Reverse Design and Additive Manufacturing of Furniture Protective Foot Covers

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Reverse design and additive manufacturing technologies are fast ways to develop customised products. In this study, furniture protective foot covers were taken as the design object. Using flexible filaments of polylactic acid (PLA) and the development process of reverse design to additive manufacturing, the protective foot covers were designed and manufactured to fit the shape of the chair feet. Furniture protective foot covers have high practical value. They have a certain buffering effect, avoiding the damage caused by the collision of furniture feet with the ground when moving furniture; secondly, they reduce the noise generated by the collision of furniture feet with the ground, creating a quiet and comfortable home environment. According to the finite element simulation results, the maximum stress value of the European-style chair installed with protective foot covers was decreased by 90.8% in the case of vertical fall, which verifies that the protective foot covers have an obvious buffering effect. Noise test results show that the noise of the European-style chair installed with protective foot covers was decreased by 51.0%, which verifies that the protective foot covers have an obvious quieting effect.

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INTRODUCTION

With the development of additive manufacturing technology, more and more products are being 3D printed by fused deposition method (FDM), using flexible materials. Polylactic acid (PLA) is a bio-based material that can be made from starch derived from renewable plant resources (Deng *et al*. 2023). Flexible PLA filaments are made from PLA resin with the addition of thermoplastic polyurethane (TPU) elastomers, which allows the rigid molecular chains in the PLA resin and the flexible molecular chains in the TPU elastomers to produce a block polymerisation, giving the PLA filaments strong flexibility and elasticity recovery properties (Ding *et al*. 2022). Through the FDM additive manufacturing method, flexible PLA filaments are widely used for applications that have high requirements for resilience and easy processing; the PLA filaments are especially suitable for the manufacture of a variety of customised cushioning protection products (Feng *et al*. 2022).

To protect furniture feet and the overall structure of furniture from collision damage during moving, and to reduce the noise generated by furniture feet colliding with the ground, it is necessary to install foot covers that can cushion and protect the furniture (Han *et al*. 2022). Traditional furniture foot covers cannot adapt to various furniture foot shapes and are prone to falling off (Huang *et al*. 2022). Moreover, traditional furniture foot covers have poor cushioning, protection, and quieting effects, which discourages the widespread use of furniture protective foot covers to be widely used (Xia and Yan 2024). In response to the above issues, this study proposes a customized method for 3D printed furniture protective foot covers and conducts practical applications.

3D printing offers a practical way to prepare furniture protective foot covers having customized design for furniture feet with special shapes, such as those with complex carved patterns or curved surfaces (Zhang *et al.* 2023). By combining reverse scanning technology with 3D printing technology, it is possible to quickly design and manufacture protective foot covers that not only fit the shape of furniture feet but also have cushioning and protective properties. Furniture protective foot covers have high practical value. Firstly, due to the use of flexible materials, the protective foot covers have a certain buffering and energy absorption effect, avoiding the damage to the furniture structure caused by furniture feet colliding with the ground when moving furniture (Yang *et al.* 2022). Secondly, protective foot covers reduce the noise generated by furniture feet colliding with the ground, creating a quiet and comfortable home environment (Yu *et al.* 2023).

EXPERIMENTAL

Reverse design is the process of 3D reconstruction and redesign of the point cloud data on the surface of a physical prototype acquired by 3D scanning equipment. The European-style chair was selected as the design object, and the product development process from reverse design to additive manufacturing was adopted. The reverse design process used in this work consisted of three main steps: (1) usage of a non-contact laser 3D scanner (MetraSCAN, HandyPROBE 780, Levi's, Canada) to scan the foot of the European-style chair in three dimensions and obtain its point cloud data; (2) usage of Geomagic Studio software (Geomagic, Studio 12.0, North Carolina, America) to simplify and smooth the triangular mesh model of the European-style chair foot; and (3) Based on the triangular mesh model, SolidWorks software (Dassault Systemes, Education Version 2016, Paris, France) was used to carry out the reverse design of the protective foot covers of the European-style chair.

