SHr $\leq (PH+2.5) * \cos 5^\circ + BPL * \sin 45^\circ \leq$ upper limit SHr
SW	$HW < SW$
SD	$0.80BPL \leq SD \leq 0.95BPL$
SDC	$TT + 2 < SDC$
LD	$(BPL + PH \sin 30^\circ + FL) - AD < LD$
DH Sitting	$(PH + SC)\cos 30^\circ + EHSit \leq DH \leq (PH + SC)\cos 5^\circ + EHSit * 0.8517 + SHSit * 0.1483$
*DH Standing	$EHStanding \leq DH \leq EHStanding * 0.8517 + SHStanding * 0.1483$

* Hybrid sitting postures SH, seat height; SHr, seat height range; SW, seat width; SD, seat depth; SDC, Seat to Desk Clearance; LD, leg room depth; DH, desk height; PH, popliteal height; SC, shoe correction; HW, Hip width; BPL, buttock-popliteal length; TT, thigh thickness; FL, foot length; AD, abdominal depth; EHsit, elbow height sitting; SHSit, shoulder height sitting; EHStanding, elbow height standing; SHStanding, shoulder height standing.

3.4. Procedure

As described in the introduction, sitting, perching and standing scenarios were tested using the available anthropometric data, each addressed in respective subsections below. All alternatives were compared against the standard criteria from the Chilean *Instituto de Salud Pública* (ISP, 2016) and European Committee for Standardization (CEN, 2011, 2000). All mismatch equations involving heights included a shoe correction factor (SC) of 2.5 cm (25 mm), since all measurements were taken barefoot as established by the respective ISO standard (ISO, 2008).

Table 2 summarizes standard dimensions. The acceptable level of accommodation is considered 90%, following (Pheasant and Haslegrave, 2006). Note that Table 2 shows seat to desk clearance considers two configurations: a) adjustable seat height and fixed desk (SDC) b) adjustable seat height and adjustable desk height (SDCa).

The match of the office furniture dimensions in Table 2 were tested against both single metrics and cumulative anthropometric dimensions. Calculated cumulative fit or transversal mismatch values - defined as the mismatch between cumulative values of the different furniture dimensions (Castellucci et al., 2014) – are given as percentage of workers whose anthropometric data match furniture dimensions. Cumulative fit was applied using a bottom to top approach, starting from the base (feet flat on the ground), following Castellucci et al. (2014).

Some equations in the following sections are two-way, i.e. with both minimum and maximum limits. These cases use three categories to classify match levels: (1) “Match” level, when the furniture dimensions are between the minimum and maximum limits; (2) “High mismatch” level, where the maximum equation limit is less than the furniture dimension, indicating greater furniture dimensions than needed; and (3) “Low mismatch” level, where the minimum equation limit is greater than the furniture dimensions, which are thus insufficient for the recommended standards (Castellucci et al., 2016a,b).

