Investigation of Parameters of Fused Deposition Modelling 3D Prints with Compression Properties

1. Introduction

Three-dimensional (3D) printing has been attracting a great deal of attention in recent years because it can create objects layer by layer with satisfactory geometric accuracy [1]. Fused filament fabrication (FFF) is the most commonly used method for its easy operation and flexibility in material utilization. These days the FFF 3D printed objects are used in the aerospace [2] and construction industries [3], art and education [4], medical fields [5], and protection [6].

However, 3D printed products application is limited because of their limited mechanical properties [7]. During 3D printing, the melt solidifies at a high cooling rate, which results in less crystallinity in polymer materials, and this leads to lower strength of the prints for the random polymer chains do not have enough time to arrange into an ordered structure within short time [8]. Researchers recommend incorporating additives to improve the mechanical properties instead of modifying the printing parameters [9]. For instance, researchers incorporate PLA nanofibers with PLA as a matrix to develop 3D printed composites. As reported in their research, 3D printed composites with the incorporation of 6.5% nanofibers improved the degree of crystallinity of the prints by 41% and the storage modulus by 10.3% and the strength by 10.1% over the neat PLA 3D prints [10].
On the contrary, there are research results indicating that the modification of printing parameters can improve the mechanical properties of the 3D prints. According to [11, 12], as the printing temperature increases, the tensile strength and elastic modulus tend to rise first and then decrease. Moreover, thinner samples and lower build-platform temperatures led to higher mechanical properties. In addition, lower mechanical properties were found when the unstable disordered crystalline form was present. A thermal treatment (annealing at 120°C for 10min) improved the mechanical properties because of the change in the crystallinity of the printed samples [13–15]. On the other hand, the impact strength of PLA is not sustained upon aging. Heat treatment can change the strength of 3D printed PLA, but it was verified upon testing that the initial strength tested right after the heat treatment was not sustained over time as the impact strength of the samples deceased although not to the initial strength prior to heat treatment [16].

Mechanical properties of 3D printed lattice structures were investigated by [12], and the result showed that as the printing temperature increases, the tensile strength and elastic modulus tend to rise in the optimum printing temperature (up to 230°C) because the extended temperature (240°C) will tend to influence the property of the polymer. Similarly, as the printing speed increases, the tensile strength and elastic modulus show an upward trend. In all cases, we found that the performance of the 3D printed products is dependent on different factors, which can be type and properties of materials, printing parameters, printing methods, and the technology used in printing. The most influencing factors are not yet determined, but researchers are still under investigation to identify and set such factors. But this research presents a novelty with the investigation of the parameters of the 3D prints instead of printing parameters, materials, and methods. The study aims to investigate the performance improvement of 3D prints within the products itself over the process parameters. The 3D printed products are typically not produced with a solid interior. Instead, the printing process uses a pattern for interior surfaces that is called infill and its density is referred to as the infill percentage.

The 3D print was designed with the filling types as shown in Figure 1, and it represents the top view of the Prusa slices at the 296th layer of the total 301 layers of cubes.

2.2. Methods. Autodesk Fusion 360 was used for designing the cubes and Prusa Slicer to slice the model suitable for the printer. Original Prusa i3 MK3S 3D printing machine has been used for developing 3D printed products in this study. The machine has only one nozzle so that one can print only one plastic filament at a time. The printer cannot process functional filaments. The machine filling speed, printing temperature, infill density, and related parameters are determined by the printing raw materials and the specifications of the item to be produced.

2.2.1. Constant Printing Parameters. Constant printing parameters include layer height 0.2 mm, nozzle diameter 0.4 mm, extruder temperature 225°C of all layers, fan speed 100%, and infill density 60 m/min; bed temperature during first layer is 50°C; afterwards, it is 30°C.

2.2.2. Design and Designed Process Parameters. The 3D prints are designed as cubes of different print parameters. The honeycomb and gyroid are the filling types used in this study. The samples produced from honeycomb represented by D and gyroid by G with the sample numbers for identifying. Samples from 1D to 5D and 11D to 12D are honeycomb filled, while 6G and 13G are gyroid-filled 3D prints. These samples are grouped into different parametrical analysis categories in the result and discussion section. 3D printed parts are typically not produced with a solid interior. Instead, the printing process uses a pattern for interior surfaces that is called infill and its density is referred to as the infill percentage.