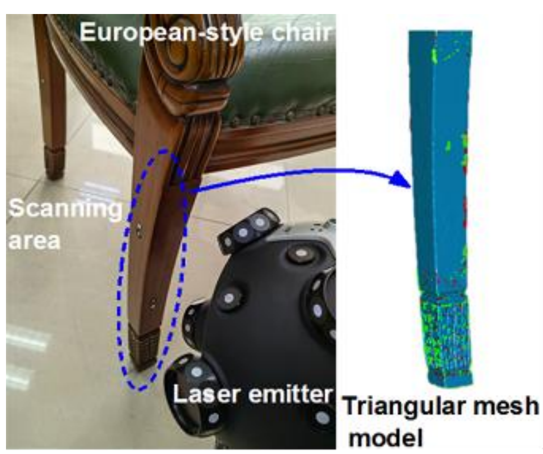

Fig. 1. Scanning principle and triangular mesh model

3D Scanning

3D scanning is the process of transforming the shape of an object into spatial coordinate points by means of specific measuring equipment to obtain point cloud data (Li *et al*. 2020). A non-contact laser 3D scanner was used for 3D scanning of a European-style chair foot, and the laser receiver position was adjusted and calibrated by a calibration plate before scanning (Zhou *et al*. 2023). During the scanning process, the integrity of the scanned point cloud needed to be observed in real time, and the position of the laser emitter was moved in time to target the missing parts of the point cloud for supplemental scanning, so as to make the point cloud data complete (Li *et al*. 2022). After scanning, the point cloud data was streamlined and noise reduced to encapsulate the point cloud data into a triangular mesh model (Yu and Wu 2024). The scanning principle and the triangular mesh model are shown in Fig. 1.

Triangular Mesh Processing

Triangular mesh processing is a key step before reverse design, and the quality of the triangular mesh directly affects the quality of the reverse design model (Liu *et al*. 2021). Geomagic Studio software was used to process the triangular mesh of the European-style chair foot. The processing flow is divided into five steps: (1) import the triangular mesh model; (2) use the mesh doctor to repair the defects of the triangular mesh model (*e.g.*, holes, non-fluid edges, *etc*.); (3) reduce the number of triangular meshes by a certain percentage (50%) to achieve the simplification of the triangular mesh model (Zou *et al*. 2023); (4) delete the redundant features in the triangular mesh, including pegs, widgets, *etc*.; and (5) reduce the noise of the triangular mesh to make the triangular mesh smoother (Liu *et al*. 2020). The effect of the triangular mesh before and after processing is shown in Fig. 2, which shows that the model has been simplified and smoothed after the triangular mesh processing.

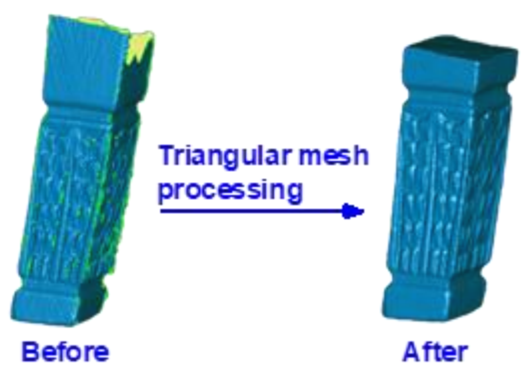

Fig. 2. Effect of triangular mesh processing

Reverse Design

Based on the triangular mesh model, the reverse design of the furniture protective foot covers is carried out, and the design process is divided into four steps: the first step is to import the triangular mesh model into Solidworks software and convert the triangular mesh model into a surface solid model; the second step is to draw the shape curve of the chair foot with the help of the sketch module, *i.e.*, to fit the cross-section profile of the chair foot by commands such as straight line, circular arc, and spline curve; the third step is to enter the solid module and create the solid model of the protective foot covers by using feature commands such as stretching, combining and shell extraction (Mo *et al*.

2022); the fourth step is to enter the assembly module to assemble the solid model of the protective foot covers with the surface model of the chair feet to check the assembly effect. The reverse design process of the protective foot covers is shown in Fig. 3.

