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3-D Printing Open Source Click-MUAC Bands for Identification of Malnutrition

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Abstract

Objective An effective method for the diagnosis of severe acute malnutrition is the measurement of the middle upper arm circumference (MUAC). Current methods to measure MUAC in a pre-hospital setting is through the use of measuring tape indicators, which require users to be trained in how to apply, adjust the tightness and read the device properly. This represents a challenge to using MUACs in many developing world contexts. This study explores the technical viability to overcome some of these challenges with conventional MUAC measurement methods using open source 3-D printable click-MUAC bands.

Design: The dimensional accuracy of the open source 3-D printable click MUAC band was quantified with a digital micrometer to ensure reproducibility. The durability is evaluated by putting bands through a deformation test to simulate the use of the band in the field 500 times. The production costs are quantified using the mass of the filament and electricity consumed to manufacture each band.

Results: The click MUAC bands are dimensionally accurate (inner circumferences of +/- 0.50 mm) and durable (surviving 500+ deformations with no notable residual deformation). The 3-D printable click MUAC bands are easier to use and provide a significant cost savings (92% to 97%) when compared to current MUAC measurement methods.

Conclusions: The open-source 3-D printed click-MUAC bands offer a viable alternative to the current methods of obtaining MUAC measurements.

Introduction

Nearly half of all deaths in children under five years old are attributed to undernutrition, which equates to three million deaths annually [1]. Malnutrition has also been linked to cognitive deficits and stunted growth [2-4]. One in six children being underweight and in danger of malnutrition and one in three children are stunted in developing countries [5]. Nutrition programs have been shown to be effective in reversing life threatening cases of malnutrition [6]. These nutrition programs are capital intensive [7] and many organizations considering funding these programs have developed criteria to determine their necessity. The World Health Organization recommends the use of a cut-off for weight-for-height below three standard deviations of their published health standards to identify children with severe acute malnutrition (SAM) [8]. Another criterion for the diagnosis of SAM is the measurement of the middle upper arm circumference (MUAC). Several studies have shown that MUAC measurements correlates with weight-for-height measurements and is an accurate predictor of malnutrition wasting [9-12]. In a study including anthropometric measurements on 450,000 children in 31 countries, the prevalence of SAM defined by weight-for-height below 3 SD of the WHO standards and by a MUAC cut-off of 115 mm were very similar: 3.22% and 3.27%, respectively [13]. MUAC measurements below 115mm have also been shown to be a reliable diagnostic criteria for elevated risk of death due to malnutrition [14]. These findings were supported by in hospital studies that concluded MUAC measurements was a significant predictor of death ($P = .001$) and was both more accurate and precise as a nutritional assessment tool than BMI [15].

Current methods for measure MUAC in pre-hospital settings is through the use of measuring tape indicators, such as the four-colored mid-upper arm circumference tape indicator. The indicator tapes offer ranges which are colored to designate different levels of malnutrition severity (less than 115mm – severe malnutrition; 115mm-125mm – moderately malnourished; 125mm-135mm – risk of malnourishment; above 135mm – properly nourished). These indicators require users to be trained in how to read the device properly. Users must be able to properly apply the tape, adjust it to the correct tightness, make the correct circumference measurement, and understand the implications of that number. This represents a challenge to using MUACs in many developing world contexts, as it has been shown that the largest source of error in anthropometric measurements is introduced by human error during the measurement [16]. Commercial indicators sell at prices ranging from \$0.39 to \$1.19 a piece for quantities under twenty-five [17-18].