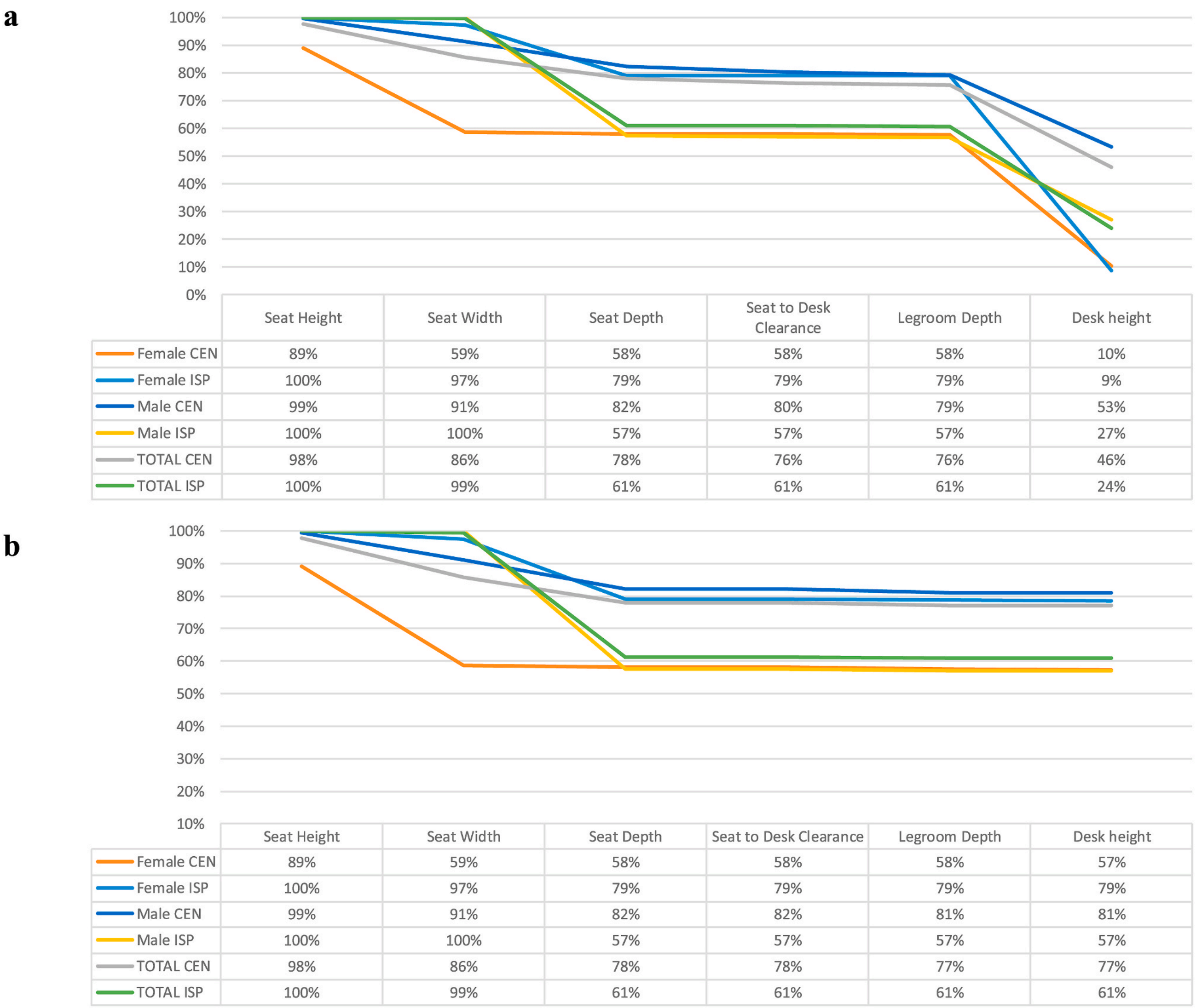
3.4.1. Traditional seating

Table 3 shows the different mismatch equations used, as discovered in the literature review (see, e.g. Castellucci et al., 2015). Testing was performed in the order of seat height, seat width, seat depth, seat to desk clearance, legroom depth, and desk height. Hybrid sitting posture equations were developed by the researchers, as explained in the Theory/calculation section, to include legroom depth, and seat and desk heights. These are indicated in Table 3 with an asterisk (*). Also, perching equations used can be seen in Table 3.

Mismatch levels were calculated using the equations presented in Table 3 for the two traditional seating configurations. Adjustable height

Table 4
Percent mismatch, traditional seating.

