R. Ação Ergon., 17(2), 2023.
ISSN 2965-7318. doi: 10.4322/rae.v17n2.e202309.en

DIGITAL FABRICATION FOR TEACHING IN ERGONOMICS AND UNIVERSAL DESIGN

Sabine de Paris[1]*

Mariana Pasa[2]

Angela Weber Righi[3]

Vanessa Goulart Dornéles[4]

Abstract

Teaching Ergonomics and Universal Design in Architecture and Engineering courses requires a theoretical and practical approach through methodologies that use new technologies available on the market. Specifically addressing Anthropometry, the use of digital fabrication and 3D printing allows students to develop experimentation and problem-solving skills. The objective of this study is to present the process of developing teaching materials for Ergonomics and Universal Design (UD) through digital fabrication and 3D printing, in a way that offers support and contributes to the understanding of the topics. The development of a scale prototype involved testing and improvement studies for the dimensioning of a model that uses anthropometric percentiles. Through scale models in the desired percentiles (5%, 50% and 95%), it is possible to demonstrate in the classroom the relationship between the environment and its user by printing elements of our daily lives such as furniture, ramps, stairs and windows. It is understood that the use of digital manufacturing in teaching Ergonomics and Universal Design meets new methodologies for the teaching-learning process, encouraging students to study them.

Keywords: Ergonomics; Universal Design; Digital Manufacturing; Anthropometry.

1. INTRODUCTION

The study of user-centered spaces involves both the knowledge of human physical dimensions (standing height, sitting height, among others) and the work dimensions, which address the dynamics of the body in space. In addition, factors such as age and physical limitation demonstrate that it is not appropriate to use in the project dimensioning established by average values, disregarding the real needs of those who use the space (PANERO, ZELNIK; 2008). In the relationship between the user and the built space, cultural elements and individual values of the perception of space are also included, which affect people's quality of life (HERZBERGER, 1999; HALL, 2005). Areas of knowledge such as Ergonomics and Universal

[1]UFSM.* sparis.arq@gmail.com.
[2]UFSM.
[3]UFSM.
[4]UFSM.

Design (DU) provide methods of understanding the user's needs and, therefore, can collaborate with user-centered design processes (DORNELES; BINS ELY, 2018).

For Iida and Buarque (2016), Ergonomics consists of the application of concepts of anatomy, physiology and psychology to solve problems arising in the relationship between man and the environment. Moraes & Mont'Alvão (2003) consider Ergonomics beyond the relationship between man and tool, including the interactions and communications that take place in the environment. In the case of Universal Design, MACE *et al.* (1996) define it as the design of products, buildings and open spaces that meet the different spatial needs and the different limitations of users. However, DU differs from accessibility, so that accessibility promotes design that is accessible to specific individuals or groups of individuals with limitations (ORMEROD; NEWTON, 2011).

The themes are gaining more and more space within the training of new professionals. The DU, for example, became mandatory content for Architecture and Engineering courses through resolution No. 1, of March 26, 2021 (CNE, 2021). Therefore, different perspectives related to the teaching-learning process and methodological strategies are fundamental to meet the resolution (MALULI; LEE; VERGARA, 2022; GRANDSON; ANDRADE; RIBEIRO, 2022; SIMONETTO; MEDEIROS, 2022). The theoretical and practical approximation, both in Ergonomics and in DU, through teaching dynamics that relate concepts to experimentation is fundamental for students to develop the ability to solve problems (BRAATZ et al., 2017). The multidisciplinarity of Engineering with Architecture allows the relationship between human-technology interaction systems in the design of artifacts (VERGARA, 2005), which provide the discussion of concepts through the application of usability tests (GONÇALVES, 2017). Additionally, the use of new technologies in the production of artifacts makes the themes more attractive to students while preparing students for the market.

