

## Evaluating a novel maximum desk height equation

### Integrating biomechanical safety and anthropometric fit in educational furniture design

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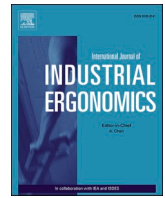
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## Evaluating a novel maximum desk height equation: Integrating biomechanical safety and anthropometric fit in educational furniture design

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### ABSTRACT

This study evaluates a new equation for defining maximum desk height in educational settings, comparing it with the traditional Chaffin and Anderson-based equation through biomechanical analysis. The new equation, based on 30° shoulder abduction and 35° flexion, was tested against established criteria in a quasi-experimental study involving 34 participants. Using motion capture and surface EMG, we analyzed shoulder kinematics and muscle activity during six standardized tasks performed at two desk heights. Results showed no significant differences in shoulder kinematics safety parameters between setups, while EMG data revealed consistent muscle activity patterns below 10 % MVC for both conditions. Performance metrics across tasks showed no significant differences between desk heights. Preference analysis indicated no overall significant difference between conditions, although gender-specific patterns emerged with 66 % of women preferring the proposed height. Discomfort levels were comparable between conditions. Theoretical testing of the new equation on existing databases (n: 2261 students; n: 2946 workers) demonstrated improved anthropometric fit, increasing match rates from 63 % to 94 % in students and reducing high mismatch cases from 46.7 % to 7.1 % in workers. The findings validate that the new equation maintains biomechanical safety while significantly improving anthropometric fit. This alignment between biomechanical and anthropometric criteria represents an advancement in educational furniture design, particularly relevant for contemporary educational tasks requiring forearm support.

### 1. Introduction

The current educational model has determined that students (and workers) are faced with completing long shifts (6 or 8 h a day) in a seated position in classrooms (or offices) around the world (Gligorović et al., 2018; Kett and Sichtung, 2020) that forces a static, restricted, and uncomfortable posture, which over time can be harmful to health. Castellucci et al. (2017) found that a change in school furniture dimensions (better fit or match) resulted in an improvement in posture, muscle activity and a reduction in discomfort/pain. Students are usually

exposed to furniture with fixed dimensions, which makes it almost impossible to adjust to the anthropometric changes they suffer during their school life. The main reason for not having height adjustable school furniture is mainly due to viability issues related to increased costs and maintenance requirements, both of great concern for school systems in general. For the same reasons, international standards use grading/scalability techniques which are based on the use of different equations to define sizes (e.g. clothing S, M, L, XL, XXL) (de Bruin and Castellucci, 2023). These equations are widely used worldwide, specifically prescribing school furniture dimensions (standards) or to evaluate

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the level of match/mismatch between anthropometric measures (Cantin et al., 2019; Carneiro et al., 2017; Castellucci et al., 2021; Kahya, 2019; Macedo et al., 2015; Obinna et al., 2021; Parvez et al., 2019; van Niekerk et al., 2013; Yanto et al., 2017). Regarding desk height or seat to desk height, there are different equations to define this dimension (Castellucci et al., 2015). The most used equation is based on Chaffin and Anderson's principles (1991) and was used for the first time in the context of school furniture by Parcels et al. (1999) and is continued to be used by different authors (e.g. Altaboli et al., 2023; Khoshabi et al., 2020; Lee et al., 2021; Lee and Yun, 2019).

However, it can be very difficult to define a convincing equations or special criteria for desk height. In that regard, Castellucci et al. (2014) showed that the interrelation between seat to desk height and seat to desk clearance can be contradictory, even with a customized design. This design considered a chair height designed for each student; under-table space based on their tight highness plus 2 cm to allow free movement of their legs plus 7 cm table thickness considered for the structure. In the latter paper cited, a mismatch analysis was carried out using anthropometric data of 2261 students testing for levels of match/mismatch for several design criteria, including desk height. The analysis showed that 37 % of the students will use a higher seat to desk height (high mismatch), when using the recommended seat to desk height given by the Chaffin and Anderson's principles (Chaffin and Anderson, 1991). This high % of mismatch is quite large, thus making it hard to align anthropometric/design criteria and biomechanical ones. This situation can be attributed to the different values of Elbow height sitting and Thigh thickness, that are influenced by different reasons such as age, since before puberty the legs grow more rapidly than the trunk, but contrarily in adolescents, the growth spurt is largely focused on the trunk (Bass et al., 1999). Obesity also plays a significant role, since this condition has increased worldwide (Phelps et al., 2024) and will imply having higher thigh thickness, therefore more space underneath the table as obesity levels increase in the population. Even though it was not considered in the study of Castellucci et al. (2014), ethnicity could influence the results of desk height mismatch, since there are differences in body proportions between different ethnic groups (Evans et al., 1988; Lin et al., 2004).

Taking the above considerations into account, and following a bottom-to-top approach, the design and evaluation of school furniture should always begin with seat height (Castellucci et al., 2015). Students require sufficient under-table space to push their chairs underneath, allowing for free leg movement. The seat-to-desk clearance equation remains largely unchanged as it effectively determines the necessary space and can be readily applied. Additionally, there is insufficient data to justify the continued use of the maximum desk height proposed by Parcels et al. (1999). Furthermore, the criteria presented by Chaffin and Anderson (1991) do not account for elbow or forearm support, which could help alleviate shoulder strain (Slot and Charpentier, 2009). Some authors have suggested that for writing and drawing with forearm/elbow support, the table should be positioned 10 cm above elbow height (Kroemer and Grandjean, 1997; Pheasant, 2003). A 30° abduction is considered a safe posture for the shoulder, as elbow/forearm support alters shoulder biomechanics by shifting the pivot from the shoulder to the elbow, thereby reducing strain on the shoulder (Marras, 2012). These two criteria could address the limitations of Chaffin and Anderson's approach when evaluating and designing school furniture, aligning anthropometric/design criteria with biomechanical considerations. Despite the widespread use of the Chaffin and Anderson equation in school furniture design, a significant research gap exists regarding its compatibility with actual anthropometric fit in modern educational settings. The traditional equation fails to reconcile biomechanical safety with anthropometric design principles, as evidenced by the high mismatch rates observed in previous studies. Furthermore, contemporary educational tasks frequently require forearm support, which is not adequately addressed in existing desk height calculation methods. This research gap necessitates a new approach that can maintain

biomechanical safety while improving anthropometric fit for modern educational environments. While previous studies have evaluated furniture dimensions and anthropometric fit, this study is novel in that it specifically tests a new maximum desk height equation that incorporates both safe biomechanical angles and practical forearm support requirements. This is the first study to comprehensively evaluate such an equation through multiple parameters including kinematics, EMG, performance, preference, and discomfort while validating its anthropometric fit on large databases of both students and workers.

The aim of the current paper is to determine the differences in the kinematics, EMG, performance, preference, and discomfort variables during the use of maximum desk height of the equation considering the principles of Chaffin and Anderson (original from 1991) and the new equation based on 30° of abduction and 35° flexion (proposal) that is aligned with the anthropometric/design criteria.

## 2. Theory/calculation

**The critical limitation of existing desk height equations is their inability to simultaneously satisfy both biomechanical safety parameters and anthropometric fit requirements. This fundamental disconnect creates a practical implementation problem for furniture designers and ergonomists, who must often choose between theoretical biomechanical correctness and real-world anthropometric accommodation. The equation most commonly utilized to define desk height, proposed by Parcels et al. (1999), considers that acceptable elbow resting height (AERH) depends not only on Elbow Height Sitting (EHS), but also on the shoulder flexion and abduction angles.** To determine AERH it is necessary to know the Shoulder Height Sitting (SHS) and EHS, since by subtracting these anthropometric measures, the Upper Arm Length (U) can be calculated. Shoulder Flexion ( $\theta$ ) and Shoulder Abduction ( $\beta$ ) need to also be considered in the following main formula:

$$AERH = EHS + U[(1 - \cos \theta) + \cos \theta(1 - \cos \beta)] \quad \text{Eq. (1)}$$

