26th International Congress on Sound and Vibration
7-11 July 2019, Montreal

AN EARCANAL-SIZING TOOL AT THE TIP OF YOUR FINGERS

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The human earcanal remains a mostly unchartered territory: earcanal shapes and dimensions are unique to each individual and despite recent advances in 3D scanning, the capture of the earcanal's exact geometry remains a challenge. Nevertheless, the proper selection of an intra-aural hearing protector often requires that the earcanal size be estimated. Therefore, several tools -such as earcanal and concha gages- have been developed over the years to quickly and approximately assess one's earcanal dimensions and recommend an appropriately-matching earplug size. In this anthropometric study, sparked by the lexical similarity in the French language between the name for the little finger (*auriculaire*) and the adjective related to aural parts (*auriculaire*), we explore whether Nature did not provide a suitable earcanal sizing tool... at the tip of our fingers. The methodology is based on the calculation of a correlation coefficient matrix obtained by comparing the characteristic geometric features of both the ear canal and the little finger. The results from a recent pilot study will be presented together with possible field applications for hearing protectors and a selection of in-ear wearables.

Keywords: earcanal geometry, earplug size selection, hearing protection, morphology, anthropometry

1. Introduction

1.1 Why is earcanal sizing critical?

The proper selection of a worker's earplugs is critical because their being too small or too large will lead to attenuation and comfort issues [1]. In order to cover this range, earplug manufacturers often offer their products in a variety of sizes with different diameters or/and lengths. Past studies have shown that the human earcanal size and shape varies significantly amongst individuals [2]. There are now several different technical solutions that can capture the precise geometry of the earcanal, in addition to the traditional ear impression taken by an audiologist and that can be 3D scanned. Optical methods [3], ultrasound images [4], and computed tomography imaging [5],[6] have been used to successfully reconstruct individual earcanal geometries. These research methods work with great accuracy, however, each earcanal geometry reconstruction proves to be a cumbersome task in terms of time and resources and is not often feasible *in situ*.

1.2 Existing tools

A limited number of tools - such as a concha gage - exists to select earplugs that are size-suitable. Figure 1 illustrates some of the tools developed in the early 1970s to estimate the diameter at the earcanal opening and help select an apt earplug. One category of these tools is sometimes the earplug itself (part a) and b) of Figure 1). However, this still involves trying several sizes and thus discarding those that do not fit properly. The last tool (part c) of Figure 1) is the only generic tool that seems to be available on the market. In addition to the fact that these tools were developed 50 years ago, they are proprietary solutions and no scientific data about their development and design are available in the literature. Furthermore, as to the variety of proposed earplug sizes, the pressing question of categorization still remains, i.e. the number of divisions needed to correctly cover the range of earcanal geometries. An attempt has been made to use the Eargage as a tool for anthropometric classification. The authors have concluded that while this tool may be useful for multi-sized earplugs, it is not adequate for classification and the circular shape of the Eargage has a potential risk of distorting or wrongly measuring a predominantly elliptical earcanal [7].