The new forms of production associated with digital technology work as great allies in the innovation of projects, manufacturing and construction. Recent means of production, which include rapid prototyping and digital fabrication, incorporate the making of artifacts with new perspectives of advancement and innovation in learning and assimilation of knowledge (SCHEEREN, 2021). Thus, the objective of this article is to present the

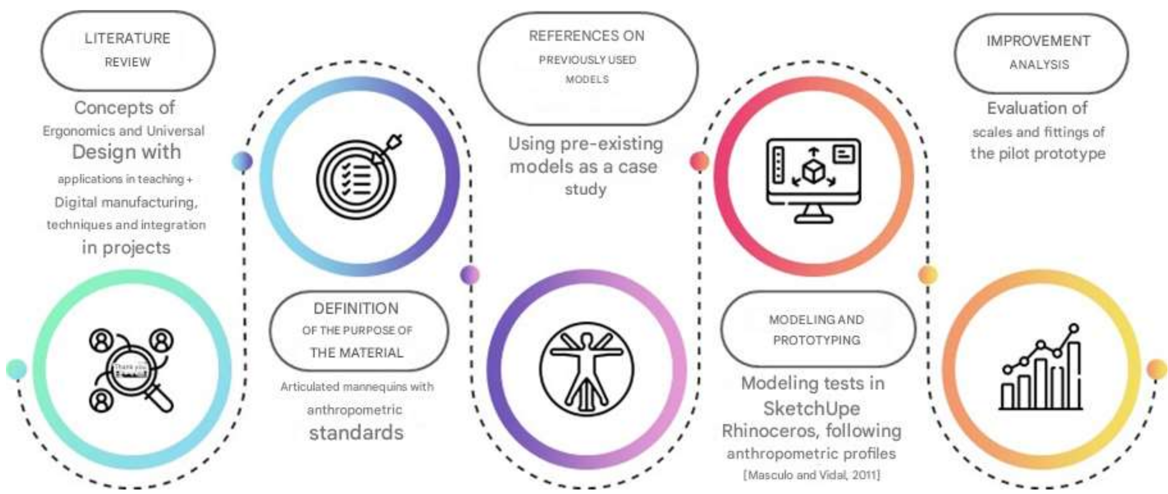
process of development of didactic material for teaching in Ergonomics and Universal Design, through digital fabrication and 3D printing, so that it offers support as didactic material and contributes to the understanding of the themes.

2. Development

The study is characterized as quantitative-qualitative in terms of its approach, focusing on the explanation of the dynamics that involve the relationship between the user and the space. As for its nature, it is characterized as applied research, as it is directed to the resolution of specific problems. As for the objectives, the research is classified as exploratory, since it seeks information and the construction of hypotheses (GERHARDT; SILVEIRA, 2009).

Figure 1 illustrates the development stages of the present study: Stage 1. literature review; Step 2. definition of the purpose of the material; Step 3. references about previously used models; Step 4. modeling and prototyping; and Step 5. analysis of improvements. In order to bring the researcher closer to the content already published on the themes of study (MARCONI; LAKATOS, 2003), Stage 1 of this study consisted of data collection involving research in journals and scientific events about the concepts of Ergonomics and DU and their teaching in Architecture and Engineering courses. In addition, the literature review on the use of digital fabrication, fabrication techniques and the integration of prototyping in the design design stage as well as its impacts on experimentation, solution of design problems and the development of students as reflective professionals.

Figure 1 – Research development stages



Source: Authors, 2023

Due to the breadth of the study themes, after the literature review, it was realized that anthropometry brings Architecture and Engineering courses closer together by involving procedures and techniques for understanding measurements and shapes of the human body and its relationship with the environment (GONÇALVES, 2017). In the design design, the understanding of these measurements is a fundamental part of defining the dynamics of uses and dimensioning of spaces. It was noted, as part of Stage 2, that the articulated mannequins portray, generally in reduced scales, human measurements and proportions and are tools that, together with constructive elements, can be used in the teaching of Ergonomics and DU. Therefore, this was the theme chosen for the development of the following stages.

For a better understanding of the links between anthropometric models and the teaching of Ergonomics and DU, Stage 3 aimed to search for previously used models, inside and outside the scientific environment by case studies, considering physical characteristics and identifying applied guidelines.

After the literature review and theoretical formulation of the anthropometric study related to digital fabrication, the modeling tests (Stage 4) were initiated based on the anthropometric percentiles available in the book by Másculo and Vidal (2011). Due to the authors' previous knowledge, it was decided to initially use the educational version of the SketchUp software. During the modeling, it was realized the need to look for other software that would enable more complex modeling, since the SketchUp tools are limited for anatomical modeling.

The program chosen for the study modeling was Rhinoceros, using the free trial version, which met the previously perceived demand. The production of the pilot prototypes was printed on PLA (Polylactic Acid Biopolymer) filament on a Creality printer, model CR-10S Pro, in the spaces of the Digital Fabrication Laboratory of the Technology Center of the Federal University of Santa Maria (UFSM) - CT Factory.