This study explores the technical viability to overcome some of these challenges with conventional MUACs using open source 3-D printable click-MUAC bands. First, click MUAC bands are designed using an open source CAD package to minimize material costs, print time, and embodied energy, while ensuring that they can be easily printed without support or special materials on a standard fused filament fabrication (FFF) based desktop 3-D printer. The click MUACs designed had a specific inner circumferences of 115mm, 125mm, and 135mm. They can be elastically deformed and wrapped around the mid-upper arm of a child. If the clasp clicks closed while the band is around the middle upper arm, the child's MUAC will be known to be less than the given inner circumference. The accuracy of the click MUAC bands are quantified with a digital micrometer after repeated prints to ensure the click MUAC are consistently reproducible. The durability is evaluated by putting bands through a deformation test to simulate the use of the band in the field 500 times. Finally, the production costs are quantified using the mass of the filament and electricity consumed to manufacture each band. The results are discussed in the context of 3-D printed click-MUAC band being considered as a new instrument

for MUAC measurements due to their simplicity, accuracy, durability, cost effectiveness.

Methods

The experimental verification of the 3-D printed click MUAC band's accuracy, durability, and production cost was completed through the experimental protocol below. Ten click MUAC bands were 3-D printed and tested as follows.

The most accessible and lowest cost 3-D printers available widely throughout the world are fused filament fabrication (FFF) -based 3-D printers [19], derived from the open source RepRap (self REplicating RAPid prototyper) 3-D printer [20]. They are a good selection for distributed digital manufacturing in the developing world as they can produce most of their own parts as well as a long list of appropriate technologies [21]. Solid models of the click MUAC bands were created using OpenSCAD [22], an open-source script based solid modeling software program. The model was designed to minimize plastic use and the concomitant cost, print time, embodied energy and environmental impact [23]. The designs are parametric – but also feature a dimple code to ensure that they are printed in the appropriate color to minimize human error. The click MUACs are designed to have a specific inner circumferences of 115mm (1 dimple), 125mm (2 dimples), and 135mm (3 dimples) and can be printed without supports. Fig. 1 shows the solid model rendered in the OpenSCAD software. On the left of Fig. 1 is the commented script showing how the band was designed. The click MUAC bands can be printed without support or special materials on a standard FFF based 3-D printer. The free and open source designs are made available under a GNU General Public License (GPL) 3.0 in SCAD and .stl format [24].

The .stl files were sliced with an open source slicing program, Cura [25]. The click MUAC bands were printed with 50% infill on a delta style RepRap [26] running free and open source Franklin control software [27] with 1.75mm PLA filament (Hatchbox) with a tensile strength of 56.6 MPa and standard printer settings for PLA material [28]. The click MUAC bands were printed one at a time although they can be plated to fill the platform of the 3-D printer used. Cross platform reproducibility was tested on Cartesian style FFF-based TAZ 6 3-D printer (Aleph Objects).

Each click-MUAC band's diameter was measured using a Mitutoyo Absolute Series 500 digital micrometer caliper (+/-0.01mm). Three diameter measurements were collected from each band with approximately 120 degrees of rotation between diameter measurements. The measurements from each individual band were averaged, then the mean inner circumference was calculated using the equation for the circumference of a circle being 2π times the diameter. Each band was weighed five times on an electric digital scale (+/- 0.01 grams).

The bands were then put through a durability test consisting of mechanical deformation of the bands from their circular shape to a point passed a straight line. The bands were deformed repeatedly until plastic deformation that would interfere with function was observed. The durability testing consisted of an expected failure analysis. In this failure testing bands were subjected to elastic deformation similar to what would be expected in the application of a band to a patients arm, but to a greater extent. In the testing the bands were bent through four points of contact, one at each end and one approximately 20 mm from the clasps, until the bands were close to a straight line. A band was said to fail the test if after any number of deformations the

degree of plastic deformation inhibited proper use of the device.

The material cost of each band was calculated by multiplying the bands weight by the cost of PLA per gram (\$19.99/kg Amazon), as previous work has shown that the electrical consumption costs are not needed [29].

Results

The click MUAC printed successfully on both the delta and Cartesian based RepRap 3-D printers tested. Fig. 2 shows three click-MUAC color and dimple coded to correspond with the inner circumference of the bands.