The equation considering Chaffin and Anderson's principles (1991) of both acceptable shoulder flexion (angles from 0° to 25°) and shoulder abduction (from 0° to 20°) calculates minimum seat to desk height (DH) using a minimum shoulder flexion and abduction of 0°. For both, the corresponding cosines are 1. Given that the cosines are monotone functions of the angles, the minimum desk height is determined by the EHS. On the other hand, the maximum seat to desk height is calculated by considering the 25° of shoulder flexion and 20° of shoulder abduction, where the corresponding cosines are 0.9063 and 0.9397, respectively (Fig. 1A). Replacing these values in Eq. (1), the equation proposed is:

$$\text{Maximum desk height} = EHS + U[(1 - 0.9063) + 0.9063(1 - 0.9397)] \quad \text{Eq. (2)}$$

$$= EHS + U(0.1483)$$

$$= EHS + 0.1483 SHS - 0.1483 EHS, \text{ since } U = SHS - EHS$$

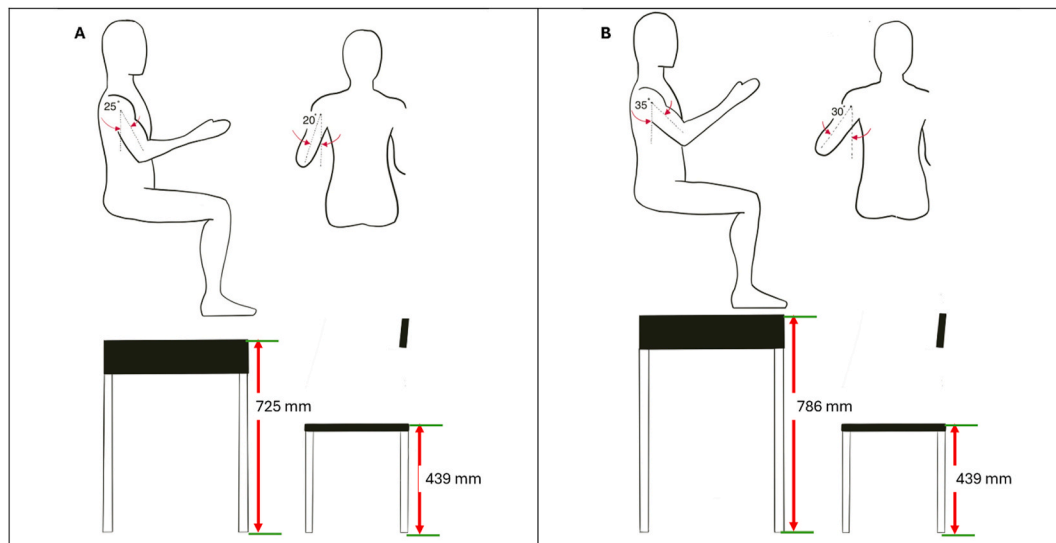
$$= 0.8517 EHS + 0.1483 SHS$$

The desk height proposal is based on a 30° of shoulder abduction and 35° of shoulder flexion (Fig. 1B). As was mentioned previously, the values are based on what is considered a safe shoulder posture, since supporting the elbow and forearm modifies shoulder biomechanics by shifting the pivot point from the shoulder to the elbow, thereby reducing strain on the shoulder.

$$\text{Proposal maximum desk height} = EHS$$

$$+ U[(1 - 0.8191) + 0.8191(1 - 0.8660)] \quad \text{Eq. (3)}$$

$$= EHS + U(0.2906)$$



**Fig. 1.** Comparative drawing of the equation considering Chaffin and Anderson's principles (A) and the proposed new equation (B). The Figure shows an example of the results of the two equations considered a person of SHS: 650 mm; EHS: 222 mm; PH: 421 and 2 cm of shoe correction (SC). To define Seat height the used equation is:  $(PH + SC) \cos 5^\circ$ . It is also important to note that the seat height stayed the same in both conditions.

$$= EHS + 0.2906 SHS - 0.2906 EHS, \text{ since } U = SHS - EHS$$

$$= 0.7094 EHS + 0.2906 SHS$$

The purpose of the proposed equation is to align safe biomechanical criteria with anthropometric design principles. The latter can be theoretically tested in two large databases (students and workers) as follows: Considering the data from a sample of 2261 students used in Castellucci et al. (2014), when applying the desk height proposal equation, 94 % of the students may use a desk height suitable to their anthropometric dimensions compared with only 63 % when applying the original desk height equation based on the Chaffin and Anderson's principles (Chaffin and Anderson, 1991). This way, the new desk height proposal will allow to use in average a desk higher in  $44 \pm 6$  mm compared with the original desk height. Performing the same calculation in a sample of 2946 workers (Castellucci et al., 2021), it can be established that 46.7 % of workers will use a desk higher (high mismatch) than the recommended by the original equation compared to only a 7.1 % of workers using the desk height proposal equation. The new desk height proposal will allow to use, on average, a desk higher in  $52 \pm 4$  mm compared with the original desk height.

Finally, to evaluate the biomechanical safety of the proposed equation, a comparison will be conducted against the original desk height equation, which is based on the principles of Chaffin and Anderson.

### 3. Methods

The following quasi-experimental repeated measures study was conducted at the Ergonomics and Biomechanics Laboratory in the Faculty of Medicine at Universidad de Valparaíso, Chile. The 34 participants who met the inclusion criteria completed all five tasks under both desk height conditions. All procedures were conducted following the Declaration of Helsinki and approved by the Bioethics for the Research Board of the Faculty of Medicine at Universidad de Valparaíso – Chile (approval no. 20/2022).

#### 3.1. Sample

A sample size calculation was conducted using G\*power for a Two-way ANOVA for repeated measured, 80 % power,  $\alpha$  0.05, giving a total sample size of 34 participants. A convenience sample of 34 healthy

right-handed participants (17 males and 17 females, aged 18–25 years) was recruited for the study. All participants had no history of upper-extremity musculoskeletal disorders or any medical conditions that could affect their posture or performance during the study. Additionally, participants with neurological, orthopedic, or chronic pain conditions that could interfere with the tasks were excluded. Participants were recruited through university announcements. Detailed participant characteristics are presented in Table 1.

#### 3.2. Independent variable

The desk height used as the independent variable (original versus proposal) only considered the higher level of desk height and considered the Popliteal height to define seat height.

Original Desk height:  $DH \leq (PH + SC) \cos 5^\circ + EHS * 0.8517 + SHS * 0.1483$

Proposal Desk height:  $DH \leq (PH + SC) \cos 5^\circ + EHS * 0.7094 + SHS * 0.2906$

Where PH is popliteal height; SC is shoe correction (2 cm was considered); EHS, elbow height sitting; DH, desk height; and SHS, shoulder height sitting.

Table 2 illustrates the dimensions of desk height calculated using two different equations. On average, the proposed desk height was  $48.5 \pm 5$  mm higher than the original. It is also noteworthy that the seat height remained consistent across both experimental conditions (Appendix 1. Physical measurements and furniture dimensions).

#### 3.3. Dependent variables

Dependent variables can be grouped into five categories: kinematics,

**Table 1**  
Sample characteristics.

|                        | Women (n: 17) |       | Men (n: 17) |       |
|------------------------|---------------|-------|-------------|-------|
|                        | mean          | SD    | mean        | SD    |
| Age (years)            | 22.00         | 1.62  | 21.82       | 2.19  |
| Height (cm)            | 159.82        | 5.69  | 173.53      | 7.16  |
| Weight (Kg)            | 61.75         | 9.36  | 74.69       | 12.85 |
| Shoulder height (mm)   | 579.47        | 45.19 | 584.24      | 31.48 |
| Elbow-seat height (mm) | 246.94        | 27.26 | 235.18      | 31.89 |
| Popliteal height (mm)  | 404.00        | 18.32 | 458.24      | 25.70 |

**Table 2**  
Furniture dimensions.

|                           | Women (n: 17) |       | Men (n: 17) |       | TOTAL (n: 34) |       |
|---------------------------|---------------|-------|-------------|-------|---------------|-------|
|                           | mean          | SD    | mean        | SD    | mean          | SD    |
| Seat height (mm)          | 422.30        | 18.25 | 476.32      | 25.59 | 449.31        | 34.98 |
| Original Desk height (mm) | 718.56        | 34.46 | 763.26      | 44.31 | 740.91        | 45.55 |
| Proposal Desk height (mm) | 765.84        | 36.14 | 812.90      | 44.84 | 789.37        | 47.03 |

EMG, performance, preference, and discomfort. Each variable is listed within its category.