Finally, Stage 5 of analysis of the printed prototypes, and the entire development process, aiming at improvements, was carried out.

3. Findings

From the aforementioned methods, strategically defined for the objective of this study, the evidence obtained for the analysis is presented. The following sections discuss the results found for each stage of the study's development.

3.1. Literature review on digital fabrication and teaching in Ergonomics and DU

Digital fabrication enables the mass production of different personalized elements, known as *mass customization* (CELANI; PUPO, 2008). This process is associated with digital design and the virtual manipulation of forms, so that the procedures are controlled by computer and coded for subsequent production (BARBOSA NETO, 2013). Considering industrial-scale production in the civil construction sector, digital manufacturing is associated with the final production of formwork or final parts of buildings or other elements that make up construction. In the case of rapid prototyping, it is associated with the manufacture and materialization of prototypes that will be used for analysis and verification of virtual models (PUPO, 2009).

Rapid prototyping is further divided by the type of manufacturing: additive, subtractive or formative. Additive manufacturing is defined by the overlapping of layers of material, whether solid or liquid, through equipment such as the 3D printer. Subtractive manufacturing refers to the roughing of a material in equipment such as milling cutters, laser cutting, and waterjet. Formative manufacturing is that based on a mold on which the material deforms and adapts (PUPO, 2009; BARBOSA NETO, 2013; FACCA et al., 2022).

In Architecture and Engineering courses, the use of rapid prototyping serves as an aid to the design process as a tool for creation and application, uniting the digital and physical worlds. The experimentation provided by modeling and prototyping stimulates students' curiosity, while generating an environment of knowledge sharing (FACCA et al., 2022). The solution of design problems enhances the different capacities of students through data research, use of innovation and decision-making (FERREIRA; FREITAS-GUTIERRES, 2022). In addition, they provide their development as reflective professionals, reflecting on action and on action (SCHÖN, 2009).

3.2. Definition of the material's purpose: Anthropometry

In the literature, there are studies that use modeling and additive manufacturing for the manufacture of prostheses and orthoses, medical products, furniture, everyday products, and tactile maps in different disciplines and themes (BATISTELLO et al., 2015; SOUZA et al., 2017; ANDRADE; AGUIAR, 2018; SOUSA ET AL., 2019; KERMAVNAR; SHANNON; O'SULLIVAN, 2021). However, it was noted that there are few studies with anthropometric models for the teaching of Ergonomics and DU. The models available on the market, such as mannequins in a way, represent the articulation of movements and proportionality between dimensions of the human body. Models created from measurement patterns, according to anthropometric percentiles, are hardly found. In addition, elements of our daily lives such as doors, stairs and furniture, which are basic teaching examples for Ergonomics and DU, are not associated as physical models that can be used in practical teaching.

It is noteworthy that anthropometry should be understood as a tool for inclusion, since among the principles of DU (DORNELES et al., 2013) such as equitable use, low physical effort and space for approximation and use depend on an adequate dimensioning for the different users who use a space and/or furniture. The elimination of physical barriers depends on the assimilation of anthropometry and the user-environment relationship through practical applications that demonstrate to students the importance of the theme.

3.3. References to previously used models

Scientific research on models created from the 3D scanning of real bodies, digitized for later impressions of mannequins, seeks to assist in the manufacture of clothes, shoes and accessories in accordance with the measurements of the respective populations under study (SPAHIU et al., 2016; OH; SUH, 2021; COPILUSI et al., 2023). Mandesso Design, led by industrial engineer Manu Alvarez, developed 29 digital human models addressing the 1%, 50% and 95% percentiles in the ages between a 2-month-old baby and adults. Unfortunately, it is not possible to access the data from Alvarez's study (MANDESSO, 2023). Other models made available digitally, without a scientific character and free access can be found on specific 3D printing sites such as Thingiverse and Cults.

Despite the models and studies available, there are still few resources aimed at teaching ergonomics and DU, especially those that do not require high investment resources. Therefore, the development of didactic material that can be used in various courses and higher education institutions is essential for the dissemination of knowledge.