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2.2.3. Experiment

(1) Testing Machine and Settings. The tensile testing machine is used by removing the tensile clamps and fixing attachments for compression with a 28 mm diameter top stamp and an aluminium plate with holes in the bottom. The test was performed by applying 1N preforce at 10 m/min speed using Z2.5 “Zwicki Junior” with a load cell MK2.5 kN machine. The compression is stopped from running when the top stamp is compressing each cube by 5 mm indentation depth, as seen in Figure 2.

(2) Test Preparation and Testing. The 3D printed samples were conditioned in the test room at (20 ± 1)°C and (65 ± 2)% relative humidity for 24 hours. Depending on the dimensions of the products, the compressive force was applied to the six sides—top and bottom—and four side walls. In principle, all sides of all samples were tested in this way, unless the wall side was too small for the test stamp. This was the case with sample 12D. The compression force is only applied to the top and bottom of the 12D 3D print due to the dimensional constraint, so the dimensional parameters are only considered for the top and bottom of this print. The cyclic print force is applied five times on each of the five

2 Materials and Methods

2.1. Materials. Polylactic acid (Triton Soft PLA) filament was used to produce the 3D printed cubes using fused deposition modelling (FDM) method, which is also called fused filament fabrication (FFF). According to the specifications of the producer, the material should be within 210–230°C printing temperature, 1.75 mm diameter. The 3D printed item made from the soft PLA by controlling the process parameters as specified by the machine and filament manufacturers. The soft PLA has 94A shore hardness and is flexible even after printing.
specimens of each sample. The applied force is considered the final measurement force when the force is read at the 5 mm depth of the punch of the 3D print. This is the maximum force applied to compress the 3D prints by 5 mm indentation depth. The testing machine and test procedure are presented in Figure 2.

2.3. Analysis Method. The analysis of this study is supported by different analysis tools, such as Microsoft Excel and Statistical Package for the Social Sciences (SPSS). In this study, analysis of variance (ANOVA) is used to check the significance of each independent variable (print parameters) on the dependent variables (compression force). Analysis of
variance (ANOVA) can determine whether the means of three or more groups are different. F-value is simply a ratio of two variances and is calculated as variation between sample means divided by variation within the samples. Variances are a measure of dispersion, or how far the data are scattered from the mean. Larger values represent greater dispersion. To determine if the difference between group means is statistically significant, we can look at the P-value that corresponds to the F-statistic. The P-value in our case is the significant level at 0.05 confidence level. Though the F- and P-values are calculated manually, we determined them using SPSS software.

3. Results and Discussion

The results are presented to investigate the effect of print parameters on the compression strength of 3D printed products. As mentioned earlier, the parameters considered for this study are filling type, filling percentage, number of top and bottom layers, vertical walls, and dimension of 3D prints. The maximum, minimum, average, and standard deviations of the compression forces of 3D prints are shown in Table 1. This data is discussed in detail in its section of the printed parameters. The standard deviation (Std. deviation) and the standard errors of the mean (SEM) are shown in the respective figures for the respective print parameter together with the mean value of each sample.

3.1. Filling Type. The compression strength of 3D printed cubes is investigated based on the filling types. The gyroid and honeycomb are the most commonly used types of filling in the 3D printing industry, which initiates this research to carry out experimental investigations. The effect of filling types on compression strength was tested with the six sides of each cube as top, bottom, and four walls. As shown in Table 2, samples 1D and 6G are selected for this investigation by keeping other parameters uniform. The mean of 1D and 6D are different except wall 4 of the six faces 3D prints. The mean compression force of 6D is lower than the mean compression force of 1D on the top and bottom of each cube (see Figure 3). The minimum compression force of 1D is higher than the maximum force of 6D (see Table 1). This is because 1D is filled with honeycomb while 6D is filled with gyroid so that the honeycomb filled with 3D prints consumed a high amount of material and filled the majority of the internal part of the cube and enhanced the strength of the products.