### 3.3.1. Kinematics

Shoulder kinematics were recorded using a motion capture system (Vicon Motion Systems Ltd., Oxford, UK) which can detect the spatial displacement of markers attached to participants' body landmarks and reconstruct their trajectories (Gómez Echeverry et al., 2018). Data was sampled and captured at 100hz. Nineteen retroreflective markers were placed on anatomical landmarks to determine the shoulder movement following Vicon's Upper Limb Model (Vicon Motion Systems®, UK). The model calculates the desired output angle using the Euler angles technique. Shoulder flexion and shoulder abduction were considered measured in sexagesimal degrees (°).

### 3.3.2. Electromyography

Surface EMG (sEMG) signals were recorded using Trigno wireless sensors (Delsys, Inc., Natick, MA, USA) in a multichannel configuration for the right-sided target muscles, sampled at a frequency of 2000hz. Target muscles were the Deltoids, Trapezius, and Serratus, where different portions for each muscle were measured and treated as individual muscles for data capture and analysis purposes. Resulting muscle measured were: Anterior Deltoids, Medial Deltoids, Superior Trapezius, Medial Trapezius, Inferior Trapezius, and Serratus Anterior.

Before attaching the six wireless electromyography sensors, participants' skin was cleaned with alcohol-wetted disposable tissue paper to enhance adhesive adhesion of the double-sided tape and improve signal capture.

To ease the process of data capture and data comparison between and within subjects, participants were asked to yield the theoretical maximum amplitude of activation during muscle contraction against manual resistance in an Isometric Maximum Voluntary Contraction (iMVC) task. The task consisted of the exertion of maximal effort during an isometric contraction for 3 s, followed by a minute of rest. This action was performed three times. The following variables were considered.

- Average amplitude (%iMVC): The average amplitude of electromyographical activity normalized against the maximal EMG values of iMVC, measured in percentage of activation (%).
- Activity periods: Refers to the time each muscle is active during the desired task, calculated after determining a threshold for levels of activity (low, moderate, high, and very high) and inactivity periods, measured in seconds (s) (Park, 2013; Zellers et al., 2019).
- Mean Frequency (MNF): The mean frequency of EMG is a useful frequency-domain parameter of sEMG analysis that can be used to detect fatigue in target muscles (Daniel and Małachowski, 2023; Phinyomark et al., 2012; Yousif et al., 2019) by representation of the shifts of the frequency spectrum of the EMG signal. MNF can be calculated using the following equation (4):

$$MNF = \frac{\sum_{j=1}^M f_j P_j}{\sum_{j=1}^M P_j}$$

$f_j$  = frequency value of EMG power spectrum  $P_j$  = EMG power spectrum, calculated as the power spectral density (PSD) estimated for the input EMG signal  $M$  = next power of 2 from the length of EMG data in time-domain  $j$  = frequency bin Eq. (4)

### 3.3.3. Performance

Performance was measured using different variables due to the differences in the tasks to be executed. For those tasks that involved writing or reading, performance was measured as the number of words per minute; while for object manipulation tasks, performance was translated into task completion time. Finally, for tasks related to the use of electronic devices such as PCs or Tablet, performance was measured according to Fitts's Law by using software specially designed for this purpose (MacKenzie, 2018). The detailed measures of performance were the following.

- Words per minute: represents the number of words typed within a minute, the total amount of typed characters was divided by five since a "word" has an average of five characters, measured as words per minute.
- Task duration: refers to the amount of time that takes to the subject to finish the designed task, measured in seconds.
- Throughput: Fitts's index of performance is calculated over a sequence of trials as a simple quotient, as shown in equation (5):

$$TP = \frac{ID}{MT} \quad \text{Eq. (5)}$$

Where TP is throughput; ID, index of difficulty of the task (in bits); MT, mean movement time (in seconds).

Throughput computed using Eq. (5) is a measure of human performance in the context of the task and device, combining speed and accuracy in performing a target acquisition task (Scott MacKenzie, 2015), measured as bits per second.

### 3.3.4. Preference

Indicates the tendency of individuals to prefer one condition over another given the presented experimental design. Preference was measured using a two-option survey, interpreted as nominal data. Options were A. Original desk height preferred, or B. Proposal desk height preferred.

### 3.3.5. Discomfort

To measure the discomfort a 10-point Visual Analog Scale (VAS) was used, where 0 represents no discomfort at all and 10 represents extreme discomfort (Asundi et al., 2012). Participants were asked to answer the scale for three central regions of the body (Head-Neck, Lower Back, and Hip) and five regions regarding their dominant side (Shoulder-arm, Elbow-forearm, Wrist-hand, Thigh-knee, Leg-foot). The resulting data was treated as an ordinal measurement.

## 3.4. Procedure

Participants attended the Ergonomics and Biomechanics Laboratory of the Faculty of Medicine at Universidad de Valparaíso between April to August 2023 for a 3-h procedure. Before being assessed, all participants read and completed the informed consent and intake forms.

Participants then underwent 30 min of data collection preparation. This included the evaluation of height, popliteal height (PH), shoulder height sitting (SHS), and elbow height sitting (EHS) using the principles of ISO 7250-1 (2017). Afterward, the placement of retro-reflective markers and wireless electromyography sensors (described in detail before) and further explanation of trial procedures (Fig. 2). Prior to starting the test, both the desk and seat were set to match the anthropometric dimensions of each subject with the criteria of each equation. A commercially available adjustable height desk (E-model®) and an adjustable height stool were used for this purpose. The seat was adjusted for each subject making sure both feet were flat on the ground, knees and hip at 90° angles according to principles of ISO 7250-1 (2017). After setting the stool with the posture criteria for the seating posture, desk heights were adjusted to meet both equations. The study design utilized

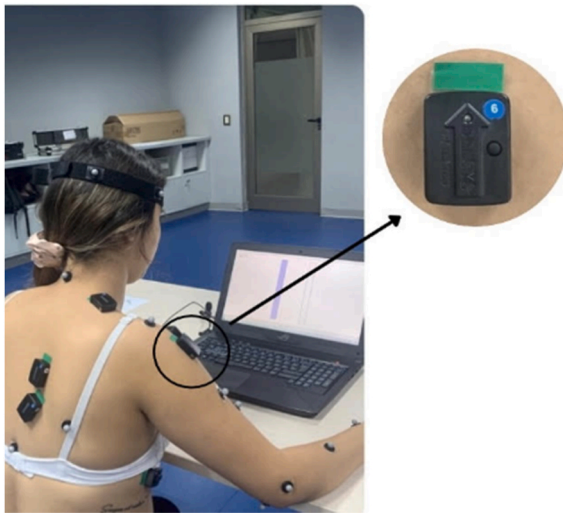


Fig. 2. Procedure setup.

backless stools to control for confounding factors and isolate the specific effects of desk height on upper limb biomechanics. According to Pope et al. (cited in Rincón et al., 2020), students tend to adopt a forward-leaning posture when engaged in writing or computer-based tasks. Floyd and Ward (cited in Pade et al., 2019) found that children during the performance of different tasks spent up to 80 % of their time in sitting positions without ever leaning on the chair backrest. This was particularly relevant for our study design, as writing and computer work represent the primary activities where desk height impacts upper limb biomechanics, and these tasks require students to maintain a forward-leaning position for extended periods.

Prior to data collection, participants completed a calibration trial for the Vicon system, which included the capture of a 3-s window trial for the whole body in a specific position to establish a baseline for markers into the three-dimensional space formed by the Vicon system, and the capture of muscular activity during isometric maximum voluntary contractions (iMVC), as previously described.

To avoid the fatigue and learning effect, the order of desk height was randomized, ensuring that half of the participants started with one of the two conditions, original or proposal. Researchers adjusted the seat height and desk height for the different experimental conditions (independent variable). Participants were instructed to perform the 5 tasks freely but in the same order. While performing the tasks, neither the desk nor stool heights were modified, however subjects could move their upper limbs freely above the desk in both conditions.

To ensure markers reliability within trials, each participant was asked to begin and end each task in a neutral position designated as the calibration position, which consisted of maintaining a straight back, both arms raised and flexed, hands clasped close to the chest at the level of the xiphoid process, and head looking straight ahead. Subsequently, the participants performed the following tasks freely and in the most comfortable position according to their preference:

- Handwriting test: The subject transcribed a 250-word text displayed on a notebook onto a sheet of paper using a pen.
- Reading and attention: The participant read aloud a paragraph of text of no more than 350 words. The positioning of hands and arms during this task was free.
- Typing test: the participant transcribed a 300-word text into the notebook, using a dedicated typing test (TypingStudy, 2003)
- Device usage test: The participant performed target acquisition tasks according to Fitts' Law for mobile devices such as Tablets, and computers (using a mouse). Data acquisition and performance

variables were measured using GoFitts (Pc) and Fitts Touch (Tablet) software from York University (Scott MacKenzie, 2015).

- Manipulation of objects: The participant cut a piece of paper with scissors following a predetermined path.

Once all tasks were performed for the first of the two experimental conditions, participants rested for 30 min before the repetitions of the tasks for the next condition; before and after each set of tasks, participants were asked to answer a quick survey regarding discomfort. During the rested period, participants were informed that they could either remain seated or stand up and walk around the laboratory as they wished. This flexibility was provided to ensure that the participants were comfortable and could choose the behavior that best suited their needs during the session. Finally, participants indicate their preference for some of the experimental conditions (workstation configuration). The overall experimental workflow can be seen in Fig. 3.

### 3.5. Data processing

The processing and analysis of each dependent variable will be presented individually following the five categories mentioned above, kinematics, electromyography, performance, preference, and discomfort.

#### 3.5.1. Kinematics

Shoulder kinematics reconstruction was performed based on the definition of a local joint coordinate system for each rigid body present in our model: Thorax, Head, Arm, and Wrist. Once kinematics was reconstructed for each task separately, markers' trajectory noise was minimized by applying a Woltring filter routine based on *mean squared error* (Molloy et al., 2008). *Since each task started and ended in the same subject's position (calibration position) event-related processing was necessary to determine the exact moment when each task started and ended.*

*Target motion-related variables, shoulder flexion and shoulder abduction, were calculated using Vicon Upper Arm model for dynamic trials, where shoulder angles were obtained using Euler angles sequences XZ'Y'' (intrinsic rotations, where X represents the first rotation, Z the second rotation, and Y is the third rotation).*

#### 3.5.2. Electromyography

Following the procedure from kinematics variables, event-related processing was performed for electromyography variables. Data from each of the six muscles was extracted and filtered by implementing a 2nd order low-pass Butterworth filter with a cutoff frequency of 20hz, a frequency previously determined by Fourier analysis of subjects' EMG data (Lindstrom, 1985).

Normalization of muscle activity by using iMVC is a common technique utilized to compare EMG activity between muscles within and between subjects (Halaki and Gi, 2012; Zellers et al., 2019). Next, an iMVC task was asked to be performed by participants prior to the test session to be taken as the reference value for muscle activity for each target muscle. iMVC signal was rectified by calculation of the root mean squared. Then, the maximum value obtained from the processed signal during all three repetitions was used as the reference value for normalizing the EMG signals, resulting in muscle activity from each task to be represented as a percentage of the maximum value (%iMVC).

Following normalized muscle activity calculations, threshold for levels of activity were set based on previous studies (Park, 2013; Zellers et al., 2019). Therefore, mean %iMVC for arm muscles during writing and typing tasks was reported between 10 and 15 %. Thus, low level of muscle activity was set at 5 % of iMVC, moderate level at 15 %, high level at 25 %, and very high levels of activity was any value beyond 25 %.

Electrical activity of muscles during dynamic and static contractions can be related to muscle fatigue, described as the decline in the ability of an individual to maintain a level of performance (De Luca, 1984). As such, mean frequency (MNF) is commonly used to detect fatigue in

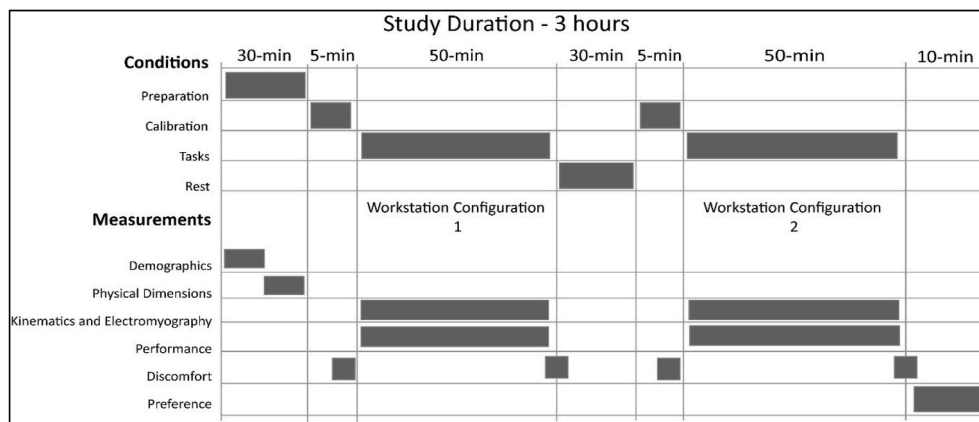


Fig. 3. Experimental workflow.

target muscles. By definition, MNF is an average frequency which is calculated as the sum of product of the EMG power spectrum and the frequency divided by the total sum of the power spectrum (Phinyomark et al., 2012). In this regard, a negative shift in frequency obtained by MNF, meaning a transition from high frequency range to low frequency is usually and indicator of muscle fatigue (Shair et al., 2017). To determine the effects of the Tasks and Condition in muscle fatigue, a linear regression analysis is performed, where slope of the resulting curve is compared between muscles and conditions.

### 3.5.3. Performance

Performance variables were processed depending on each source of data. For writing, reading, and typing tests, data was obtained from the Vicon system combined with the designated text to be written, read, or typed, taking into consideration the final duration of the task, after the event-related preprocessing, and the number of characters of each text. Data was then averaged for each subject. For the manipulation test, data was obtained also from the Vicon system, but taking only into consideration the time it took for each participant to finish the task at each condition. Finally, performance evaluation in the use of devices were obtained from Fitts Touch and GoFitts test software, using the Fitts index of Performance. The index was calculated as the relationship between the task effective index of difficulty (in bits) computed from the movement amplitude and target width, and the mean of movement time (in seconds), as previously shown in equation (3).

### 3.5.4. Preference

Preference score given by two options: Original desk height first or Proposal desk height first. The survey was manually processed and exported into a csv file.

### 3.5.5. Discomfort

Indicates the level of discomfort of each subject, comparing pre (basal) and post levels of discomfort regarding the use of each experimental condition, original and proposal desk height. Discomfort data were normalized by subtracting pre-tasks discomfort ratings from post-tasks discomfort ratings obtained during the same experimental condition (Wiggemann and Keyserling, 2012). Positive values of discomfort against baseline, was interpreted as an increase in discomfort.

## 3.6. Statistical analysis

Following the same structure, all statistical analysis was performed using GraphPad Prism software (version 9.3 for Windows, GraphPad Software, San Diego, California USA, [www.graphpad.com](http://www.graphpad.com)). To determine the type of statistical analysis to be used on the performance data, a distribution test was performed for each subset of data using Anderson-Darling, D'Agostino & Pearson, Shapiro-Wilk, and Kolmogorov-Smirnov tests.

Distribution for electromyography and kinematics data was determined using a QQ plot.

### 3.6.1. Kinematics

Kinematics data follows a Gaussian distribution, and to compare the differences between both conditions a paired *t*-test for total angle of movement for each condition, calculated as the mean of the six tasks for each subject, was performed to determine the effect of the condition regarding the overall shoulder activity. Furthermore, to compare the differences between both conditions regarding kinematics during each task, Two-way ANOVA for repeated measured was performed for shoulder flexion and shoulder abduction variables, where column factor was set as the experimental condition (desk height) and data was entered as means. Multiple comparisons between tasks and the independent variable were also calculated using the Sidak multiple comparisons test.

### 3.6.2. Electromyography

QQ plot revealed a Gaussian distribution for each subjects' muscles dataset. It was performed for normalized muscle activity and muscle activity time following the same procedure as for kinematics variables.

### 3.6.3. Performance

A distribution test was performed, resulting in a Gaussian distribution for each subset of data. To determine the effects of the experimental condition on the performance for each task, a paired *t*-test with a confidence level of 95 % was performed.

### 3.6.4. Preference

Preference data was sorted by their preference regarding condition (Original and Proposal) and preference (1st or 2nd) was presented into a 2x2 contingency table. A Chi-square test was performed to determine the relation between these two factors.

### 3.6.5. Discomfort

Discomfort after the execution of tasks was measured against baseline for five regions of the body, Head and Neck, Shoulder and Arm, Elbow and Forearm, Wrist and Hand and Lower Back. Wilcoxon signed-rank test for paired sample was performed to determine the effects of desk height regarding discomfort.

## 4. Results

In this study, we analyzed all dependent variables using data from all 34 participants. This approach gave us better statistical strength and helped us draw conclusions that represent everyone in the study, as we included all measurements and results from the entire sample.

#### 4.1. Kinematics

A two-way ANOVA revealed that there was a statistically significant interaction between the effects of desk height and tasks only for shoulder flexion angles ( $F_{(6,198)} = 7.172, p < .001$ ). Moreover, simple main effects analysis showed that desk height and task did have a statistically significant effect on both shoulder flexion and shoulder abduction angles (all  $p < .001$ ).

Fig. 4 shows the results of Šidák test for multiple comparisons, where there is a significant difference between conditions for Reading ( $p < .001$ ), Typing ( $p < .001$ ), Device usage for both PC ( $p < .001$ ), and Tablet ( $p = .003$ ) for shoulder flexion, as well as for Typing for Shoulder abduction ( $p = .001$ ).

#### 4.2. Electromyography

Results indicate that there was not a statistically significant interaction between the effects of desk height and task for muscle activity on any of the six measured muscles. Fig. 5 shows the results of the Šidák test for multiple comparisons, where statistical differences between task and condition were found for: Anterior Deltoids at reading task ( $p = .015$ ); Superior Trapezius at writing ( $p = .015$ ) and use of electronic device (tablet) ( $p = .002$ ) tasks. For Medial ( $p = .001$ ) and Inferior Trapezius ( $p = .004$ ), significant differences were found at object manipulation task. For Serratus Anterior, significant differences were found at use of electronic device (tablet) task ( $p = .014$ ).

In terms of muscle activity and inactivity periods, there is no statistically significant difference between conditions for all tested muscles, as well as no difference regarding task and condition, as shown in Fig. 6.

Fig. 7 shows changes in the slope of MNF calculated from all muscles during both conditions of desk height and across all six tasks. A two-way ANOVA revealed that there was no statistically significant interaction between the effects of desk height and tasks for muscle fatigue. Revealing that only for Task 5. Use of electronic device (Tablet) there was a simple main effect of muscle fatigue ( $F_{(5,198)} = 5.081, p < .001$ ) on Inferior Trapezius, with more fatigue during the use of original desk height.

#### 4.3. Performance

Statistical analysis shows that there are no significant differences between the two tested conditions for the different performance-measured variables. Fig. 8 shows each variable regarding both desk height conditions.

#### 4.4. Preference

Descriptive analysis shows that 53 % of subjects ( $n:18$ ) preferred the proposed desk height and the other 47 % of subjects ( $n:16$ ) preferred the original desk height. By applying the Chi-square test it was established that there is not dependency between condition (Original and Proposal) and preference (1st or 2nd) ( $X^2 = 0.2353, p\text{-value} = 0.6276$ ).

#### 4.5. Discomfort

A total of 22 participants reported discomfort, A total of 22 participants reported discomfort. Of those, 19 reported discomforts in at least one body region after the use of the original desk height, while 17 subjects reported discomfort for the proposal condition. The severity of postural discomfort in the participants while executing the assigned tasks while working with either desk height is presented in Table 2. A Wilcoxon signed rank test revealed that there was no significant effect of desk height on change in discomfort (Table 3).

### 5. Discussion

#### 5.1. Kinematics

As expected, the desk height proposal presented greater angles in both flexion and abduction. Although this could, in theory, present a greater strain on the shoulder joint and muscles, the current study used a desk depth of 80 cm coupled with a "free" posture instructed to the subjects, which allowed them to naturally sit with the forearms fully supported on the desk surface. It was possible to determine that most of the time the participants performed the activities with forearm support in both height desk conditions (Fig. 9). The practically null differences could be explained by the type of task and the free posture instructed. Traditionally, the original equation by Chaffin and Anderson was conceived with the use of typing machines and the initial desktop computer set up, that relied on the assumption of a lower desk height due to subjects using either a typing machine desk or the use of chair armrest for forearm support, which are inherently lower and closer to the traditional elbow height sitting anthropometric dimension (EHS). These results reveal the need for the dimensions of the desk to allow support for the forearms, as corroborated in previous studies (Cabegi de Barros et al., 2022; Santiago et al., 2023) and international regulations, especially with the massification of notebook use over desktop use and typical school activities such as hand writing, painting, cutting among others.

Considering that some authors estimated the higher level of desk

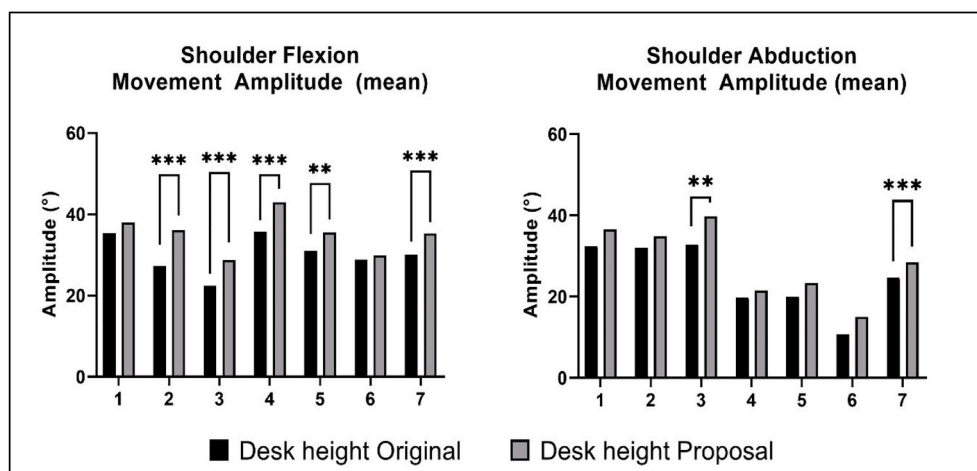


Fig. 4. Shoulder Kinematics. Differences between both experimental conditions regarding shoulder flexion angle and shoulder abduction angle for each of the six tasks. Tasks: 1. Writing; 2. Reading; 3. Typing; 4. Device usage (PC); 5. Device usage (Tablet); 6. Object manipulation; 7. Total. \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ .

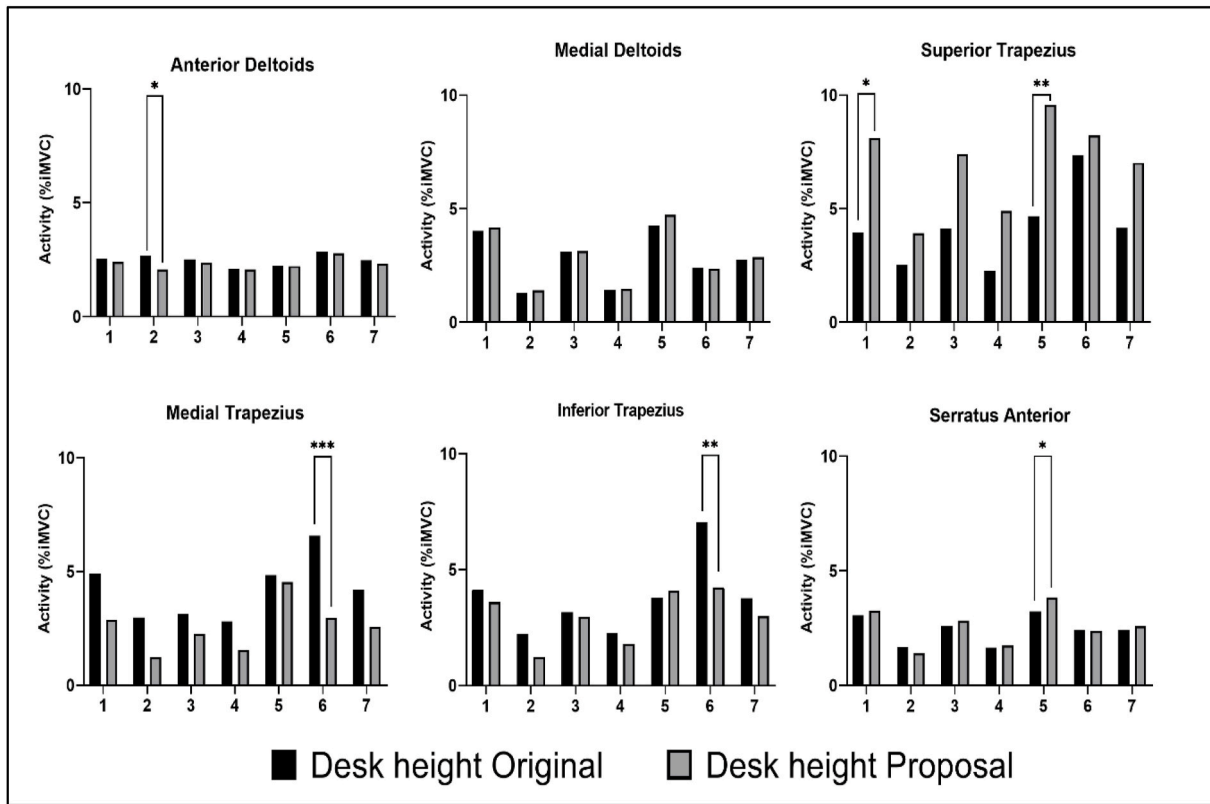


Fig. 5. Muscle Activity sEMG Normalized against iMVC. Differences between both experimental conditions regarding normalized electromyographical activity presented as % iMVC. Tasks: 1. Writing; 2. Reading; 3. Typing; 4. Device usage (PC); 5. Device usage (Tablet); 6. Object manipulation; 7. Total. \*\*\*p < 0.001, \*\*p < 0.01, \*p < 0.05.

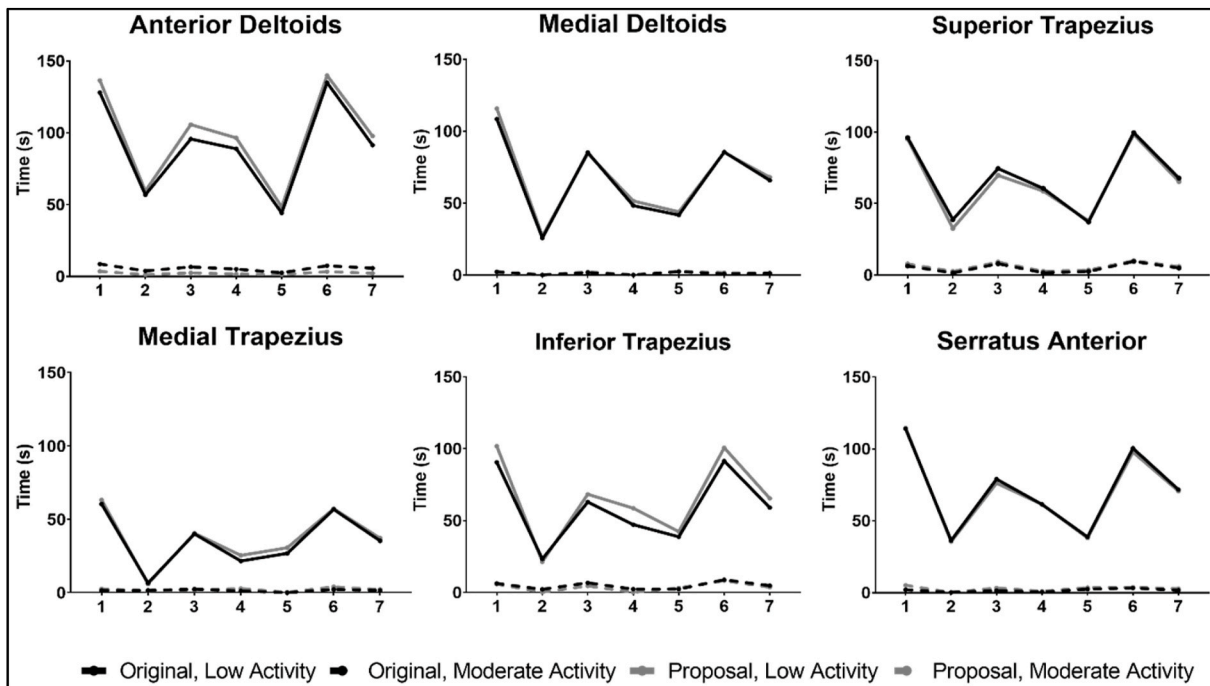


Fig. 6. Muscle Activity period. Low and Moderate levels of muscle activity of each target measured muscle during each task measured in seconds. Tasks: 1. Writing; 2. Reading; 3. Typing; 4. Device usage (PC); 5. Device usage (Tablet); 6. Object manipulation; 7. Total. \*\*\*p < 0.001, \*\*p < 0.01, \*p < 0.05.

height based on the elbow height sitting (EHS) + 50 mm (Dianat et al., 2013; Obinna et al., 2021), the results of the current study could be used to test other data sets. For example, considering the data from previous

studies on workers (Castellucci et al., 2021) and schoolchildren (Castellucci et al., 2014), the new proposal will allow to establish new higher level limits for desk height, of EHS + 100 mm and EHS + 80 mm

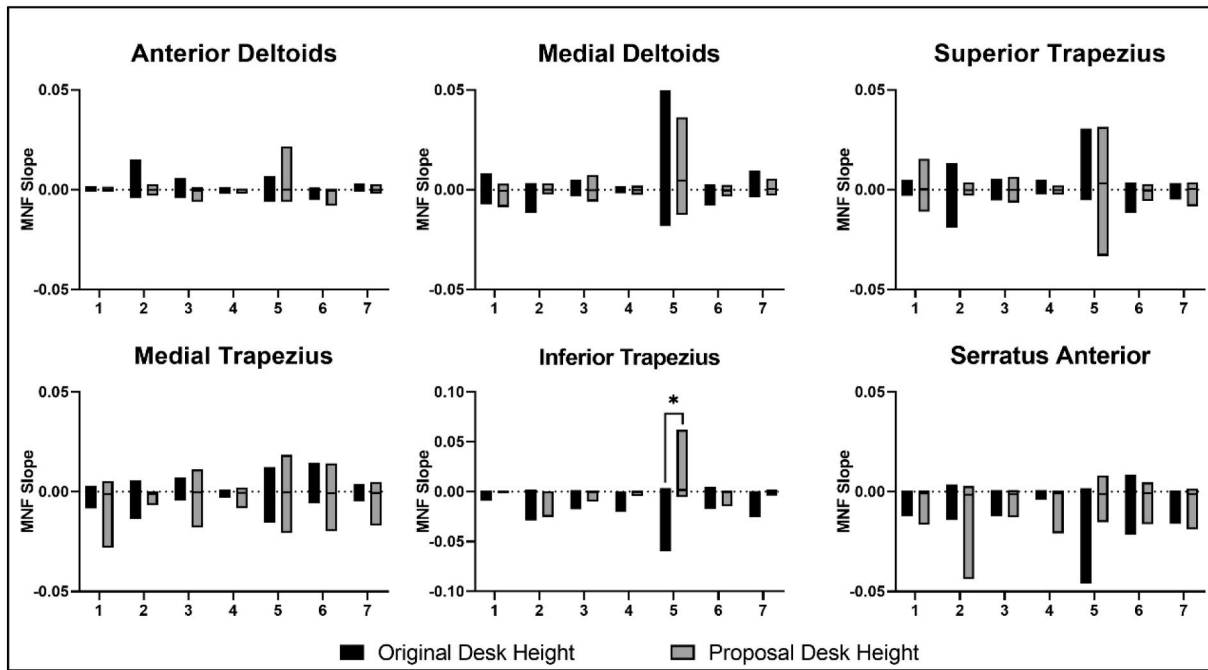


Fig. 7. Fatigue. Changes in the slope of Mean Frequency (MNF) were calculated from spectral analysis of sEMG signals from all six muscles measured. Tasks: 1. Writing; 2. Reading; 3. Typing; 4. Device usage (PC); 5. Device usage (Tablet); 6. Object manipulation; 7. Total. \*\*\*p < 0.001, \*\*p < 0.01, \*p < 0.05.