3.4. Modeling and prototyping

For the initial development of the study model, the drawing by superimposing images in the Sketchup software was tested. Based on the fitting of the wooden mannequins available on the market, it was verified that the original fitting made by nails and springs was difficult to access for manufacture due to the scale of printing. Although the tests were carried out in the 1:20 and 1:10 scales (Figure 2), it would hardly be possible to produce the necessary parts for fitting, becoming a manual and artisanal production, which did not

consistent with the objective of the study. The use of a bench drill and the making of the springs would make the process long and difficult to replicate.

Figure 2 – Printing and drilling of tests based on wooden mannequins

Source: Authors, 2023

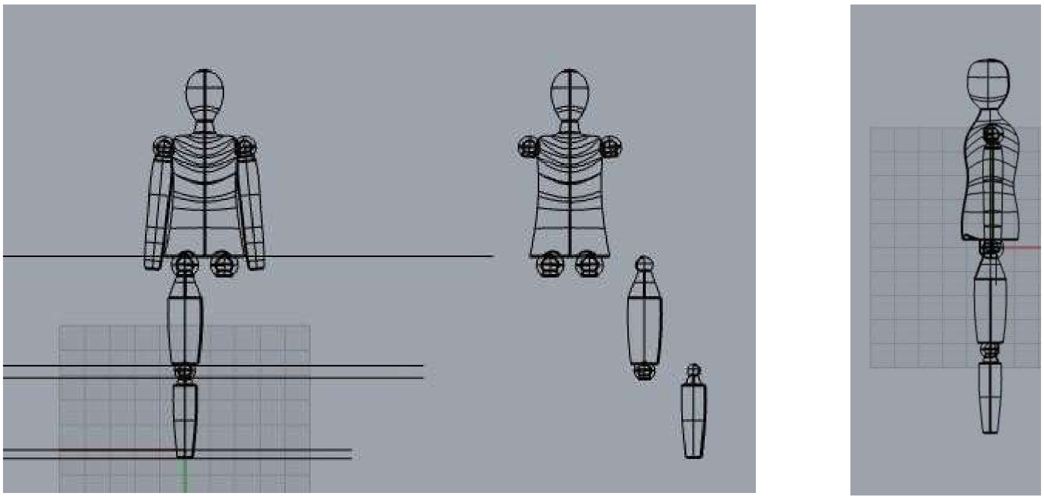
Thus, in a second phase, it was decided to use an articulated model available in the library of the Thingiverse website (Figure 3). Despite not having ergonomic measurements, the model has a fitting system that, after printing, worked properly for the study. However, the model has rights of use and did not meet desired positions such as the fixation of reaches and the standing/sitting position, having joints beyond those necessary for the objective of the study.

Figure 3 – Printout of a model available on the internet

Source: Makermachine, 2023

In the third phase, based on the fitting system and the review of the desired positions, the authors began to develop their own model in the Rhinoceros software (Figure 4). The software, aimed at digital modeling, allows different shapes to be created and modified. Its features allow the interaction and associations of different objects, as well as the development of a parametric design by means of the Grasshopper plugin. Its main disadvantage is the condition of having a paid license, even for students. Therefore, it was used in the free trial version to verify that it fits the proposed study.