Fig. 3. Reverse design process

Additive Manufacturing

Because FDM technology has the characteristics of low cost, stable equipment, convenient operation, *etc*., FDM 3D printer (XYZ printing, 0.4 mm nozzle diameter, Miracle 3D, Kunshan, China) and flexible PLA filament (White color, 1.75 mm diameter, Miracle 3D; China) were selected in this study to manufacture furniture protective foot covers. The additive manufacturing process mainly involved two steps: (1) using Cura software (Ultimaker, Cura 4.2.0, Utrecht, Netherlands) for slicing processing; (2) using an FDM 3D printer to carry out additive manufacturing.

Slicing Processing

The model of the protective foot covers obtained from reverse design was imported into Cura software for slicing. The slicing process was carried out with attention paid to the following three points: (1) Set a smaller printing speed (40 mm/s), due to the slower cooling rate of the flexible PLA filament; a smaller printing speed can make the cooling time of the flexible PLA filament longer and the curing more complete, so as to achieve better layer-to-layer contact better and thereby to obtain a better adhesive effect (Qi *et al.* 2023); (2) Set a larger pumping speed (60 mm/s); the pumping process occurs at the end of each layer of the print trajectory. The flexible PLA filament in the molten state has a strong mobility, so it is necessary to set a larger pumping speed to avoid the accumulation of material in the process of printing and pulling phenomenon, which affects the surface quality of the model; (3) Set a lower filling rate (20%) for slicing, so that the filling inside the protective foot cover is a porous structure, which can bring better cushioning and energy absorption effect (Zhou *et al.* 2022); (4) Set a higher heat bed temperature (75 °C), in order to make the molten state of the flexible PLA filament can be more tightly deposited and stick to the printing platform, to avoid the warping of the model due to rapid cooling during the printing process. The rest of the main slicing parameters are shown in Table 1.

Table 1. Slicing Parameters

Slicing Parameters	Recommended Settings
Extrusion temperature	210 °C
Extrusion flow rate	100%
Wall thickness	1.2 mm
Filling structure	Lattice-type

3D Printing Process

The sliced G-code file was imported into the FDM 3D printer, and the flexible PLA filament was used to complete the 3D printing of the protective foot covers. Flexible PLA filament needs to use a proximity extruder because the distance between the feeder wheel and the throat of the proximity extruder is shorter, which can prevent the flexible PLA filament from winding and accumulating in the throat, thus avoiding the problem of plugging. The physical and installation effect of the completed 3D printed protective foot covers is shown in Fig. 4. The outer surface of the protective foot covers is smooth and free of printing defects, the inner surface is highly adapted to the shape of the chair foot, and the overall structure is easy to disassemble and install.

Fig. 4. 3D printed protective foot covers and installation diagram

RESULTS AND DISCUSSION

Create 3D Model of European-Style Chair

To verify the protective properties of 3D printed furniture foot covers, SolidWorks software was used to simulate and analyse the situation of a European-style chair falling vertically and hitting the ground. The forward mapping method was used to model the European-style chair in three dimensions.

Fig. 5. Actual chair and 3D model

While accurately replicating the shape and size of the European-style chair, some details of the chair were simplified, such as removing the carved patterns on the legs and armrests. Simplifying the details is beneficial for achieving mesh division of the entire structure of the European-style chair. The actual chair and 3D model of the European-style chair are shown in Fig. 5.

Mesh Division and Material Setting

Because the 3D model of the European-style chair contains many surface structures, the curvature division method was chosen for meshing in this study. The curvature division method adopts variable-size tetrahedron as the basic unit, which is more flexible when dealing with small feature structures or shaped surfaces, and the mesh division range is wider and more efficient. The completed mesh model is shown in Fig. 6.

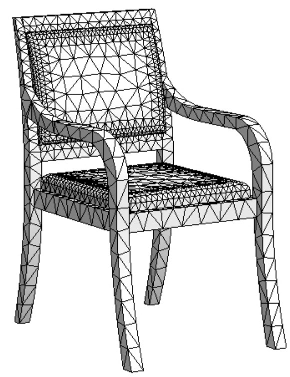

Fig. 6. Mesh model

The material of the European-style chair is walnut, which is considered as orthotropic and anisotropic material. In the literature, the axial (EL), radial (ER), and chordal (ET) elastic modulus values of walnut are 11239, 1172, and 621 MPa, respectively, and the Poisson's ratios μRT (chordal and radial strain), μLR (radial and axial strain), and μLT (chordal and axial strain) of walnut are 0.72, 0.49, and 0.63, respectively. The material of the protective foot covers is flexible PLA, which is an isotropic material. The elastic modulus of flexible PLA is 4000 MPa and Poisson's ratio is 0.5 as shown in the literature (Wang *et al.* 2023).