Table 1 shows the average of three diameter measurements for each of the 3-D printed click MUAC bands. These measurements were averaged to find the overall mean diameter, which was used to calculate the average inner circumference of the bands. The average inner diameter of all ten click MUAC was 36.50 +/- 0.16 mm, which resulted in an average inner circumference of 114.66 +/- 0.50 mm.

In the expected failure analysis all bands tested passed a series of five hundred deformations without any significant plastic deformation that would inhibit the proper use of the device. One band was deformed eight hundred times and showed no significant residual deformation, indicating the bands could be used in the field over an extended time period. The experimental average mass of the click MUAC bands was 1.15 grams for the 115mm bands, 1.24 grams for the 125mm bands and 1.49 grams for the 135mm bands. This results in a material cost from \$0.023 (red) to \$0.030 (green) per click MUAC band.

Discussion

The 3-D printed click MUAC bands are designed to be digitally distributed and manufactured in hospitals or field offices anywhere in the world. This new model of production enables those investing in medical research to maximize their return on investment [30] and follows the current paradigm shift underway in scientific hardware [31-33]. The results here show that the 3-D printed click MUAC bands are dimensionally accurate when 3-D printed by a user assembled RepRap after calibration. An error of 0.287% existed between the average 3-D printed inner circumference and the specified 115mm circumference of the OpenSCAD solid model file. This small error is insignificant in the application of these devices.

Consistent reproducibility is imperative in this context. There are now hundreds of types of FFF 3-D printers, many of which are built from kits and from scratch. Thus, errors created from user assembly can be anticipated. This challenge is solved within the design. The separation between the clasps in the digital design is minimized as well as the attachment points for the clasps to ensure any distributed manufacturers' 3-D printer is properly calibrated to print the bands. If under extruding, the clasp will not print whole and if over extruding, it will fuse the clasp together in a solid ring. Thus the design ensures that if the band prints whole on any FFF device the measurements should be accurate enough to use as a medical diagnostic tool.

When compared to the current tape measure indicators, the use of the 3-D printable click MUAC device leaves less room for user error due to the fact that the click MUAC gauge does not require the user to either correctly tighten the device around a subject's arm or make a

measurement using the scale, which can be complicated for inexperienced users. The dimples printed on the devices ensure that even if a 3-D printer user error occurs and the band is printed in the wrong color (or if only 1 color of filament is available) the proper diagnosis is made. The click-MUAC bands will require minimal training to use due to the binary nature of the test of each band. For example, if the clasp closes with the 115mm band around the middle-upper arm of a patient then that patient has an elevated risk of death due to malnourishment and should be assigned a spot in a nutrition program.

The click-MUAC bands proved to be extremely durable, as none of the tested bands failed under a greater extent of stress than would be expected in the use of the devices in a clinic setting. The bands were printed in PLA, which is the most popular and accessible 3-D printing filament. However, it should be noted that PLA has a glass transition temperature of 60–65 °C and a melting temperature 173–178°C, which means that in extremely hot environments the plastic will deform and a higher melting point polymer (e.g. ABS) should be substituted.

If a FFF-based 3-D printer is available locally the click MUAC bands can be printed in five minutes per band. Thus they fall into the category of disaster relief items currently in use by groups like Field Ready, that utilize 3-D printers to print items on demand [34]. One of the core advantages to this approach is the cost of shipping can be reduced, particularly if 3-D printing filament is available locally. However, even if shipping costs are ignored the 3-D printable click MUAC provides a substantial economic savings ranging from 92% to 97% when compared to commercially available MUAC tapes. Even when three MUAC bands (one of each size) are printed to replace the least expensive tape measurement system there is more than a factor of five savings using 3-D printing. This savings does not include the cost of shipping and distribution, which can be significant when attempting to disseminate supplies to developing countries across the world. To further enhance cost savings, readily available waste plastics can now be used with an open-source hardware machines called recyclebots [35] to produce printing filament from discarded plastic waste at costs less \$0.10/kg [36]. Thus, if recycled plastic is used, ten U.S. cents could produce over 800 click MUAC bands.