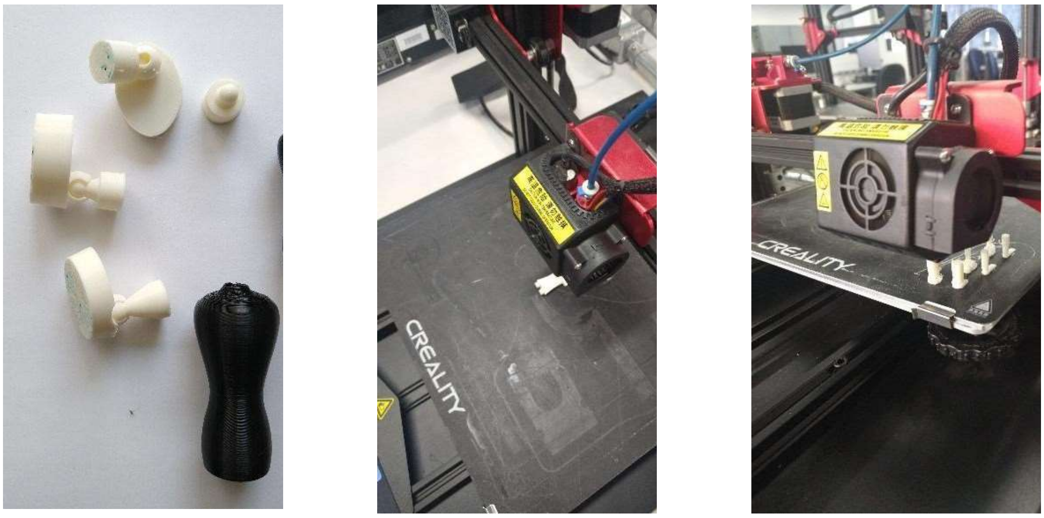
Figure 4 – Prototype modeling



Source: Authors, 2023

Several tests were necessary on parts of the pieces for the functioning of the fittings, so that minimum movements were possible, such as: extension of arm reach, standing position, sitting position (Figure 5). The lack of movement stabilization, as well as the breakage of parts during movement were the biggest challenges for modeling to work in print. The fine adjustment of the dimension of each joint with its socket, as well as its proportionality to the movements, was ensured after constant printing tests. Likewise, the configuration of the 3D printer software, Ultimaker Cura, allows you to change densities, layer quantities and thickness sizing to reinforce the part and prevent it from breaking. It is also intended to explore the balance of composition of the body shapes with these fittings, making the whole more harmonious.

Figure 5 – Printing and testing of prototype fittings



Source: Authors, 2023

3.5. Analysis of improvements

The pilot prototype was printed at 1:20 and 1:10 scale (Figure 6) with the anthropomorphic dimensions of the 50% percentile (VIDAL, 2000) for the final verification of the modeled fittings. It was found that in the upper scale the model works more adequately for the proposed study, as well as the reinforcement performed on the spherical structures to avoid breakage during use. The slim fit brings greater stability and durability to the final model.

Based on the adjustments, it is possible to model the other percentiles (5% and 95%) and create models that are close to the daily life of the population.

Figure 6 – Prototype and simulation ports.

Source: Authors, 2023

In general, it should be considered that it is necessary to deepen skills in the use of the Rhinoceros software to speed up the modeling process and minimize errors. The correct fit of the model requires knowledge and experience to identify problems such as incorrect closure and intersection of objects, proportionality of shapes and dimensioning between fitting parts. Additionally, the configuration of the Ultimaker Cura printing software that generates the supports, layer thickness, type of adhesion of the object to the table and filling added to the type of filament used, which needs to meet the needs of the prototype.

4. Conclusions

The prototype developed for this study, through digital fabrication and 3D printing, with the objective of being used as didactic material for the teaching of Ergonomics and Universal Design, represents the practical application of anthropometric dimensions and percentiles. The methods used for the making of the model and the tests in 3D printing required the investigation of the best means for the design of a model that could meet the perspectives of an innovative material. By means of scale models in the desired percentiles (5%, 50% and 95%) it is possible to demonstrate in the classroom the relationship between the environment and its user with the impression of elements of our daily lives such as furniture, ramps, stairs and fenestrations.

However, the learning curve required in the knowledge of different modeling and printing software is observed as a limitation. Specifically for printing, there are also variations depending on the type of 3D printer, which can use generic software (such as Ultimaker Cura) or its own software. The relationship between the modeled object and the printed object must also be taken into account, taking care with the scales that each software uses and the possible gap between them.

Encouraging students to participate in the making of the elements and reflect on the interaction between different human bodies, their dynamics and their reach is fundamental for active teaching that prepares them for the professional market. The use of the model in Architecture and Urbanism courses can occur in the design disciplines while in Engineering courses it can occur in the Ergonomics disciplines, since anthropometry must be understood by the diversity of measurements and the interaction of the human body with space.

Finally, the practical application and knowledge of the different types of users and how they relate to the environment makes it possible to sensitize students to the barriers that are found in our daily lives and minimize the barriers that do not guarantee inclusion in the whole.

References

ANDRADE, A. F.; AGUIAR, B. C. X. C. O uso de mapas táteis no auxílio do processo de ensino-aprendizagem por meio do desenho universal. In: VII Congreso Internacional y XV Congreso Nacional de Profesores de Expresión Gráfica em Ingeniería, Arquitectura y Carreras Afines. Facultad de Arquitectura y Urbanismo UNLP, 2018.