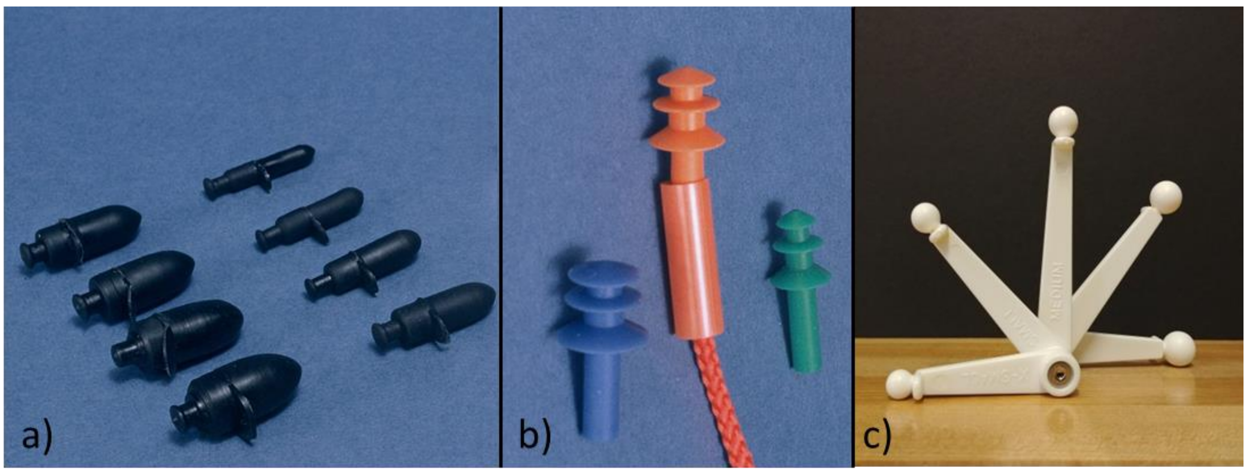

Figure 1: Examples of tools developed in the 1970s to estimate earcanal entrance size. a) Hollow earplugs, 5 to 12 mm, can be used as an eargage, developed by SMR (Surgical Mechanical Research), now discontinued; b) North Safety Com-fit, discontinued by the manufacturer, now sold as Tasco Tri-Fit earplugs, earplug-sizing kit; c) 3M™ Eargage (3M), sold as general earcanal-sizing tool. Images a) and b) kindly provided by Elliott H. Berger, retired senior scientist at 3M.

1.3 Need for a better tool

A generic tool able to estimate the earcanal-opening size in order to correctly pre-select the earplug size could be beneficial. Such a tool could be useful to guide the occupational health and safety manager and hygienist in the complex task of selecting the right hearing protector [8]. It is also important that this tool include the widest range of observable earcanal geometries. Without going all the way back to Leonard Da Vinci's famous Vitruvian Man, past studies have shown the propensity of the human body to be proportionate. For instance, research in the field of anthropometric morphometry has highlighted the correlation between the left hand digit ratio and several behavioural or physiological aspects, such as facial asymmetry [9] or puberty [10].

The original angle of this research project is to study the possibility of a sizing tool that uses the geometric correlation between the little finger and the earcanal cross-section perimeters. The first objective is to verify whether or not there is a correlation, i.e. is it possible to predict the general profile of an individual's earcanal based on the geometry of his pinky? In the context of developing a generic tool, the second objective is to verify whether the individual correlation, as highlighted in the first step, still applies over a group, and to determine the best location on the pinky's geometrical profile to take a measurement to maximise the chance of correctly estimating the size of the ear-canal opening.

To meet these two objectives, the geometry profiles of 8 participants' little fingers and earcanals were collected using various molding techniques and 3D-scanning methods, to obtain discretized geometries that could be compared and analysed using 3D software. The collected data were then used to perform statistical correlation calculations.

2. Materials and methods

2.1 From human body to discretized geometry

Eight individuals (seven males, one female), aged between 22 and 45 were recruited to capture the geometry profile of their pinkies and earcanals. The participants did not have any known or visible pathology regarding their earcanal or pinky. Figure 2 illustrates the steps performed to collect the data.

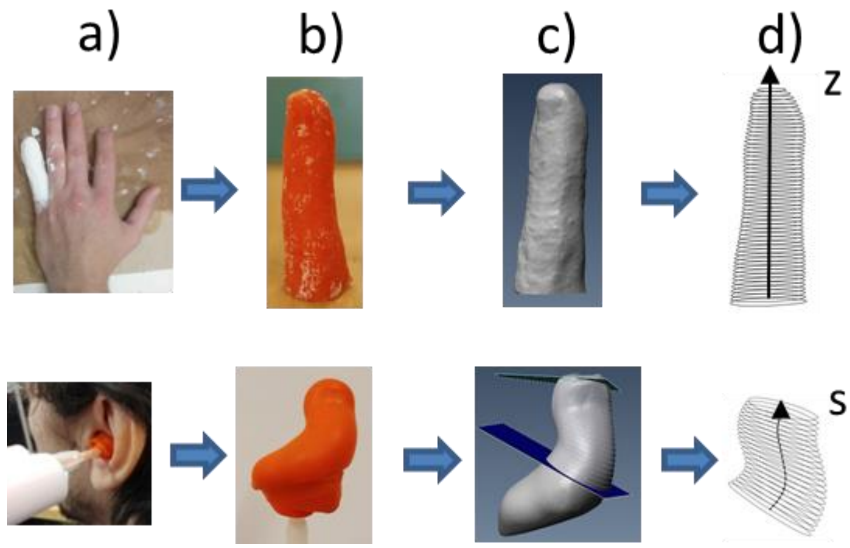

Figure **2**: Steps to obtain a discretized geometry of an individual little finger and earcanal geometry profile. a) Plaster mold of pinky and custom earplug; b) Pinky and custom earpiece silicone mold; c) 3D-scan of step-b pieces; d) discretized geometries.

To obtain the pinky's geometry profile, strips of plaster are placed around the little finger to make a mold of its individual profile. The mold was then filled with rubber silicone to produce a replica of the pinky. The replica was digitalized using a 3D scanner (EinScan-S, Shining3D, China) to obtain a mesh (cloud of geometric points) representing the entire geometry. Finally, the mesh was converted into a sequence of 1-mm step cross sections oriented along the *z*-axis, using the 3D software PolyWorks® (InnovMetric Software Inc., Quebec, Canada). To estimate the earcanal geometry, the same process was followed except that the custom earplug used as an ear impression was digitalized. The custom earplug seen in Figure 2a) was instantly molded using the SonoFit [11] process, which consists in expanding a generic earpiece directly in the earcanal through the injection of a medical grade silicone inside its expandable earpiece. A cross-section discretization was then made using two radial planes defining a curvilinear axis (*s*-axis in Figure 2) with an average step of 0.5 mm between each slice. This process was repeated for the eight individuals, for both right and left earcanals and the little finger.

2.2 Geometry comparisons and statistical calculations

To finalise the arrangement of the data, all the discretized geometries were aligned along the *z*-axis for the pinky and along the *s*-axis for the earcanal. The perimeters of each little finger and ear canal cross-sections were collected and associated to a position along the *z*-axis or the *s*-axis, respectively. These data are plotted in Figure 3 for the eight participants and sixteen associated geometries, which helped to identify the zones where data was available for all the participants (to the left of the dashed line on each chart of Figure 3) together with a highlighted zone where the profiles are suitable for linear regression calculations. For example, the tip of the finger where cross-section perimeters rapidly tend to 0 were not considered in the correlation calculations. A trend is observable in Figure 3 in which the order between the largest and smallest cross-section perimeters at position near 0, on both the s and *z*-axes, is almost the same, implying that a large earcanal opening will be associated to a large pinky finger. The data retained were imported in Matlab® environment (MathWorks®, Natick, USA) to perform individual and group correlation calculations. For the individual correlation, the coefficient R^2 was calculated based on linear regressions between earcanal and pinky cross-section perimeters. For the group correlations, the evolution of coefficient R^2 was calculated by scanning group cross-section perimeters of the earcanals and computing the associated regression coefficients to each group finger cross-section perimeters.

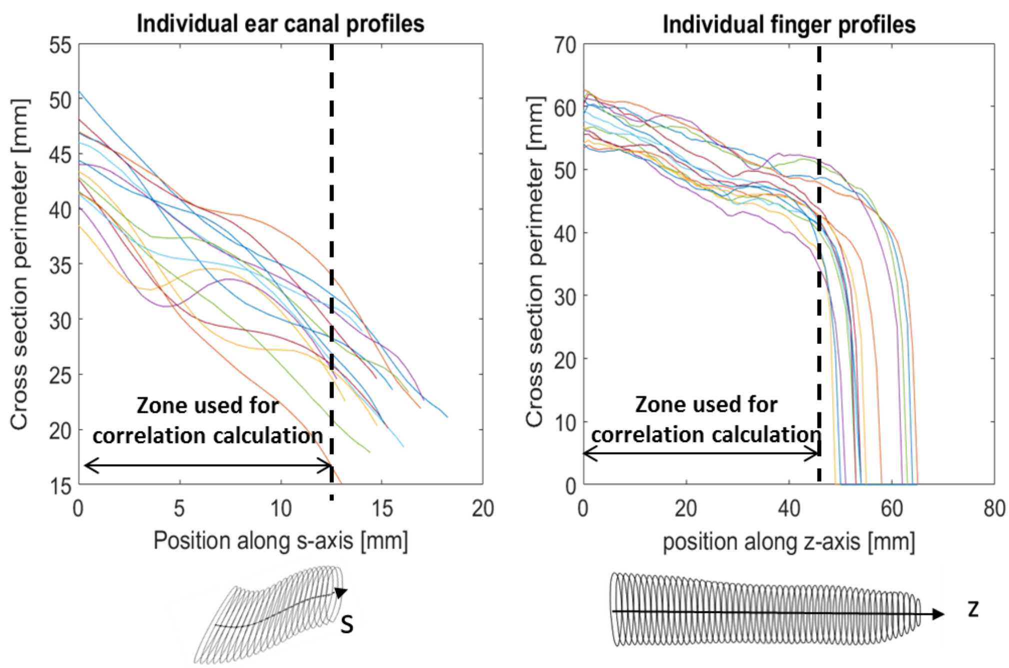

Figure **3**: Individual geometry profiles for the eight participants' cross-section perimeters as a function of the position on the *z*-axis or *s*-axis. Left: earcanals; right: little fingers.

3. Results

3.1 Individual geometric correlations: finger vs earcanal

The results for the individual correlation calculation together with the individual linear correlation coefficient R^2 are presented in Figure 4. The degree of linearity between the two parameters is relatively high, ranging from about 0.65 to 0.96. In approximately 50% of the set of data, the value of R^2 is higher than 0.9. These results suggest that it could be possible to estimate the cross-section perimeter of the earcanal based on a precise knowledge of the little finger geometry combined to the most adequate linear model selected from several linear regression models. Even if this linear model is unique to an association between an earcanal and a pinky, it could be possible to establish an abacus based on these data in order to select the most appropriate linear relation and estimate the earcanal cross-section perimeters. A greater number of participants will help to augment this database and refine the number and the coefficient of linear models that should be used to cover the range of inter-individual variations. To complete this study and for further investigation, approaches such as principal components analysis or more general multiple regression models will be considered in future works.

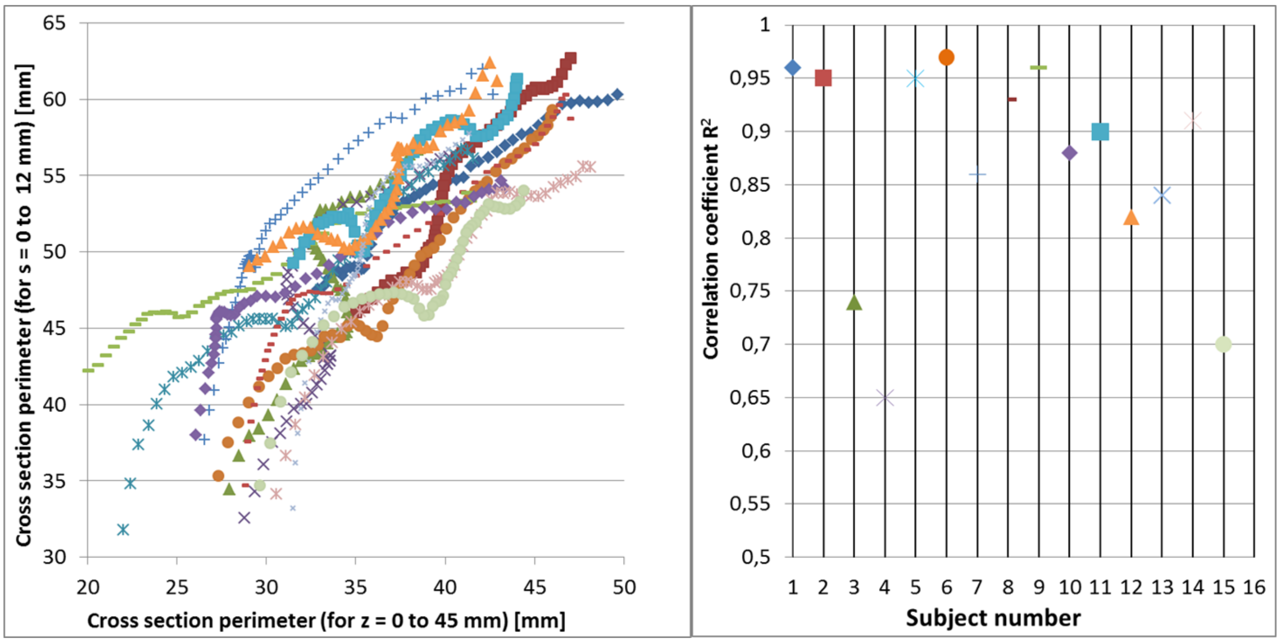

Figure **4**: Scatter plot of individual earcanal cross-section perimeters as a function of individual cross-section perimeters of the little finger (left) and the associated linear correlation coefficient R^2 (right).

Questions that remain at this stage pertain to the selection of earplug size: what becomes of this linearity correlation if a group is considered and more specifically, if only one measurement is taken, where is the "best" place on the pinky to measure, to classify an earcanal in a category of large, medium or small? To answer this, correlation calculations were performed on the group of participants' data.

3.2 Group geometric correlations

A matrix of correlation coefficients was evaluated by scanning the group cross-section perimeters of the sixteen earcanals at different locations along the *s*-axis and the degree of linearity was verified by evaluating R^2 at every single location on the *z*-axis and for the entire group data of the pinky cross-section perimeters. The cross-section perimeters of the earcanal (as a function of coordinate *s*) and of the little finger (as a function of coordinate *z*) and for all the participants ($n = 16$) are defined respectively as:

$$\boldsymbol{C_e(s)} = \begin{Bmatrix} \boldsymbol{C_{e,1}} \\ \vdots \\ \boldsymbol{C_{e,i}} \\ \vdots \\ \boldsymbol{C_{e,n}} \end{Bmatrix}, \qquad (1)$$

$$\boldsymbol{C_f(z)} = \begin{Bmatrix} \boldsymbol{C_{f,1}} \\ \vdots \\ \boldsymbol{C_{f,i}} \\ \vdots \\ \boldsymbol{C_{f,n}} \end{Bmatrix}. \tag{2}$$

The correlation coefficient at a fixed coordinate s and z is then expressed in terms of the covariance of $C_f(z)$ and $C_e(s)$:

$$\boldsymbol{R}\left(\boldsymbol{C_f(z), C_e(s)}\right) = \frac{\boldsymbol{cov}\left(\boldsymbol{C_f(z), C_e(s)}\right)}{\boldsymbol{\sigma_{C_f(z)}\sigma_{C_e(z)}}}, \tag{3}$$

where $\sigma_{C_f(z)}$ and $\sigma_{C_e(z)}$ denote the standard deviation of $C_f(z)$ and $C_e(s)$, respectively. R^2 is then evaluated for all the possible combinations of s and z. The results are presented in Figure 5.

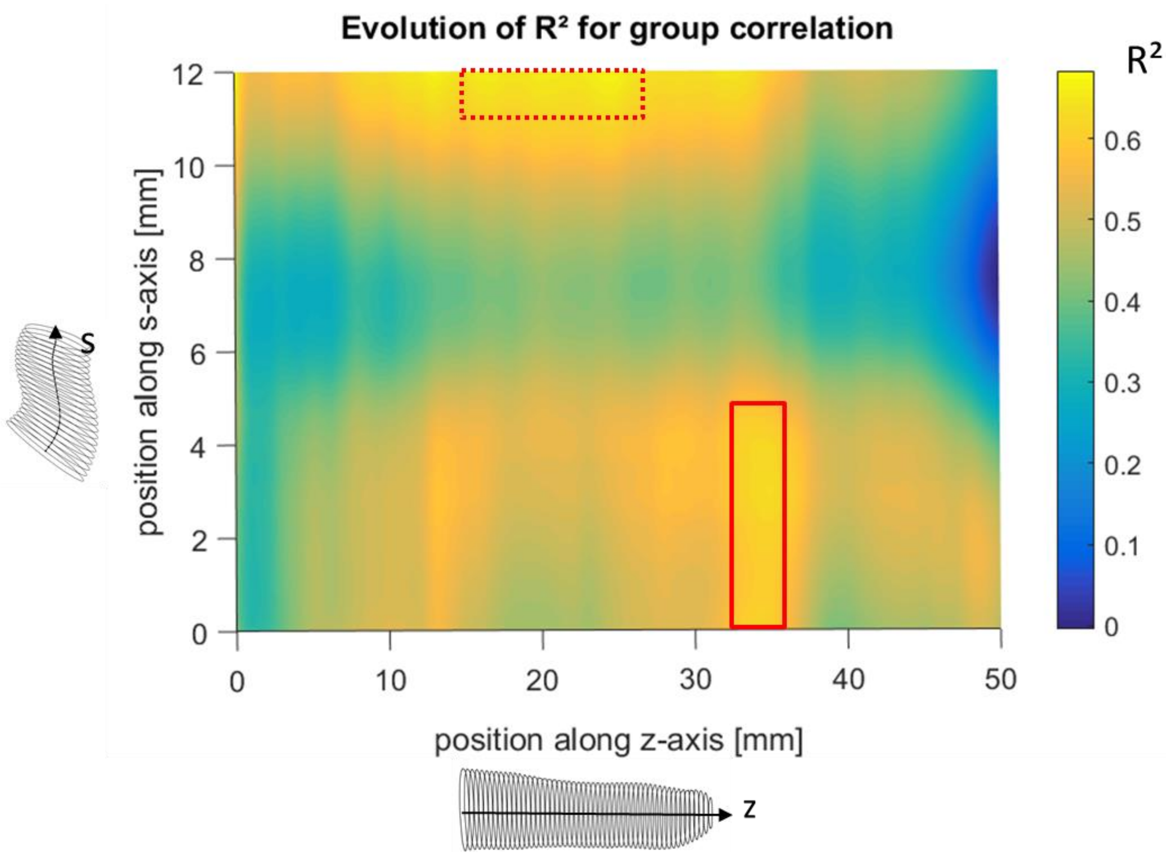

Figure **5**: Evolution of R^2 for group correlation as a function of the location on both the earcanal and little finger. The red rectangles indicate the zones where R^2 reaches a local maximum. Maximum in full lines will be considered, maximum in dotted-lines will not be considered.

Figure 5 indicates that the correlation coefficient R^2 reaches its maximum, around 0.7, in two particular zones. The zone highlighted with a red dotted-line on Figure 5 must be considered carefully, because it corresponds to a zone relatively close to the ending of the custom earpiece, an area that can particularly differ from the real shape of the earcanal at this position. In addition, in the context of selecting an earplug size, it is more appropriate to select a zone closer to the opening of the earcanal. Therefore, the most interesting zone for this research is the one highlighted in solid red lines in Figure 5, which is roughly the cross-section perimeter of the earcanal for an area comprised between its opening to approximatively 6 mm and for the pinky cross-section perimeter, around 35 mm from the base of the pinky.

These results are preliminary and at the time of writing, a recruitment campaign is underway to increase the amount of data, refine the results, and be able to integrate more advanced statistic computations, such as confidence intervals. However, a first prototype based on these results has been designed and will be refined in future works. This tool is presented in the next section.

3.3 First prototype of an earplug-selection tool

The prototype designed with the help of the results obtained in this research is presented in Figure 6. Considering that this tool is based on a relatively small data set and that it will be improved in the future, only the basic concept is presented [12]. It consists in a series of holes with increasing sizes where an individual can introduce his pinky. Each hole is a truncated cone, its length based on the results presented in Figure 4 and Figure 5. The finger is introduced in the different holes and the size is selected when a pressure neither too tight nor too wide is felt. The material used for the prototype will be transparent to make it possible to verify the contact between the tool and the skin.

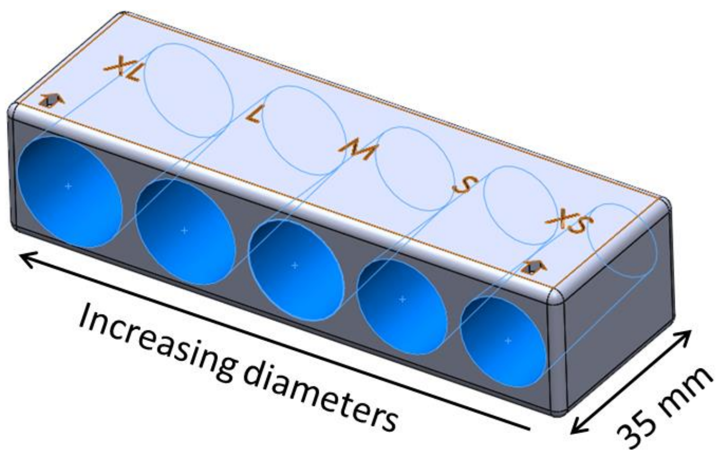

Figure **6**: Design of the envisaged prototype for an earplug-size selection tool based on the gage of the little finger. Each truncated cone is about 35-mm long. The diameter of each slot increases from size XS to XL.

4. Future works

The preliminary results of this research show good potential. Future works that will be considered are:

- To increase the database and refine the results by recruiting more participants. The data will also help to build an abacus for a linear regression model that could be used to estimate the ear-canal cross-section perimeters and by extension, size the tool designed for earplug pre-selection.
- To test the prototype and the selected earplug's attenuation with a standard test to validate that the pre-selection step procures the most suitable earplug.
- To explore other geometric features, such as concha volume and finger length to highlight whether there are or are not other linear relations in these two parts of the human body.
- To study the possible bias introduced in the data by gender, age and body mass index (BMI).

5. Conclusion

This research studied the possibility of making geometrical correlations between the geometries of the earcanal and the pinky finger. These anatomical parts of the human body were measured on eight participants using molding techniques and 3D scanning. There was a high degree of correlation between the cross-section perimeters when comparing the individual data sets. The calculation of a matrix correlation coefficient for the entire group of participants indicates that the best cross-section perimeter location on the little finger is at about 35 mm from its base to estimate the size of the earcanal opening. These results served to design a preliminary prototype that could be used to pre-select the appropriate size of earplug for an individual.

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