Future work is needed to test the effectiveness of this approach in the field and in various countries with different levels of medical and technical support as well as various 3-D printing experience levels.

Conclusion

The WHO has established a MUAC measurement of under 115mm as a diagnostic criteria of severe acute malnutrition. The FFF-based 3-D printable open source click MUAC bands discussed in this study offer a viable alternative to current methods for determining the MUAC of a child. The click MUAC bands offer a high degree of simplicity due to the binary pass/fail nature of their application. The results of this study show that click MUAC bands are both dimensionally accurate (inner circumferences of +/- 0.50 mm) and durable (surviving 500+ deformations with no notable residual deformation) enough to be used in developing world medical contexts. The bands can also be produced for under 92% of the cost of current measuring tools.

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```
//C=115mm x pi r =
h2=5;
h=10;
b=0.75;
r=18.3;
$fn=100;

difference() {
  rotate([0,0,-20])translate([r+7.5,0,0])cube([h, h/2, h2], center=true);//left hold
  rotate([0,0,-20])translate([r+h/2,0,h2/2]) sphere(r=1);
}
rotate([0,0,20])translate([r+7.5,0,0])cube([h, h/2, h2], center=true);//right hold
rotate([0,0,-3])translate([r+12,0,0])cube([h/4, h/6, h2], center=true);//left clasp

rotate([0,0,3])translate([r+7.5,0,0])cube([h/2.5, h/6, h2], center=true);//right clasp
rotate([0,0,-4.5])translate([r+6,0,0])cube([h/2, h/6, h2], center=true);//right clasp hook
rotate([0,0,-3])translate([r+4.5,0,0])cube([h/10, h/2, h2], center=true);//right clasp top of hook

difference() { //ring
  cylinder(r=r, h=h2, center=true); //outside
  cylinder(r=r, h=h2+1, center=true); //inner diameter to be 115mm
  translate([r/2+b+.1,0,0])cube([r, .3, h2+1], center=true);//break in the ring
}
```

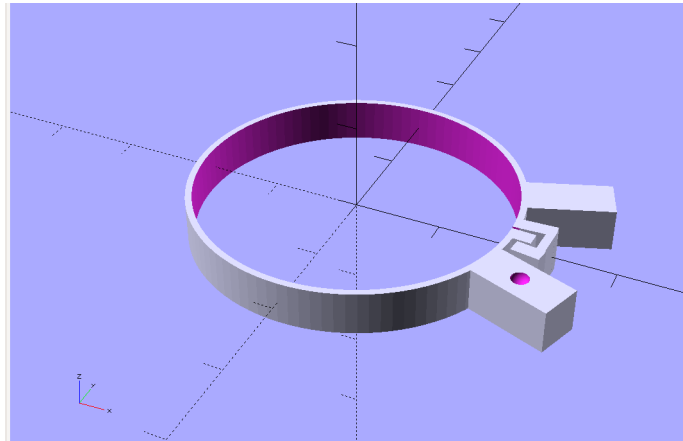


Fig. 1. The OpenSCAD code (left) and solid model (right) of the 115 mm 3-D printable click MUAC band [24].



Fig. 2. Color coded 3-D printed click MUAC bands. From left to right the bands have an inner circumference of 135mm (green 3 dimples), 125mm (yellow 2 dimples), and 115mm (red 1 dimple).

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27

330

331 Table 1. Average Inner Diameters and Calculated Circumferences for 3-D Printed click MUAC
332 Band.

Experimental Band	Avg. Inner Diameter (mm)	Avg. Inner Circumference (mm)
1	36.55	114.83
2	36.34	114.16
3	36.53	114.75
4	36.17	113.63
5	36.75	115.46
6	36.55	114.81
7	36.47	114.57
8	36.65	115.15
9	36.52	114.73
10	36.49	114.64
Mean	36.50	114.67
STD	+/- 0.16	+/- 0.50

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334