Furniture Dimensions	Condition	Adjustable Chair and Fixed Desk						Adjustable Chair and Desk					
		CEN			ISP			CEN			ISP		
		Female	Male	Total	Female	Male	Total	Female	Male	Total	Female	Male	Total
Seat Height	**H. Mismatch**	11.0%	0.5%	**2.3%**	0.0%	0.0%	**0.0%**	11.0%	0.5%	**2.3%**	0.0%	0.0%	**0.0%**
	Match	89.0%	99.5%	**97.7%**	100.0%	100.0%	**100.0%**	89.0%	99.5%	**97.7%**	100.0%	100.0%	**100.0%**
	L. Mismatch	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**
Seat Width	**H. Mismatch**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**
	Match	65.2%	91.7%	**87.2%**	97.4%	99.9%	**99.5%**	65.2%	91.7%	**87.2%**	97.4%	99.9%	**99.5%**
	L. Mismatch	34.8%	8.3%	**12.8%**	2.6%	0.1%	**0.5%**	34.8%	8.3%	**12.8%**	2.6%	0.1%	**0.5%**
Seat Depth	**H. Mismatch**	0.6%	0.1%	**0.2%**	0.6%	0.1%	**0.2%**	0.6%	0.1%	**0.2%**	0.6%	0.1%	**0.2%**
	Match	96.6%	87.8%	**89.3%**	80.4%	57.4%	**61.3%**	96.6%	87.8%	**89.3%**	80.4%	57.4%	**61.3%**
	L. Mismatch	2.8%	12.1%	**10.5%**	19.0%	42.5%	**38.5%**	2.8%	12.1%	**10.5%**	19.0%	42.5%	**38.5%**
Seat to Desk Clearance	**H. Mismatch**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**
	Match	99.8%	92.6%	**93.9%**	100.0%	95.8%	**96.5%**	100.0%	100.0%	**100.0%**	100.0%	100.0%	**100.0%**
	L. Mismatch	0.2%	7.4%	**6.1%**	0.0%	4.2%	**3.5%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**
Legroom Depth	**H. Mismatch**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**
	Match	99.0%	97.0%	**97.4%**	98.6%	95.3%	**95.8%**	99.0%	97.0%	**97.4%**	98.6%	95.3%	**95.8%**
	L. Mismatch	1.0%	3.0%	**2.6%**	1.4%	4.7%	**4.2%**	1.0%	3.0%	**2.6%**	1.4%	4.7%	**4.2%**
Desk height	**H. Mismatch**	74.6%	27.6%	**35.6%**	83.0%	39.3%	**46.7%**	1.6%	0.1%	**0.4%**	0.2%	0.0%	**0.0%**
	Match	25.4%	72.2%	**64.3%**	17.0%	60.7%	**53.3%**	98.4%	99.9%	**99.6%**	99.8%	100.0%	**99.9%**
	L. Mismatch	0.0%	0.2%	**0.1%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**	0.0%	0.0%	**0.0%**



	Seat Height	Seat Width	Seat Depth	Seat to Desk Clearance	Legroom Depth	Desk height
Female CEN	89%	59%	58%	58%	58%	10%
Female ISP	100%	97%	79%	79%	79%	9%
Male CEN	99%	91%	82%	80%	79%	53%
Male ISP	100%	100%	57%	57%	57%	27%
TOTAL CEN	98%	86%	78%	76%	76%	46%
TOTAL ISP	100%	99%	61%	61%	61%	24%

	Seat Height	Seat Width	Seat Depth	Seat to Desk Clearance	Legroom Depth	Desk height
Female CEN	89%	59%	58%	58%	58%	57%
Female ISP	100%	97%	79%	79%	79%	79%
Male CEN	99%	91%	82%	82%	81%	81%
Male ISP	100%	100%	57%	57%	57%	57%
TOTAL CEN	98%	86%	78%	78%	77%	77%
TOTAL ISP	100%	99%	61%	61%	61%	61%

Fig. 5. Cumulative mismatch with CEN and ISP standards, by gender and total sample a) adjustable chair and fixed desk; and b) adjustable height chair and desk.

chair and desk setups, in contrast, were calculated using minimum and maximum chair and desk ranges (adjustability ranges) with adequate population accommodation (at least 90%).

3.4.2. *Hybrid sitting (sitting, perching and standing) using adjustable chair and desk height*

This section analyzes only heights; depths and widths are excluded, since they were already checked for mismatch in the previous section. Height matches were assessed with a bivariate method, with at least two anthropometric dimensions significant to product ergonomics following (Dianat et al., 2018). All equations used can be seen in Table 3.

This section focuses on height - and seat height in particular - as an important measure of mismatch (Castellucci et al., 2016a,b) through a bottom-top approach, in the order of seat height and desk height (Table 3). The authors undertook this setup to test if a single design could match the sample population across sitting, perching, and standing behaviors. Dimensions, for adjustable chair configurations, were compared using Capisco (by HAG®) and Balance (by Score Amazone®) saddle chairs; and, for desks, a commercially available adjustable height desk (E-model®) and the European standard (CEN, 2011).

Since full adjustability allows users to readily modify seat to desk clearance, this variable was not tested.

4. Results

4.1. *Traditional seating*

Table 4 shows the levels of dimension mismatch for the total sample, for females, and for males under two configurations: a) adjustable height chair, with a fixed height desk; and b) adjustable height chair and desk. Note from Table 4 that, for an adjustable height chair with a fixed height desk, both Chilean (ISP, 2016) and European (CEN, 2000, 2011) standards have match percentages above 90% for the following dimensions: seat height (CEN:97.7%; ISP:100%); seat to desk clearance (CEN:93.9%; ISP:96.5%); and legroom depth (CEN:97.4%; ISP:95.8%). The lowest level of match for both standards was desk height, with a mismatch of CEN:35.7%; ISP:46.7% (high mismatch); followed by seat depth, with CEN:10.5%; ISP:38.5% mismatch (low mismatch). Seat width showed a low mismatch by CEN standards (12.8%).