Analysis of Simulation Results

Through SolidWorks software, the simulation analysis of the European-style chair falling vertically and hitting the ground (assumed to be a rigid body) was carried out, with a fall height of 200 mm, and the fall mode was free fall. According to the finite element simulation results, the fall stress cloud of the European-style chair with protective foot covers (shown in Fig. 7) and the fall stress cloud of the European-style chair without protective foot covers (shown in Fig. 8) are obtained. As shown in Fig. 7 and Fig. 8, the maximum stress area of the European-style chair with protective foot covers is located at the outer side of the back legs (this area has the largest bending arc, resulting in the largest bending moment under external forces), and the maximum stress value is 0.43 MPa, while the maximum stress area of the European-style chair without protective foot covers is also located at the outer side of the back legs (the maximum stress area is enlarged), and the maximum stress value is 4.68 MPa. The maximum stress value of the European-style chair decreases by 90.8% after the installation of the protective foot covers, which shows that the protective foot covers have good cushioning and protection properties.

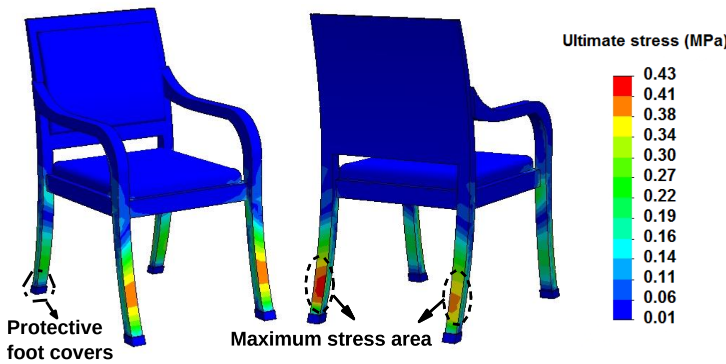

Fig. 7. Fall stress cloud of European-style chair (with protective foot covers)

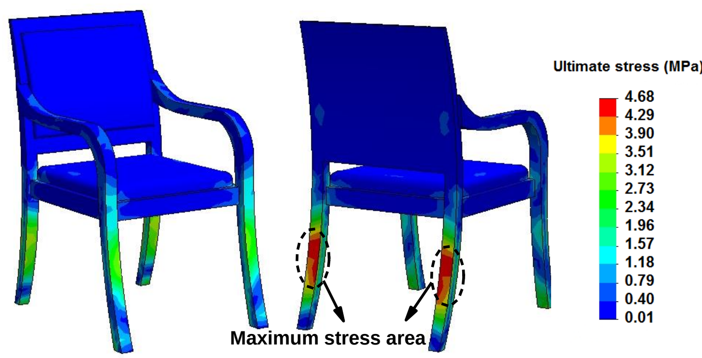

Fig. 8. Fall stress cloud of European-style chair (without protective foot covers)

Noise Test

To test the quiet effect of the protective foot covers, a noise test was designed to simulate the noise generated by the Chair's feet rubbing against the ground in the home environment.

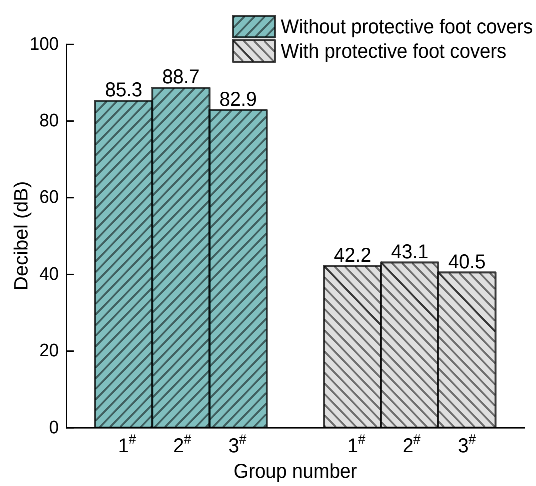

Fig. 9. