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3D-Printed Ergonomic Tool Handles

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Abstract. Although hand tools serve as an instrument for extending one's capabilities through the use of hands, the comfort it brings is important especially since the welfare of the user is at stake. Aside from using the hand tools repetitively and with an awkward posture, the tool handle compositions and design also contribute to accumulating some work-related musculoskeletal disorders that require further attention in the long run. To provide a long-term solution, 3D-printed new designs of six commonly used hand tools that fit the average hand measurements of Filipinos have been developed. The hand tools are printed using two filaments namely; thermoplastic polyurethane (TPU) which was found to be skin-friendly and polylactic acid (PLA) which is proven to be more functional, both are used on the outer and inner layer of the handle, respectively. The 3D-printed tool handles were evaluated through the use of a comfort questionnaire for hand tools distributed to 10 respondents per tool handle testing, results show that 3D-printed tool handles are found to be more comfortable and convenient rather than the commercial ones. Meanwhile, the researchers note that the adequate length of tool handles may also vary according to functions and not rely alone on the average hand measurements.

Keywords: Additive Manufacturing, Musculoskeletal Disorder, Tool handles

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1. Introduction

In this contemporary world, the adaptation of automated machines and advanced technologies is frequently seen in different industries. Regardless, many workers still opt to use manual hand tools that they are very familiar with instead of other variations with a touch of newer technology. Hand tools, in layman's terms, can be referred to as something that can be used easily by hands. The establishment of the past generation primarily relied on the utilization of hand tools accessible at that time. Nowadays, using these hand tools is frequently seen everywhere, and a flawed design of tools in a production area could affect almost 10% of workers annually. These hand tools have paved the way for humans to showcase their skills of making crafts or any other works. Albeit hand tools serve as an instrument for extending one's capabilities through the use of hands, the discomfort it brings is challenging, especially since the welfare of the user/worker is at stake [1]. Aside from using the hand tools repetitively and with an awkward posture, the tool handle compositions and design also contribute to accumulating some work-related musculoskeletal injuries that require attention in the long run as the user's health might be put in peril—in some severe cases. As defined by the Centers for Disease and Prevention, work-related musculoskeletal disorders (WMSDs) are mostly injuries or disorders of the muscles and nerves on the hands, wrist, and the other parts of the body that are painful and hard to endure over the long run [2]. Such disorder is often a result of the hazardous environment where the work takes place and even the prolonged usage of equipment like hand tools. Based on the studies by Cupar et al., designing the appropriate tool handles must be addressed to avoid the WMSDs, since the users' comfort rely primarily on the tool handles [3]. Therefore, a proper design of tool handles that focuses on the size, material used, and the average hand size of the Filipino workers is necessary to have an ergonomic and comfortable connection between the user and the tool itself. An ergonomically designed tool handle is important in preventing various disorders such as shoulder acute trauma diseases (ATD) and cumulative trauma disorders (CTD). Carpal Tunnel Syndrome is a type of CTD that causes numbness, tingling, or weakness in the hand, blisters on the hand, hand tendinitis, and certain other conditions under musculoskeletal disorders (MSDs) [4].

Several researchers have also demonstrated that a well-designed handle may improve the entire user-product system's safety, performance, and comfort. They have established recommendations and mathematical analysis for calculating handle sizes and forms to enhance finger-force exertion, grip force to the handle, contact area, comfort, and lower the likelihood of ATD and CTD development [3]. So, in this study, the application of the Additive Manufacturing process has been adapted in making a 3D-printed tool handle to customize further the designs and the materials in constructing a new tool handle. Additive Manufacturing (AM) or 3D Printing is now widely used in different applications such as electronics, robotics, construction, automotive, agriculture, medicine, aerospace, desalination, education, satellites, oil & gas, and many others [5]–[14]. 3D printing is the process of creating three-dimensional objects through a layering method from a 3D computer-aided design model. The 3D modeling software, such as Fusion 360, allows the ability to design and customize models based on the desired product. This study will use a subjective comfort questionnaire to assess further the quality and comfortability of various 3D-printed tool handles. It aims to give an answer or enlightenment if producing customized and ergonomically designed 3D-printed tool handles would prevent the accumulation of ergonomic-related injuries when using ordinary hand tools.