Next, incorporating an adjustable height desk provides match percentages above 90% for the following dimensions: seat to desk clearance (ISP:100%, CEN:100%); seat height (ISP:100%, CEN:97.7%); desk height (ISP:99.9%, CEN:99.6%); and legroom depth (ISP:95.8%, CEN:97.4%). The lowest total level of match for both standards was seat depth (ISP:61.3%, CEN:89.3%). Seat width under CEN standards had 87.2% match.

All single metrics had higher match levels in males than in females, with the exception of seat depth and legroom depth.

Fig. 5 graphs the cumulative matches for each configuration of traditional seating from Table 4. Fig. 5a, the fixed desk, shows significantly lower total cumulative match in both standards (CEN: 46%; ISP: 24%). Under Chilean standards for traditional office furniture, only 24% of users are accommodated by the design. Female users suffer especially low cumulative match (ISP: 9%, CEN: 10%) when compared to males (ISP: 27%, CEN: 53%). In almost all comparisons, CEN standard dimensions, while still low, have twofold match levels over ISP dimensions; it would seem that the European standard provides a better match for Chilean users than the corresponding national ISP Standard.

Next, Fig. 5b, adjustable chair and desk height, shows that total cumulative match dimensions are considerably improved over those of the fixed desk (Fig. 5a): 31% and 37% for CEN and ISP, respectively. This reduced mismatch is almost certainly due to the addition of an adjustable desk. Despite improvements, this configuration still yielded low match percentage for both standards (ISP:61%, CEN:77%). The highest level of cumulative match was for ISP dimensions and females (79%); and CEN dimensions and males (81%). In general, cumulative match is higher in males under CEN standards compared to ISP dimensions, and vice versa for female users.

4.2. *Hybrid sitting (sitting, perching, and standing) using adjustable height chair and desk*

4.2.1. *Hybrid sitting with adjustable height chair*

The current research also tested match levels under a hybrid sitting

Table 5
Mismatch percentage for hybrid sitting with adjustable height chair.

Gender	Condition	HAG Capisco			Amazone Balance		
		Small	Medium	Large	Small	Medium	Large
Female	Sitting 90°	11.0%	99.2%	100.0%	99.6%	100.0%	100.0%
	Perching 120°	70.6%	59.6%	0.0%	86.6%	0.4%	13.4%
	Sitting 90° and Perching120°	81.4%	100.0%	100.0%	100.0%	100.0%	100.0%
	Sitting 90°	11.0%	99.2%	100.0%	99.6%	100.0%	100.0%
	Perching 135°	100.0%	100.0%	2.2%	100.0%	53.4%	0.0%
	Sitting 90° and Perching135°	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Perching 105°	0.0%	0.6%	87.6%	1.6%	78.4%	99.6%
	Perching 135°	100.0%	100.0%	2.2%	100.0%	53.4%	0.0%
	Perching 105° and Perching135°	100.0%	100.0%	89.8%	100.0%	100.0%	99.6%
Male	Sitting 90°	0.5%	80.7%	100.0%	90.4%	100.0%	100.0%
	Perching 120°	96.2%	92.9%	0.0%	99.0%	5.8%	1.0%
	Sitting 90° and Perching120°	96.7%	100.0%	100.0%	100.0%	100.0%	100.0%
	Sitting 90°	0.5%	80.7%	100.0%	90.4%	100.0%	100.0%
	Perching 135°	100.0%	100.0%	26.4%	100.0%	90.3%	2.7%
	Sitting 90° and Perching135°	100.0%	100.0%	100.0%	90.4%	100.0%	100.0%
	Perching 105°	1.6%	0.8%	39.7%	6.3%	27.6%	93.7%
	Perching 135°	100.0%	100.0%	26.4%	100.0%	90.3%	2.7%
	Perching 105° and Perching135°	100.0%	100.0%	66.1%	100.0%	100.0%	96.4%
Total	Sitting 90°	2.3%	83.8%	100.0%	92.0%	100.0%	100.0%
	Perching 120°	91.9%	87.3%	0.0%	96.9%	4.9%	3.1%
	Sitting 90° and Perching120°	94.1%	100.0%	100.0%	100.0%	100.0%	100.0%
	Sitting 90°	2.3%	83.8%	100.0%	92.0%	100.0%	100.0%
	Perching 135°	100.0%	100.0%	22.3%	100.0%	84.0%	2.2%
	Sitting 90° and Perching135°	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	Perching 105°	1.4%	0.8%	47.9%	5.5%	36.2%	94.7%
	Perching 135°	100.0%	100.0%	22.3%	100.0%	84.0%	2.2%
	Perching 105° and Perching135°	100.0%	100.0%	70.2%	100.0%	100.0%	97.0%

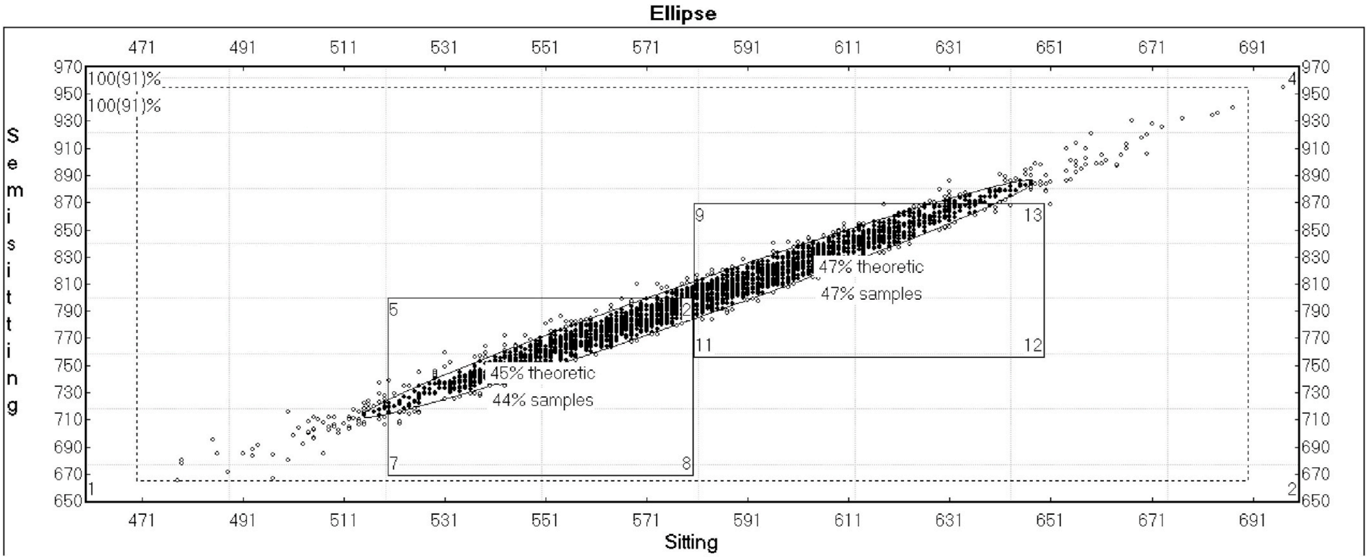


Fig. 6. Seat proposal for sitting and perching. Sitting at 105° and 135° trunk/thigh angle. Axes units in mm.