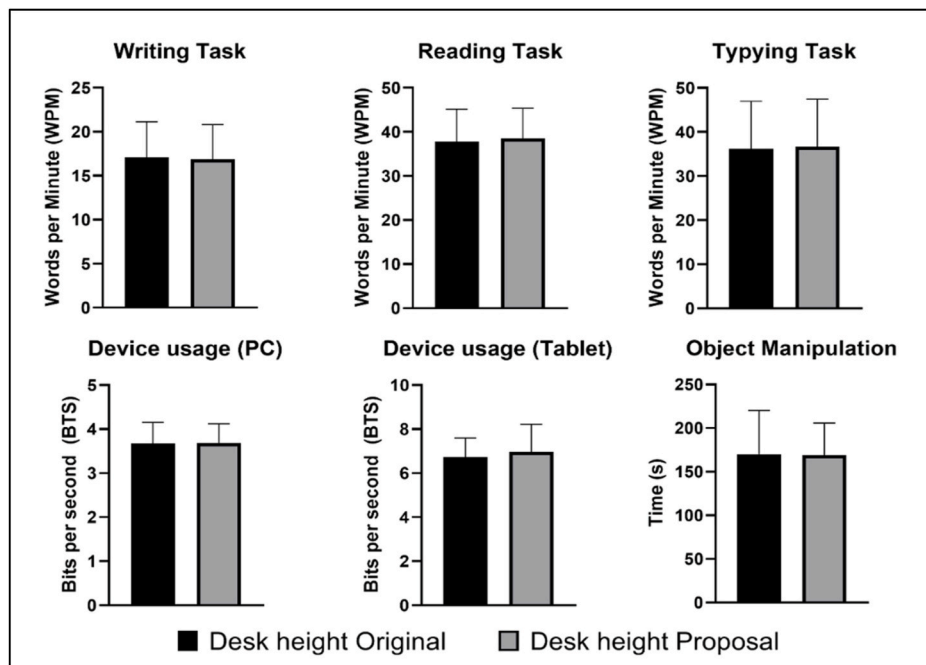


Fig. 8. Performance. Performance for writing and reading tasks were measured as Words per Minute, whereas Throughput and Time were measured for the use of digital devices and object manipulation tasks respectively.

for workers and schoolchildren respectively. Other authors are encouraged to try the new proposal in other data sets.

### 5.2. Electromyography

Although there was a consistent pattern of higher levels of muscle activity for the Superior Trapezius, the magnitude of changes was only statistical significance for the activities of writing ( $p = .015$ ) and use of electronic device (tablet) ( $p = .002$ ). Even though greater angles were

obtained for the new desk height proposal (Fig. 4), the results could be related to the amount of supported time of the forearm during these activities (Fig. 9). Similar results were obtained by Gonçalves et al. (2017) who established that forearm support reduced upper trapezius and anterior deltoid activity for all shoulder flexion angles. Furthermore, the use of forearm support compared to the no-support condition has been significantly associated with less shoulder muscle activity (Onyebeke et al., 2014). In the current study, there was no notable distinction in muscle activity across the two conditions, with the

**Table 3**  
Discomfort ratings (in points).

| Body regions      | Discomfort           |                      | p-value | Summary |
|-------------------|----------------------|----------------------|---------|---------|
|                   | Original Desk Height | Proposal Desk Height |         |         |
| Head and Neck     | 0.147                | 0.147                | 0.875   | ns      |
| Shoulder and Arm  | -0.029               | 0.382                | 0.141   | ns      |
| Elbow and Forearm | 0.029                | 0.147                | 0.500   | ns      |
| Wrist and Hand    | 0.147                | 0.088                | 0.688   | ns      |
| Lower Back        | 0.441                | 0.324                | 0.738   | ns      |

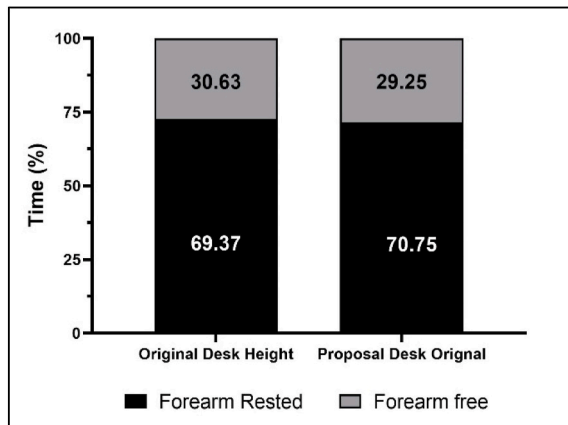


Fig. 9. Total time of the tasks performed with support and unsupported forearm.

exception of the inferior Trapezius muscle, where the Chaffin and Anderson equation condition showed more fatigue. As it was shown in Fig. 4, all other muscles tested in terms of %Maximum Voluntary contraction (%MVC) never went beyond 10 %, which is far less than the overall criteria of 15 % (Kroemer and Grandjean, 1997). This fact implies that below the 15 % MVC threshold, theoretically a certain posture can be maintained for extensive periods of time, without experiencing muscle fatigue (Jacquier-Bret and Gorce, 2024; Kroemer and Grandjean, 1997). Additionally, the results presented in Fig. 7 indicated that there was no statistically significant interaction between desk height and task type on muscle fatigue. Therefore, considering the obtained results for the electromyography, it can be said that the new proposal is as safe for the shoulder as the original criteria stated by Chaffin and Anderson, assuming the forearm is fully supported on the desk's surface. The lower back muscles were not tested, and it would be interesting to know if the new set up proposed in the current study has an influence on electromyographic data in this body region.

### 5.3. Performance

The results obtained reveals that there are no noteworthy distinctions observed between the two conditions tested across various performance-measured variables. Performance measures did not show significant differences between the two desk height conditions, suggesting that performance outcomes were not influenced by desk height variations.

In this study was not possible to establish a difference in the preference between the 2 conditions (Original and Proposal). However, analysing only the first preference response, it is possible to notice that for the proposal condition (n: 18) 66 % of them were women (n:12). However, for the original desk height, most of the preference belongs to men with a 68 % preference (n: 11). Chi-Square tests showed a dependency between desk height preference (original first v/s proposal

first) and sex ( $X^2 = 4.25$ , p-value = 0.03925). A possible explanation may be due to the fact that in general, women are more prone to musculoskeletal disorders in the upper limbs and their previous early symptoms, such as pain and discomfort, thus influencing somehow the preference results (Bai et al., 2024) (Yifan Bai et a 2024). The previously cited systematic review states the need to specify gender contribution with its specific characteristics regarding the preference and evaluation of ergonomic design of office furniture. For example, in the current study, gender could have had a role on the dependency of gender and preference, since it has been show that posture varies between man and women (Ohlendorf et al., 2023). Gender specific differences regarding posture could yield preference towards higher or lower desk heights. This hypothesis should be further addressed in specific designs that can account for the role of gender and preferences mediated by specific physical characteristics related to gender specific postures.

### 5.4. Discomfort

The study findings reveal that there was no primary influence of workstation setup on discomfort. These results could be explained due the small difference between the two-desk heights, where on average the desk height proposal was  $48.5 \pm 5$  mm higher than the original desk height. Previous studies have shown that students prefer higher furniture mainly because of the benefits and positive sensation on the lower back (Mandal, 1994b). It is likely that the small difference between the two configurations contributed to not showing significant differences in these domains. Also, the amount of time performing the test could have been not big enough to show differences between the two conditions. The study by Kar and Hedge (2021) did not show differences in discomfort when comparing two workstation configurations during a test of 60 min each.

Other studies presented differences, however the time of intervention ranged from 4 h (Waongengarm et al., 2020) to 3 months (Cabegi de Barros et al., 2022). Prolonged seating in experimental settings must be carefully considered to not induce any damage in the subjects. For example, the study of Christensen et al. (2023) shows that with 15 min seated computer task caused neck pain in an otherwise healthy population, irrespective of sitting posture. Also, the study of Nunes et al. (2021) showed that the significantly risk factors for neck pain were "working without a break for 2 h" [OR: 1.82 (1.00–3.31) P = 0.05] or "more than 3 h". In general, experimental protocols go through review of the ethics committees, who considering the presented evidence may delay or even reject projects that expose subjects to musculoskeletal pain. Perhaps other field studies could be used in order to test during long period of time in real settings where subjects are already exposed to prolonged seating and assess time exposure related to discomfort reports.

### 5.5. Anthropometric design criteria and biomechanics of the proposed equation

The research group observed in a large sample of school children, that even if desk heights were adjusted with ideal custom settings, when using the Chaffin and Anderson formula, at least 37 % of them would be using desks that are too tall, thus they will experience a high mismatch. This is the main shortfall of the Chaffin and Anderson equation, namely, that even if the biomechanical criteria are safe from a biomechanics perspective, there is a lack of real-world compatibility with anthropometric design criteria. What we mean by that, is that while using the Chaffin and Anderson formula it is more likely to attain more false positive high mismatch results when evaluating desk height. Additionally, the desk height can be increased, thus allowing a larger threshold for design and manufacturing of products, increasing product sustainability (Nadadur and Parkinson, 2013). The proposed formula does not imply more risk, since results of the current study where not significantly different from the ones tested with Chaffin and Anderson criteria.

It was even proved to cause less fatigue in the inferior trapezius muscle. The novel approach presented in this study represents a significant advancement in educational furniture design methodology by successfully bridging the long-standing gap between theoretical biomechanical models and practical anthropometric requirements. This methodological innovation has significant implications for future research, as it establishes a new framework for evaluating and designing furniture that can be applied across different populations and settings. Future studies can build upon this approach to develop more comprehensive guidelines that accommodate various task-specific requirements while maintaining biomechanical safety. Furthermore, the significant improvement in anthropometric fit demonstrated in our theoretical testing (increasing match rates from 63 % to 94 % in students and reducing high mismatch cases from 46.7 % to 7.1 % in workers) provides a strong foundation for future intervention studies aimed at reducing musculoskeletal discomfort in educational and workplace environments.

### 5.6. Limitations and future studies

To provide context for this study, it is important to acknowledge a few limitations. First, the study was conducted in a laboratory setting, with each desk height tested during a relatively short 50-min task. This limited duration may affect the relevance of the findings for tasks that extend over a full workday. Second, although workstation assignments were rotated to reduce bias, they were completed within a single session, with a 30-min break in between. Despite these factors, no significant differences were observed between the workstations.

Additionally, while the study's sample size ( $n = 34$ ) was determined based on a priori power analysis (80 % power,  $\alpha = 0.05$ ), the relatively small number of participants may limit the generalizability of the results. We also recognize that the participants were relatively young, with an average age of 18–25 years. As such, the findings may not fully apply to middle-aged or older adults. Future research should involve larger, more diverse samples, including participants from a wider age range, to confirm the findings and assess their applicability across different demographic groups. Replication of the study in various populations would help to establish the robustness and generalizability of the results.

For future studies, we recommend measuring electromyography and lumbar posture, as higher desk heights have been shown to reduce lumbar flexion (Mandal, 1994a). It would also be valuable to assess gender differences and their impact on posture to better understand how gender, posture, and preference influence the results. Finally, the duration of experimental protocols should be carefully considered. Conducting field tests could help reduce unnecessary sitting time and discomfort for participants. Future studies should also aim to replicate the study in real-world settings with larger sample sizes and over longer periods to enhance ecological validity."

## 6. Conclusion

In conclusion, our study supports the use of a new equation to define the maximum acceptable elbow rest height considering elbow rest height based on 30° of abduction and 35° flexion. The findings of this research shed light on several important aspects related to desk height adjustment, particularly concerning kinematics, electromyography, performance, preference, and discomfort. Considering the bottom to top matching procedure, when elbow/forearms are fully supported on the

desk's surface, all the previously mentioned parameters were kept within safe thresholds. This is highly relevant since one major argument for not using the proposed equation could be shoulders with higher flexion and abduction angles (i.e. awkward posture), however while keeping the forearms fully supported the results showed no difference with the original equation. Furthermore, in the current study, most of the test time subjects assumed this position, thus reflecting that forearm/elbow support is a valid and naturally assumed posture when working with a desk in typical and frequently performed tasks, such as typing, reading or performing light manual tasks. The novel approach presented in this study makes a significant contribution to the field by demonstrating that it is possible to maintain biomechanical safety while substantially improving anthropometric fit. This is particularly significant as it challenges the long-held assumption that these two criteria must be traded off against each other in furniture design. The methodological framework established in this study opens new avenues for future research on adaptive furniture designs that can better accommodate diverse anthropometric characteristics while maintaining ergonomic integrity. Additionally, our findings have important implications for standards organizations and furniture manufacturers, who can implement these revised equations to create more inclusive and comfortable furniture solutions for educational and workplace environments. As an additional benefit, when theoretically tested in two large databases (students and workers) the levels of match increased significantly for desk height. The contribution of the current research can also be used to align safe biomechanical criteria and anthropometric design criteria.

In summary, while the proposed desk height adjustment showed promising results further research is warranted to explore its long-term effects considering gender-specific preferences and posture variations. Additionally, future studies should consider incorporating lumbar posture assessments and longer intervention durations to provide more comprehensive insights into the impact of desk height adjustments on overall workstation ergonomics.

### CRediT authorship contribution statement

**Edgardo C. Silva:** Writing – original draft, Supervision, Formal analysis. **Nicolás Concha-Opazo:** Investigation. **Fabián Morales-Gutiérrez:** Investigation. **Débora Piceros-Henríquez:** Investigation. **Rocío Soza-Gallo:** Investigation. **Héctor Ignacio Castellucci:** Writing – original draft, Supervision, Resources, Project administration, Investigation, Conceptualization. **Pedro Arezes:** Writing – review & editing, Validation, Methodology. **Johan F.M. Molenbroek:** Writing – review & editing, Validation, Methodology. **Carlos Viviani:** Writing – original draft, Supervision, Conceptualization. **Imán Dianat:** Writing – review & editing, Visualization, Methodology.

### 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.

### Acknowledgments

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## Appendix 1. Physical measurements and furniture dimensions

| Sex | Shoulder Height | Elbow-seat height | Popliteal height | Seat height (mm) | Original Desk height (mm) | Proposal Desk height (mm) |
|-----|-----------------|-------------------|------------------|------------------|---------------------------|---------------------------|
| F   | 547             | 229               | 384              | 402.4            | 679                       | 724                       |
| F   | 547             | 262               | 373              | 391.4            | 696                       | 736                       |
| F   | 650             | 222               | 421              | 439.2            | 725                       | 786                       |
| F   | 663             | 263               | 386              | 404.4            | 727                       | 784                       |
| F   | 663             | 238               | 434              | 452.2            | 753                       | 814                       |
| F   | 534             | 229               | 388              | 406.4            | 681                       | 724                       |
| F   | 547             | 265               | 402              | 420.3            | 727                       | 767                       |
| F   | 528             | 212               | 394              | 412.3            | 671                       | 716                       |
| M   | 588             | 263               | 434              | 452.2            | 763                       | 810                       |
| M   | 511             | 164               | 430              | 448.2            | 664                       | 713                       |
| F   | 605             | 309               | 432              | 450.2            | 803                       | 845                       |
| F   | 549             | 274               | 402              | 420.3            | 735                       | 774                       |
| M   | 591             | 234               | 454              | 472.1            | 759                       | 810                       |
| M   | 644             | 289               | 492              | 510.0            | 852                       | 902                       |
| F   | 510             | 188               | 406              | 424.3            | 660                       | 706                       |
| M   | 607             | 255               | 436              | 454.2            | 761                       | 811                       |
| M   | 567             | 200               | 457              | 475.1            | 730                       | 782                       |
| M   | 553             | 216               | 412              | 430.3            | 696                       | 744                       |
| F   | 593             | 278               | 393              | 411.3            | 736                       | 781                       |
| M   | 598             | 225               | 489              | 507.0            | 787                       | 840                       |
| F   | 582             | 254               | 409              | 427.3            | 730                       | 777                       |
| M   | 611             | 294               | 460              | 478.1            | 819                       | 864                       |
| M   | 617             | 215               | 510              | 527.9            | 802                       | 860                       |
| M   | 553             | 217               | 455              | 473.1            | 740                       | 788                       |
| M   | 583             | 244               | 475              | 493.0            | 787                       | 835                       |
| M   | 538             | 202               | 466              | 484.1            | 736                       | 784                       |
| F   | 592             | 250               | 388              | 406.4            | 707                       | 756                       |
| M   | 599             | 259               | 486              | 504.0            | 813                       | 862                       |
| F   | 557             | 234               | 403              | 421.3            | 703                       | 749                       |
| M   | 607             | 230               | 460              | 478.1            | 764                       | 818                       |
| M   | 593             | 234               | 451              | 469.1            | 756                       | 807                       |
| F   | 605             | 244               | 438              | 456.2            | 754                       | 805                       |
| M   | 572             | 257               | 423              | 441.2            | 745                       | 790                       |
| F   | 579             | 247               | 415              | 433.3            | 729                       | 777                       |

## Data availability

Data will be made available on request.

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