As shown in Figure 3, the mean compression force of each sample on the walls is higher in 6D than in 1D because the gyroid infills lining from wall to wall so that all walls are connected with each other. The maximum and minimum compression force values of 6D wall are higher than those of the 1D wall (see Table 1). However, the compression force of wall 2 and wall 4 of 1D and 6D are almost similar, but wall 4 is closer to the same wall in 1D. These walls (wall 2 and wall 4) are the direction of filling lines for gyroid (see Figure 1) and give similar strength to honeycomb-filled 3D prints.

This shows that not only the type of filling but also the filling direction has an effect on the performance of 3D prints.

Fixed-model one-way ANOVA of Statistical Package for Social Sciences (SPSS) was used to check the significance of the statistical data collected from testing machines. As shown in Table 3, the mean differences of compression strength of honeycomb and gyroid filled 3D prints are significant at 0.05 level and significantly dependent on the type of infill except on wall 4. The filling types have no significant effect on wall 4 due to the filling direction.

3.2. Infill Percentage. The compression strength of 3D printed cubes is investigated based on the filling percentage. The 2%, 4%, and 6% fillings are applied in this study for the development of 3D printed samples, which are experimentally investigated. As shown in Table 2, samples 1D, 2D, and 3D with respective filling percentages are produced. The effect of filling percentages on compression strength has been investigated on the six sides of each cube as top, bottom, and four walls. The mean of 1D, 2D, and 3D are different on the six faces of the 3D prints. The mean compression force of all samples and sides is highest in sample 3D with 6% filling.

The increasing order of compression force of the 3D prints is 1D, 2D, and 3D (see Figure 4). This shows that as the filling percentage increases, the compression resistance also increases because more material is consumed to fill the internal part of the prints and increases the mass (see Table 2). The maximum compression force of 3D prints with low filling percentage is lower than the minimum compression force of the 3D prints with increased filling percentages (see Table 1). As shown in Figure 4, the rate of variation of compression force of 3D prints is almost proportional to the rate of variation among filling percentages. This means that the compression force of 3D is two times of 2D and the compression force of 2D is two times of 1D in most testing sides of the print.

As shown in Table 4, the mean differences of compression strength of 2%, 4%, and 6% filling of 3D prints are significant at 0.05 levels and significantly dependent on the percentages of filling with all sides of each sample.

3.3. Number of Walls. The compression strength of 3D printed cubes is investigated based on the number of vertical walls. The 4 and 6 vertical walls are applied in this study for the development of samples 4D and 5D (see Table 2) prints, which are experimentally investigated on the six sides of each cube as top, bottom, and four walls. The mean of 4D and 5D are different on the six faces of the 3D prints. The mean compression force of all samples on all sides is highest in sample 5D with 8 vertical walls. This shows that as the number of walls increases, the compression resistance is enhanced (see Figure 5). As shown in Table 1, the maximum compression force of 3D prints with minimum number of walls is lower than the minimum compression force of the 3D prints with maximum number of walls. As shown in Figure 5, the variation of compression force of 3D prints is...
Table 1: Minimum and maximum compression forces on 3D print samples.