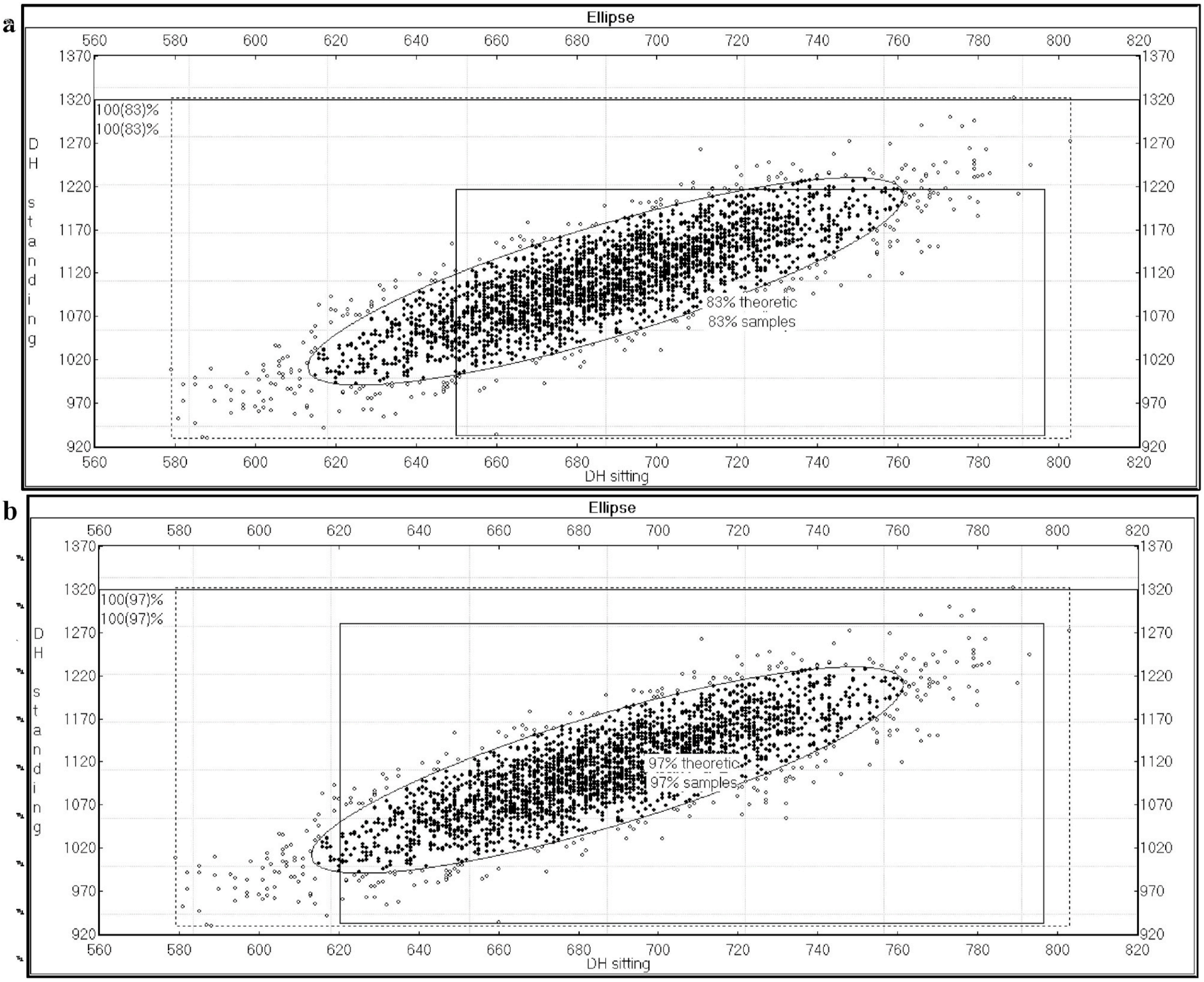


Fig. 7. Adjustable desk height (DH) levels and standing match a. CEN (2011) standard levels of match; b. Commercially available E-model® height adjustable desk. Axes units in mm.

configuration. In order to match 90% of the population, seat height was set from 410 to 760 mm. This allows users to be seated at a 90° thigh/trunk angle (using the 5th percentile of PH) and to perch at a thigh/trunk angle of 120° (using the 95th percentile of popliteal height) Also, the analysis of a perching trunk/thigh angle of 135° was done. The only way to increase angle is to also increase seat height, with users seated between 410 and 870 mm. Similarly, 90% of intended users accommodated by this configuration; however, this may provide an additional challenge, due to the large lift range needed for these minimum and maximum seat height values.

Table 5 shows total and gender-specific match and mismatch percentages for the three trunk/thigh angle ranges tested, using three lift sizes each, for the HAG Capisco (small: 400–650 mm, medium: 480–660 mm, large: 580–830 mm) and Amazone Balance (small: 490–630 mm, medium: 570–760 mm, large: 630–880 mm) chairs. Each trunk/thigh angle range is presented in terms of the mismatch for each posture (Sitting; Perching; and Sitting and Perching).

Table 5 shows that overall hybrid sitting (perching and sitting) has high levels of mismatch for both chairs and their respective lifts. For example, the lowest level of mismatch was found for sitting at 90° and perching at 120° with the HAG Capisco small lift match showing a 94.1% mismatch (5.9% match), and 100% mismatch of the intended users with medium and large lifts. Interestingly, this is the only configuration where females (81.4% mismatch) had lower levels of mismatch than males (96.7%). The 90°–135° trunk/thigh range had 100% mismatch. Note that when testing at 105° and 135° perching trunk/thigh angles provided a mismatch of 70.2% (29.8% match) with the large lift. It is worth noting that the calculations used a 105° trunk/thigh angle, which is technically where perching starts (Bendix and Bridger, 2004), thus in that case, even though there are still high levels of mismatch, it is the best result obtained, since a “lower” perching of 105° is closer to an ideal perching of 135°.

Table 5 also shows that the Balance chair did not match users at either 90° sitting and 120° perching trunk/thigh angles or at 90°–135° trunk/thigh angles. The best results also occurred at 105° and 135° perching trunk/thigh angles with the large lift, under which 97% levels of mismatch were observed (3% match).

The results obtained from the two commercially available adjustable chairs were shown insufficient in their lift capacity for a 90° seated, 120° perched, or 135° combination trunk/thigh angles. Due to this, and not considering the use of footrest, we propose a seat height that would allow users in this sample to vary between postures, i.e., perching at 105° and at 135° (Fig. 6). The former (520–800 mm) accommodates the first 44% (female: 73%, male: 38%); and the latter (580–870 mm), 47% (female: 12%, male: 56%). With these two proposed seat heights, 91% of the total sample is accommodated. Although this recommendation is meant for the adjustable saddle chair configuration, it can also be implemented with a forward slope not exceeding 15°.

4.2.2. Hybrid sitting with adjustable desk

Fig. 7a shows the levels of sample accommodation under minimum adjustable CEN (2011) standard desk heights (650 mm–1220 mm) for sitting and standing. Only 83% of the sample is accommodated by the design (female: 49%, male: 93%). Fig. 7b shows the levels of accommodation with the commercially available E-model® height adjustable desk (620–1280 mm). Here 97% of the sample is accommodated by the design (female: 86%, male: 99%).

5. Discussion

The present study demonstrates that common standards do not easily allow for dynamic seating furniture design, consistent with Dainoff et al. (1994). Though traditional seating cumulative match levels calculated using ISP and CEN standards remained under 90%, match levels were higher with both adjustable desk and chair. This trend was most evident with the height adjustable desk, providing nearly 99% match level for desk height. These results were expected, since a lack of desk adjustability will also reduce user accommodation percentage (Underwood and Sims, 2019). It was shown that a single design will not accommodate most users, and so configurations may either stratify for more than one desk height, or more simply incorporate adjustable desks or a footrest.

For single metric comparisons, seat depth presented the lowest levels of match under both standards, consistently too short for the sample population. However, across almost every single metric, while CEN standard dimensions were low, they still had twofold match levels over ISP dimensions – indicating that European standards provide better match levels for Chilean users than the corresponding ISP national Standard.

The highest levels of cumulative match occurred with ISP dimensions and female users; and CEN dimensions, for males. For males, this was markedly true for seat depth and legroom depth. In general, CEN dimensions are bigger than those in the ISP standards; therefore, these results indicate that larger dimensions fit males and their generally greater segmental anthropometrics, who tend to require more space than females. Interestingly, CEN seat width had the lowest match level, likely mediated by secular trends in the Chilean population over the last two decades related to the increase in obesity (Kagawa et al., 2016; MINSAL, 2011; Ratner et al., 2008; Salinas et al., 2014; Vio et al., 2010). The seat width mismatch found here reflects previous research results (Molenbroek et al., 2017).

In gender discrepancies, females had generally lower match levels compared to males. It seems that distinct seating designs are necessary to address female anthropometry. Indeed, even though gender equality indicators have improved in the country, females are still underrepresented in formal work and legislative power contexts (Castellucci et al., 2020), mirrored in the female anthropometric mismatches found here. Furthermore, the database used for analysis is likely limited by the trend of female underrepresentation in formal work arrangements in Chile.

In almost all comparisons, CEN standard dimensions, while low, were still double the match levels of the ISP dimensions. It is likely that the national ISP Standards have yet to adapt to more current anthropometrics.

Results from testing commercially-available chairs show that facilitating dynamic seating under ideal conditions has practical impediments: it may not be feasible to sit, perch, and stand with just one design. Furthermore, while there is a challenge in designing a chair with a lift that allows for sitting at 90° and perching at 120° or 135° trunk/thigh angles without using a footrest, some authors have cautioned against the 90° seated trunk/thigh angle (Bendix and Bridger, 2004; Mandal, 1994b, 1994a, 1991, 1981). Regardless, the equations presented here will allow ergonomists and designers to define workstation dimensions that can incorporate sitting, perching and standing positions. Finally, and due to the bivariate approach applied in this paper, further studies with other raw data sets are required to test the proposed criteria.