2. Materials and Methods

2.1 Material

The materials used in the study were thermoplastic polyurethane (TPU) and polylactic acid (PLA). The comfort of using thermoplastic polyurethane (TPU) on the hand tool’s outer handle was ensured and backed up by the study of Cupar et al. [3]. TPU can realistically emulate elastomeric characteristics because it can provide a comparable degree of softness and flexibility to a rubber. It also has excellent properties of abrasion, hardness, and thermal and chemical resistance. TPU is the most used type of Thermoplastic elastomers (TPE) in Fused Filament Fabrication (FFF) 3D printing [7]. The TPU-made handle was then supported by the inner core made from PLA, as shown in Figure 1. The reason behind using this is that it can reinforce the outer layer made from TPU and could transfer the forces from the hand back to the handle and handle back to the hand, as stated in the study of Cupar et al. [3]. PLA is a versatile and inexpensive bioplastic; thus, it is environmentally friendly and mostly made from green renewable resources. PLA is the most popular 3D printing material because almost all FFF 3D printers can use it due to its lower melting point. And it is also known for its strength and high dimensional accuracy [15].

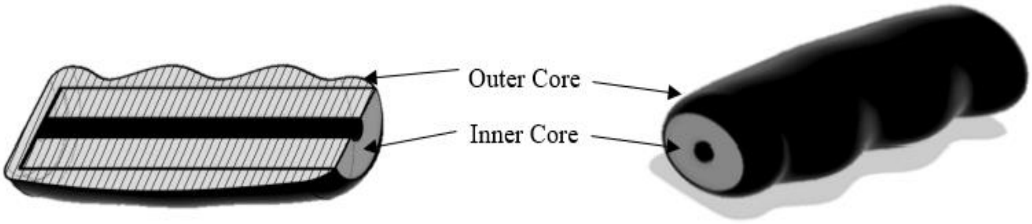


Figure. 1 General design configuration of tool handle

2.2 Experimental Method

2.2.1 Average Hand Measurements of the Filipinos

To obtain the appropriate dimension and design of tool handles, hand measurement of sixty (60) randomly selected adults from the province of Bataan and some parts of the province of Zambales was conducted. The participants consisted of 30 females and 30 males with an average age of 41. The hand measurements or dimensions were obtained based on the study of Ching-yi Wang et al. [16]. The dimensions were; hand length, hand breadth, which indicated how long the tool handle should be, and major and minor grip diameter, which could be measured only when the hand was on a grip gesture. The grip gesture that the proponents and the participants followed were based on the biodynamic hand coordinate system defined in ISO 8727 [5]. Based on the data gathered (see Table 1), the average hand length of the Filipinos is 175.23 mm, the hand breadth (the width where the fingers join the palms) is 72.92 mm, and the major and minor grip breadth is 34.43 to 38.91 mm. The length of the tool handle was indicated by the average hand breadth of the Filipinos, which is 72.92 mm—signifying that the minimum length should be 100 mm to allow the hands to glide up and down on the tool handle itself. At the same time, the minor and major diameter of the tool handle is around 34.43 to 38.91 mm, which is within the average measurement of the Filipino’s minor and major grip breadth. Moreover, the data were gathered by only measuring the right hand of the respondents as it is the most dominant side, and almost 90% of them are right-handed. The hand dimensions were measured carefully using a digital Vernier caliper and tape measure.

Table 1. Hand Measurement of the Respondents

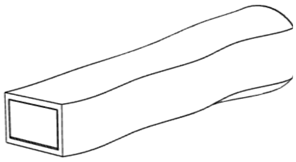
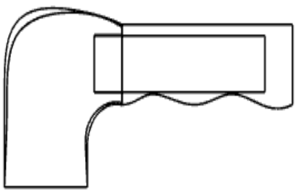
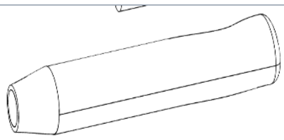
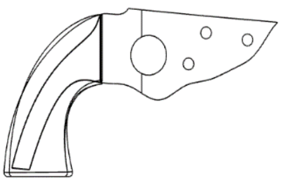
Dimension	**Male**		**Female**		**Over-all**	
	Mean (mm)	SD	Mean (mm)	SD	Mean (mm)	SD
Hand Length	184.87	13.73	165.29	9.49	175.23	13.56
Hand Breadth	75.87	7.71	69.97	13.39	72.92	13.00
Grip Breadth (W)	40.67	6.63	37.16	18.29	38.91	5.45
Grip breadth (L)	35.72	5.80	33.13	4.27	34.43	5.54

2.2.2 Design and Manufacturing of 3D-Printed Tool Handles

The design specifications of each tool handle should be in accordance with Filipinos' average hand measurements, as shown in Table 1. The shape must be in ellipse form to provide comfortability and a better grip for the users [17]. It is also crucial to identify the accurate sizes for the users to avoid unnecessary inconvenience and discomfort. The handle diameter must be related to Filipinos' average major and minor breadth diameter, which is 34.43 to 38.91 mm. This measurement is similar to the studies of Cupar et al., which stated that the average grip diameter must be within 30 to 40 mm [4].

A profound consideration was given in selecting the type of materials to be used in the 3D-printed hand tool, as it could affect the overall comfortability of the tool handles. TPU is used as the outer layer of the tool handle because of its high resistance to scratch and abrasion, thus ensuring an aesthetic value for the 3D-printed tool handle. It was printed using the Flashforge Creator Pro with an infill pattern of hexagonal as it is the strongest and best pattern available on that printer. At the same time, the infill density is 14%, as it provides comfortability and good grasping force for the user of the tools [4]. On the other hand, the inner layer of the tool handle was printed on Anycubic i3 Mega and Ultimaker 3 Extended using the PLA or polylactic acid filament with 30-50% infill density and was used to serve as a support to the force exerted by the hand on grasping the handle. Gyroid was used on the inner layer as it has a lighter weight, is easier to print, and has a shear strength as it has a uniform strength to all directions suitable for functional uses. The cross-sectional design in 2D and 3D along with the 3D-printed prototype of the tool handles are shown in Table 2.

Table 2. Cross-sectional design and 3D-printed prototype of tool handles.

Types of Tool Handle	**2D Design**	**3D Design**	**3D-Printed tool handle**
Hammer Handle			
Brush Handle			
Mallet Handle			
Saw Handle			

Shovel Handle	
Trowel handle	

2.2.3 Testing and subjective comfort rating

Figure 2. Actual photos of 3D-printed tool handle in their corresponding tools

After manufacturing, the 3D-printed tool handles were assembled and attached to their corresponding type of tool, as shown in Figure 2. Each of them will be tested and evaluated in terms of comfortability. Per testing of the tool handles, 10 Filipino respondents working in the construction field were gathered with ages ranging from 21 to 59 years old without any disorders on their arms and had a complete set of hands and fingers. The hand tools were evaluated using the comfort descriptor questionnaire which was adapted from the study of Kuijt-Evers et al., as shown in Table 3 [18].

Table 3. Sample of questionnaire used for evaluation of hand tools.

Comfort Descriptors	**Scale**						
	7	6	5	4	3	2	1
Adequate size which fits the hand perfectly							
Functional and can complete a task							
Easy to use and to grip							
Has a good force transmission when in use							
High quality product							
Emits great feeling to the user							
Results to great performance when using it							
Gives excellent outcome of the product/task when in use							
Seems professional and high quality							
Does not need much force to exert in gripping when using it							
Has a good friction between handle and the hand							
Results to inflammation of skin when used							
Produces wounds, redness, or blisters to the hand when used							
Feels sweaty or slimy							
Causes insensibility of and lack of tactile feeling in hand							
Hand muscles cramped while using it							
Give rise to spike in hand pressure while in used.							

Each hand tool was tested and evaluated by comparing the feedback of every respondent after using the hand tool with an ergonomically designed 3D-printed tool handle to the hand tool with its ordinary handle. But for every hand tool, the respondents were given and followed a specific task, and specific resting time was allotted before they could switch from one tool handle to another to avoid fatigue. For the hammer, the respondents were required to pound 2 inches of common wire nails five (5) times on a good lumber wood using the hammer with two different handles. One minute interval is allotted for rest before changing handle type. While for the paintbrush, the respondents were tasked to paint using the 3D-printed brush handle and the ordinary wooden brush for a few hours during their working day. They painted wood for about 5 minutes using paint brushes with different handles. For the hand saw, the respondents were tasked to create a 50 mm deep cut on a good lumber wood (50.8mm by 50.8 mm by 24.38 mm) for 5 to 10 minutes with a 3-minute interval after using each hand saw with a different handle for adequate rest to avoid fatigue. In the case of a mallet, the respondents were tasked to pound a particular wood using the mallet with different handles. The task was repeated five (5) times with a 5-minute interval for resting before changing the mallet. For the shovel, the respondents were tasked to scoop a blade full of sand using two different shovels with different handles. This process was done ten (10) times per shovel with 5-minute intervals for rest when switching from one type of shovel to another to avoid fatigue. Lastly, for the trowel, respondents were tasked to used the trowel for about 1.5 hours per kind of trowel: the 3D-printed and the ordinary wooden handle. After completing each task, respondents will rate each specific hand tool with two types of handles based on the comfort descriptors and overall comfort rating. Figure 3 shows the above procedures.

Figure 3. Actual testing and evaluation of (a) Hammer, (b) Paint Brush, (c) Hand Saw, (d) Mallet, (e) Shovel, and (f) Trowel.

3. Results and Discussion

Figure 4 represents the difference in overall comfort rating between the 3D-printed tool handles and the ordinary hard handles. Some are made of hard plastic or wood, which shows that the 3D-printed handles are far more comfortable than the other variation of handles. The data shows that the shovel and mallet's 3D-printed handle are model fit as it has a perfect mean score of 7 and a standard deviation of 0. While the hand saw obtained the lowest mean score of 6.2 and an SD of 0.42, it still delivers an overall good result, but improvements should be made, as suggested by the respondents.

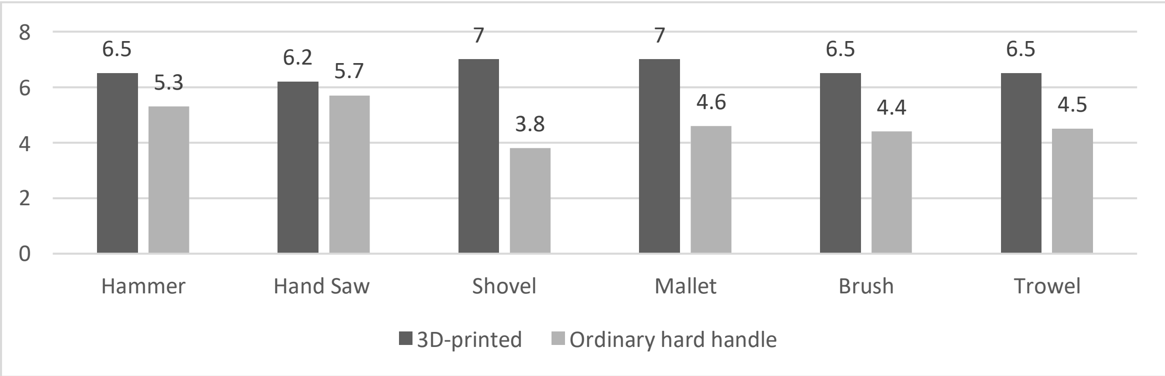


Figure 4. Overall Comfort Rating

The suitable material, ergonomic design, and exact size of the handle of the hand tools can improve the quality of work. Based on the results, it can be concluded that 3D-printed tool handles bring better comfort to end users, especially those who use it every day, thus avoiding work-related musculoskeletal disorders. They are also much better than those products made from wood or hard plastics as they were given as being hard and cannot be deformed when being grasped by the hand. The infill density of the outer layer and the infill pattern contributed massively to making these ergonomic tool handles. The creation of the outer layer using a TPU material with a 14% infill pattern and the hexagonal pattern created a very comfortable handle, as shown in the results compared to the ordinary wooden or hard handle. Also, it took less time for the 3D-printed tool handles to print, lesser material consumption, and at the same time, offering greater strength and durability.

4. Conclusion and Recommendations

This research investigated and designed ergonomic handles for six different hand tools: hammer, shovel, mallet, paintbrush, trowel, and hand saw, to provide comfortability and fitness to the users. Based on the questionnaire survey findings, the newly designed handles of hand tools are comfortable and fit the hand, except for hammer and trowel, as the length of their handles is too short stated by the subjects. Nevertheless, the overall ratings on all six tool handles indicate comfortability, functional, and professional looks in using the hand tools. The respondents are inclined to use hand tools with ergonomically designed handles as their work tools. Also, 3D printing consumes lesser materials than traditional manufacturing of hand tools through injection molding and others. Moreover, 3D-printed tool handles increase the performance of the workers, provide a long- term comfort, and may reduce the accumulation of hand injuries.

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