| Compression force on | 1D  | 2D  | 3D  | 4D  | 5D  | 6G  | 11D | 12D | 13G |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Top                  |     |     |     |     |     |     |     |     |     |
| Maximum (N)          | 49.43 | 89.10 | 149.2 | 116.1 | 191.1 | 39.10 | 135.2 | 98.68 | 72.34 |
| Minimum (N)          | 46.62 | 83.50 | 138.5 | 108.5 | 176.9 | 37.24 | 125.2 | 91.70 | 68.50 |
| Average              | 47.69 | 85.64 | 142.59 | 111.44 | 182.5 | 37.96 | 128.98 | 94.35 | 69.97 |
| Std. deviation       | 1.1  | 2.2  | 4.3  | 3.0  | 5.6  | 0.73 | 4.0  | 0.4  | 1.5  |
| Bottom               |     |     |     |     |     |     |     |     |     |
| Maximum (N)          | 47.79 | 82.55 | 129.6 | 112.4 | 159.3 | 35.66 | 79.92 | 84.09 | 74.33 |
| Minimum (N)          | 45.34 | 77.64 | 120.7 | 79.54 | 159.3 | 35.66 | 79.92 | 84.09 | 70.22 |
| Average              | 46.27 | 79.53 | 124.1 | 80.98 | 164.4 | 36.33 | 91.49 | 81.52 | 71.82 |
| Std. deviation       | 0.97 | 2.0  | 3.5  | 1.5  | 5.1  | 0.68 | 2.9  | 1.7  | 1.6  |
| Wall 1               |     |     |     |     |     |     |     |     |     |
| Maximum (N)          | 31.06 | 49.32 | 90.12 | 110.4 | 276.8 | 36.74 | 89.20 | 41.67 | 34.82 |
| Minimum (N)          | 29.53 | 46.17 | 83.66 | 103.6 | 259.4 | 34.94 | 82.99 | 39.07 | 32.74 |
| Average              | 30.12 | 47.38 | 86.13 | 106.2 | 266.1 | 35.63 | 85.37 | 40.08 | 33.52 |
| Std. deviation       | 0.61 | 1.3  | 2.6  | 2.7  | 6.9  | 0.71 | 2.5  | 0.82 | 1.0  |
| Wall 2               |     |     |     |     |     |     |     |     |     |
| Maximum (N)          | 30.96 | 44.73 | 83.15 | 85.19 | 276.4 | 34.91 | 95.22 | 43.12 | 35.36 |
| Minimum (N)          | 29.38 | 42.01 | 77.51 | 80.84 | 258.8 | 32.75 | 88.29 | 39.90 | 33.46 |
| Average              | 30.12 | 43.07 | 79.65 | 82.49 | 265.6 | 33.58 | 90.89 | 41.20 | 34.18 |
| Std. deviation       | 0.61 | 1.1  | 2.2  | 1.7  | 6.9  | 0.58 | 2.6  | 1.3  | 0.75 |
| Wall 3               |     |     |     |     |     |     |     |     |     |
| Maximum (N)          | 30.74 | 48.69 | 85.26 | 83.43 | 277.4 | 34.91 | 95.22 | 43.12 | 35.36 |
| Minimum (N)          | 29.13 | 45.21 | 79.30 | 79.19 | 259.8 | 32.75 | 88.29 | 39.90 | 33.46 |
| Average              | 29.98 | 46.52 | 81.55 | 80.82 | 266.6 | 33.58 | 90.89 | 41.20 | 34.18 |
| Std. deviation       | 0.62 | 1.4  | 2.4  | 1.7  | 6.97 | 0.85 | 2.8  | 1.3  | 0.75 |
| Wall 4               |     |     |     |     |     |     |     |     |     |
| Maximum (N)          | 29.32 | 45.53 | 79.26 | 82.88 | 279.8 | 29.49 | 105.3 | 35.36 | 33.36 |
| Minimum (N)          | 27.85 | 42.75 | 73.84 | 78.67 | 261.9 | 28.08 | 97.73 | 33.36 | 33.46 |
| Average              | 28.42 | 43.82 | 75.91 | 80.29 | 268.8 | 28.62 | 100.6 | 34.18 | 34.18 |
| Std. deviation       | 0.58 | 1.1  | 2.2  | 1.7  | 7.7  | 0.56 | 3.0  | 1.3  | 0.75 |

Table 2: Samples and designed process parameters of 3D prints.

| Infill type | Honeycomb | Gyroid |
|------------|-----------|--------|
| Sample     | 1D  | 2D  | 3D  | 4D  | 5D  | 6G  | 13G  | 11D  | 12D  |
| Infill %    | 2   | 4   | 6   | 2   | 2   | 2   | 2    | 4    | 4    |
| Vertical walls | 2   | 4   | 2   | 2   | 2   | 2   | 2    | 2    | 2    |
| Horizontal contours | 5   | 5   | 5   | 10  | 10  | 5   | 10   | 5    | 5    |
| Dimension of print in mm$^3$ | 60 × 60 × 60 | 60 × 60 × 60 | 60 × 60 × 60 | 60 × 60 × 60 | 60 × 60 × 60 | 60 × 60 × 60 | 40 × 40 × 40 | 80 × 80 × 20 |
| Mass in grams | 28.14 | 33.81 | 41.20 | 46.95 | 70.26 | 26.47 | 33.72 | 13.15 | 26.91 |

Figure 3: Compression force of 3D print filling type.
Table 3: Analysis of variance of filling types on compression strength of 3D prints.

| Compression force on | $F$  | Sig.  |
|----------------------|------|-------|
| Top                  | 266.34 | 0.000 |
| Bottom               | 349.85 | 0.000 |
| Wall 1               | 172.77 | 0.000001 |
| Wall 2               | 20.90 | 0.002 |
| Wall 3               | 65.09 | 0.000041 |
| Wall 4               | 0.34 | 0.576 |

Figure 4: Compression force of 3D prints and filling percentage.

Table 4: Analysis of variance of filling percentages on compression strength of 3D prints.

| Compressive force on | $F$  | Sig.  |
|----------------------|------|-------|
| Top                  | 1415.495 | 5.66e–19 |
| Bottom               | 1358.165 | 0.000 |
| Wall 1               | 1456.780 | 0.000 |
| Wall 2               | 1519.543 | 0.000 |
| Wall 3               | 1327.912 | 0.000 |
| Wall 4               | 1431.372 | 0.000 |

Figure 5: Compression strength of 3D prints and number of vertical walls.
proportional to that of the variation between the numbers of walls.

As shown in Table 5, the mean differences of compression strength of 4 and 8 walls of the 3D prints are significant at 0.05 levels and significantly dependent on the percentages of filling on all sides of each sample.

3.4. Horizontal Contour. The compression strength of 3D printed cubes is investigated based on the number of horizontal contours and the so-called top/bottom walls. In this study, the amount of walls of 5 and 10 horizontal contours (see Table 2) are applied for the development of 3D printed samples, which are experimentally investigated on the six sides of each cube as top, bottom and four walls of samples 6G and 13G. The mean of the developed 3D prints is different on the six faces of tests. As shown in Figure 5, the mean compression force is higher in sample 13G with 10 horizontal contours than 6G with 5 horizontal contours. This showed that as the number of contours increases, the compression resistance also increased because the contour gave support to external load on 3D prints. The maximum compression force of 3D prints with minimum contours is lower than the minimum compression force of the 3D prints with the maximum number of contours (see Table 1). As shown in Figure 6, the variation of compression force of 3D prints is almost proportional to the variation between the numbers of contours.

As shown in Table 6, the mean differences of compression strength of 5 and 10 contours of the 3D prints are significant at 0.05 level and significantly dependent on the dimensions of all sides of each cube.

3.5. Dimension of Prints. The compression strength of 3D printed cubes is investigated based on the dimension of the 3D printed cubes. The $60 \times 60 \times 60$ mm, $40 \times 40 \times 40$ mm, and $80 \times 80 \times 20$ mm length, width, and height ($L \times W \times H$) dimensions of respective samples, such as 2D, 11D, and 12D, are applied in this study. The samples are experimentally investigated on the six sides of each print except sample 12D. The mean compression force of the samples is different on the six faces of the 3D prints. The mean compression force of all samples and sides is highest in sample 11D with $40 \times 40 \times 40$ mm dimension. The increasing order of compression force of the 3D prints is 2D, 12D, and 11D (see Figure 7). This shows that as the volume of 3D prints increases, the compression resistance reduced because the load compresses the material to the center of compression direction. As shown in Table 2, the maximum compression force of 3D prints with high volume is lower than the minimum compression force of the 3D prints with low volume. The side or wall compression strength is not investigated on 12D because the surface area is narrow to apply the pressure plate for compression.

As shown in Table 7, the mean differences of compression strength of 5 and 10 contours of the 3D prints are significant at 0.05 level and significantly dependent on the number of vertical walls of 3D prints.

3.6. Summary of the Results. Compression strength of 3D prints is investigated based on print parameters. These print parameters are of 5 types in this study. These are infill types, infill percentages, and number of vertical walls, horizontal contours, and dimension of the 3D prints. All prints are cubes of different parameters as mentioned. The types and values of the parameters, representative names of 3D prints to form a particular value of parameters, and the so-called assignment of cubes to parameters are presented in Table 2.

The compression strength of the 3D printed cubes with the selected parameters is discussed in detail in the appropriate section of each parameter. As found from the results, the compression strength of the 3D prints is significantly dependant on all the parameter used in this study. Although all parameters have significant influence on the compression force resistance to 3D prints, all parameters have no equal influence. This is because the material consumption, the appearance, and arrangement of parameters in the 3D prints are different.

Figure 8 presents the compression force on the 3D prints with different print parameters such that filling type, filling percentages, number of vertical walls, number of horizontal walls, and dimensions of the prints. The compression force has been applied on the six sides of the 3D prints (cubes) as on top (T), bottom (B), wall 1 (W1), wall 2 (W2), wall 3 (W3), and wall 4 (W4).

As shown in Figure 8, the specimens with vertical walls acquire more forces to be compressed to 5 mm depth, but the 3D prints with filling types are compressed easily to the same depth. The order of the print parameters from low to high compression force are filling type, horizontal contour, filling percentages, dimensions, and vertical wall. The top and bottom of the cubes acquire high compression force, in all print parameters except the vertical walls. The force on walls of each cube is highest on the sides 3D prints with the number of vertical walls as the print parameter. The vertical walls give support to the sides by surrounding prints with the determined number of walls. As seen from Figure 8, the parameters such as filling types and contours can be used
Number horizontal contours i.e 5 shells (6G), 10 shells (13G)

Figure 6: Description of compression strength of 3D print with horizontal contours.

| Compressive force on | F     | Sig.     |
|----------------------|-------|----------|
| Top                  | 1797.746 | 1.06e − 10 |
| Bottom               | 2016.992 | 6.67e − 11 |
| Wall 1               | 63.461   | 4.5e − 5  |
| Wall 2               | 137.837  | 3e − 6   |
| Wall 3               | 126.238  | 4e − 6   |
| Wall 4               | 176.624  | 9.81e − 7 |

Table 6: Analysis of variance of the number of horizontal contours of 3D prints.

Specimen volume i.e 60*60*60 mm³ (2D), 40*40*4 mm² (11D), 80*80*20 mm² (12D)

Figure 7: Effect of prints dimension (volume) on compression force of 3D prints.
interchangeably because their effect is similar with slightly big difference within contours.

The reasons for the significant effect of the print parameters on the compression properties are the materials coverage within a cube, alignment of materials, size of the object to disperse the applied force, the walls supporting the object by reinforcing to withstand the applied force, and the contours give support to the cubes while subjected to compressional force.

Print parameters are determined according to the application of the 3D prints. The 3D prints used in the areas with high compression loads should consider the vertical walls as the excellent print parameter to withstand the intended pressure because the vertical walls hold tightly the surrounding of the cube and give high mass to 3D prints (see Table 2). 3D prints which have low exposure to load can be produced by considering filling type as the prints’ parameters so that material can be saved because the mass is relatively low unless the dimension is reduced in other parameters.

This study shows as not only printing parameters like nozzle temperature, bed temperature, curing time, material type, printing method, and layer thickness but also the 3D print parameters such as filling type, filling percentage, dimension, vertical wall, and horizontal contours have significant influence on the performance of the products for the intended applications.

### 4. Conclusion

The compressive strength of 3D prints with some selected printing parameters is deeply investigated. These parameters are filling type, filling percentage, dimension, vertical walls, and horizontal contours. Although all print parameters have a significant influence on the compression force of 3D prints, the magnitude of the force to compress up to an indentation depth of 5 mm varies depending on the parameter.

The higher the value of a parameter, the greater the compression force for all print parameters except the filling types (gyroid and honeycomb). The type of parameter and its value depend on the intended application. Vertical walls can be used to develop 3D prints for applications that have a high compression load, while filler types are used for applications with a low compression load. The dimensions of the 3D prints can improve the product when designed with other printing parameters, such as fill percentage, fill type, contours, and walls.

The combination of printing parameters increases the strength of the products. For example, the combination of dimension with filling percentage and type can increase the resistance to the applied compressive force depending on the application. Optimised and combined use of parameters can optimise the strength of products and make FDM printing techniques more efficient.
In all cases, production times increased to produce items with high performance for the intended load. The products investigated in this research can be used in construction, transportation, protection, medical, industrial, agricultural, and related fields. The figure in summary, in particular, shows that a wide range of compressive strengths can be achieved through different combinations of parameters. Further investigations in this area are to follow so that in the future it should be possible to predict the compressive strength of the components using combined parameters. By entering parameters such as material, infill type, infill quantity, and number of outer walls, a simulation should be able to better predict the behaviour of the components. With these findings, it should be possible in the future to design components with different properties in a targeted manner.

Data Availability

The data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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