This study adds to the literature on dynamic sitting. A recent review has shown that sit to stand work stations most significantly impact behavioral changes (e.g. sitting for less time) and reduce discomfort (Chambers et al., 2019); while also tending to, though less significantly, influence physiological (e.g. energy expenditure), psychological (e.g. work satisfaction), and posture outcomes. It is likely that the sit/stand time ratio, training, and follow-up impacts these outcomes, as reported by the authors of the previously cited review. Different interventions have tried to address sedentary behavior associated with office work, for instance, increasing energy expenditure through the use of dynamic chairs: although dynamic seating did result in higher levels of energy expenditure, this was still below the sedentary threshold of 1.5 METS (Synnott et al., 2017).

The proposal made in the current study may be used to inform policy regarding discomfort and behavior, especially as concerns users alternating postures among sitting, perching, and standing. In 1981, Mandal recommended a position with a 135°-trunk–thigh angle to favor physiological lumbar lordosis (Mandal, 1981), requiring furniture designers to increase either seat height or slope. However, Mandal did not take dynamism into account (Fettweis et al., 2017): even a static perching posture, while encouraging an erect spine posture with forward sloping chairs, has setbacks, such as increased pressure distribution towards the feet with slopes over 15° (Corlett and Gregg, 1994; Fettweis et al., 2017); higher knee and ankle extensor activity (Hamaoui et al., 2016); and undesirable lower limb muscle overactivity to prevent the body from sliding. To best mitigate these issues, a saddle chair with an overall height increase has been consistently proven to be both biomechanically better and preferred by users (Bendix, 1994; Bendix and Bridger, 2004; Corlett, 2009, 1999; Mandal, 1994b, 1994a; 1991, 1981; Noro et al., 2012). Furthermore, the saddle configuration has been shown to create additional benefits, such as a consistent scrotal temperature due to more open trunk/thigh and hip angles compared to traditional seating (Koskelo et al., 2005).

In spite of the promising results and validity with previous studies, the results of this research should be subjected to experimental fitting trials. Anthropometric match does not always ensure comfort and preference (Bahrampour et al., 2019). Subjective and objective measurements of discomfort in fitting trials are needed. Pressure distribution measurements, electromyography, or posture analysis – which only assess comfort indirectly - may not be apparent in subjective methods, and so both methods are generally required (Bahrampour et al., 2019).

In sum, highly adjustable office stations will likely satisfy most end-users. That said, adjustable chair functions still require further theoretical study and practical implementation. The novel models proposed here for adjustable chairs and desks should be implemented, in both initial training and longitudinal follow-up, in future experiments to test the proposed match equations with real users (Bahrampour et al., 2019; Chambers et al., 2019). Indeed, and in spite of the promising results, it has been previously shown that office workers know only - and use less than - half of their available adjustable chair functions. The lack of knowledge and barriers from complex mechanisms and individual differences can be addressed by practical implementations and case studies (Bahrampour et al., 2019).

Following Chambers et al. (2019), the authors call for further longitudinal design tests with real users regarding sit-stand ratio and exposure. Experimental designs to measure end-user experiences over time will determine short-term and long-term comfort, which may not always coincide (De Looze et al., 2003). Such future studies may also look to quantify pressure differences in the feet and buttocks during dynamic seating based on variances in trunk/thigh angles, seat shape, and height.

6. Conclusions

The recommended ISP and CEN standard dimensions tested in the current research were shown not to adequately accommodate Chilean workers. Dynamic seating, although beneficial for users, is impeded by the widespread use of less adjustable office furniture. Should users wish to sit, perch, and stand, adjustability of desks and chairs is paramount; this desire cannot be addressed with the dimensions of the office chairs tested. None of the chairs demonstrated sufficient lift to fulfil a majority sample match under traditional seating and perching models. Instead, it was shown that two distinct height configurations are needed to provide adequate matching (>90%) for a seated 105° trunk/thigh angle and its associated benefits over the traditional cubist 90° trunk/thigh angle. Furthermore, to allow dynamic sitting, perching, and standing, the study presents novel equations for higher saddle chairs or forward sloped chairs. However, the designs derived from these equations need to undergo longitudinal tests in the field for subjective and objective measures of comfort.

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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