BARBOSA NETO, W. **Do projeto à fabricação: um estudo de aplicação da fabricação digital no processo de produção arquitetônica**. 2013. Tese (Doutorado em Arquitetura e Urbanismo) – Unicamp, Campinas, 2013.

BATISTELLO, P.; BALZAN, K. L.; PIAIA, L. P.; MIOTTO, J. Prototipagem rápida e

fabricação digital em ateliê vertical: do processo à materialização. In: XIX Congresso da Sociedade Ibero-Americana de Gráfica Digital-Sigradi, p. 137-142, 2015.

BRAATZ, D., PARAVIZO, E., TONIN, L., SILVA, S. Ensino de ergonomia e projeto: experiências de aplicação de uma dinâmica de concepção de espaço de trabalho. **Revista Ação Ergonômica da Associação Brasileira de Ergonomia**, v. 27, 2017.

CELANI, M. G. C.; PUPO, Regiane Trevisan. Prototipagem rápida e fabricação digital para arquitetura e construção: definições e estado da arte no Brasil. **Cadernos de pós-graduação em arquitetura e urbanismo**, v. 8, n. 1, 2008.

CNE. Conselho Nacional da Educação. **Resolução nº 01/2001, de 26 de março de 2021**. Dispõe sobre as diretrizes curriculares nacionais dos cursos de graduação de Engenharia, Arquitetura e Urbanismo. Brasília: Ministério da Educação. Disponível em: http://portal.mec.gov.br/index.php?option=com_docman&view=download&alias=175301-rces001-21&category_slug=marco-2021-pdf&Itemid=30192. Acesso em: 21 de jul. de 2023.

COPILUSI, C.; GEONEA, I.; VLADU, C.; MARGINE, A. Design of a parameterized mannequin using rapid prototyping technology. In: International Conference of Mechanical Engineering (ICOME-2022). Atlantis Press, p. 27-35. 2023.

DORNELES, V. G.; AFONSO, S.; ELY, V. H. M. B. O desenho universal em espaços abertos: uma reflexão sobre o processo de projeto. **Gestão & Tecnologia de Projetos**, v. 1, n. 8, p. 55- 55, 2013.

DORNELES, V. G.; BINS ELY, V. H. M. Experiências didáticas em arquitetura e urbanismo: o ensino de desenho universal. **Revista Projetar - Projeto e Percepção do Ambiente**, v. 3, n. 2, p. 08-22, 2018.

FACCA, C. A.; FERNANDES, A.; ALVES, J. L.; RANGEL, B.; BARBORA, A. M. **A**

impressão 3d e as tecnologias emergentes de fabricação digital: a (r)evolução nos processos de ensino de design, engenharia e manufatura. In: ARRUDA, A. J. V.; ARAÚJO,

G. G. Design & Narrativas Criativas nos Processos de Prototipagem. São Paulo: Blucher, 2022.

FERREIRA, C. C.; FREITAS-GUTIERRES, L. F. Aprendizagem ativa por meio da prototipagem rápida em um curso de graduação em Engenharia de Energia. **Revista Thema**, v. 21, n. 3, p. 776-795, 2022.

GHERHADT, T. E.; SILVEIRA, D. T. **Métodos de pesquisa**. Porto Alegre: Editora UFRGS, 2009.

GONÇALVES, M M. O ensino de ergonomia em um curso de design de moda. **Revista de Ensino em Artes, Moda e Design**, v. 1, n. 1, 2017.

HALL, E. **A dimensão oculta**. São Paulo: Martins Fontes, 2005.

HETZBERGER, H. **Lições de arquitetura**. São Paulo: Martins Fontes, 1999.

IIDA, I.; BUARQUE, L. I. A. **Ergonomia: projeto e produção**. São Paulo: Editora Blucher, 2016.

KERMAVNAR, T.; SHANNON, A.; O'SULLIVAN, L.W. The application of aditive manufacturing/3D printing in ergonomic aspects of product design: A systematic review. **Applied Ergonomics**, v. 97, p. 103528, 2021.

MACE, R. L.; HARDIE, G. J. PLACE, J. P. **Accessible environments: toward Universal Design raleigh**. NC: Center for Universal Design, 1996.

MALULY, C. V.; LOPES, S. A. P.; VERGARA, L. G. L. Recursos ópticos para ensino-aprendizagem: revisão sistemática sobre tecnologia assistiva voltada à baixa visão. In: Anais do Congresso Brasileiro de Ergonomia da ABERGO. **Anais**[...] São José dos Campos: Parque Tecnológico de São José dos Campos, 2022.

MAKERMACHINE. Poseable mannequin. Thingiverse. Disponível em: https://www.thingiverse.com/thing:101451. Acesso em: 21 jul. 2023.

MANDESSO. **Mandesso Design, Manu Alvarez**. Disponível em: https://mandesso.com/. Acesso em: 21 jul. 2023.

MÁSCULO, F. S.; VIDAL, M. C. **Ergonomia: trabalho adequado eficiente**. Rio de Janeiro: Elsevier, 2011.

MORAES, A.; MONT'ALVÃO, C. **Ergonomia, Conceitos e Aplicações**. Rio de Janeiro: iUsEr, 2003.

MARCONI, M. A.; LAKATOS, E. M. **Fundamentos de Metodologia Científica**. São Paulo: Atlas, 2003.

NETO, V. B.; ANDRADE, E. H. A.; RIBEIRO, P. L. S. Metodologia de ensino-aprendizagem em saúde e segurança do trabalho: um relato de experiência. In: Anais do Congresso Brasileiro de Ergonomia da ABERGO. **Anais**[...]São José dos Campos: Parque Tecnológico de São José dos Campos, 2022.

OH, S.; SUH, D. Mannequin fabrication methodology using 3D-scanning, modeling and printing. **International Journal of Clothing Science and Technology**, v. 33, n. 5, p. 683-695, 2021.

ORMEROD, M.; NEWTON, R. Is your inclusive my exclusive?: Edinburgh College of Architecture. In: Open Space: People Space 3, An international conference on Research into Inclusive Outdoor Environments for All. Edinburgh, 2011.

PANERO, J.; ZELNIK, M. **Dimensionamento humano para espaços interiores**. Barcelona: Editora GG, 2008.

PUPO, R. T. **Inserção da prototipagem e fabricação digitais no processo de projeto: um novo desafio para o ensino de arquitetura**. 2009. Tese (Doutorado em Arquitetura e Urbanismo) – Unicamp, Campinas, 2009.

SCHEEREN, R. **Fabricação digital na América do Sul: laboratórios, estratégias, processos e artefatos para o design, a arquitetura e a construção**. 2021. Tese (Doutorado em Arquitetura e Urbanismo) – Universidade de São Paulo, São Paulo, 2021.

SCHÖN, D. A. **Educando o profissional reflexivo: um novo design para o ensino e a aprendizagem**. Porto Alegre: Penso Editora, 2009.

SIMONETTO, L.; MEDEIROS, C. R. P. X. "DEERGO" - Projeto de ensino da ergonomia por meio do Instagram: uma iniciativa de divulgação democrática e acessível da disciplina. In: Anais do Congresso Brasileiro de Ergonomia da ABERGO. **Anais**[...] São José dos Campos: Parque Tecnológico de São José dos Campos, 2022.

SOUSA, F.; GATINHO, N.; DEMAISON, A.; CAMPOS, L. F. Design, ergonomia e impressão 3d: um exercício prático de projeto para protetores de tomada. **Ergodesign & HCI**, v. 7, n. Especial, p. 168-179, 2019.

SOUZA, L. F. D.; ANDRADE, M. F. D.; GRAÇA, I.; CANTALICE, J. D. D. A. Projeto de

mobiliário multifuncional-ergonomia aplicada a design de produto. **Revista Ação Ergonômica**, v. 12, n. 2, 2017.

SPAHIU, T.; GRIMMELSMANN, N.; EHRMANN, A.; SHEHI, E.; PIPERI, E. On the

possible use of 3D printing for clothing and shoe manufacture. In: Proceedings of the 7th International Conference of Textile, Tirana, Albania. p. 10-11, 2016.

VERGARA, L. G. L. **Avaliação do Ensino de Ergonomia para o Design aplicando a Teoria da Resposta ao Item (TRI)**. 2005. Tese (Doutorado em Arquitetura e Urbanismo) – Universidade Federal de Santa Catarina, Florianópolis, 2005.

VIDAL, M. C. **Introdução à ergonomia. Apostila do Curso de Especialização em Ergonomia Contemporânea/CESERG**. Rio de Janeiro: COPPE/GENTE/UFRJ, 2000.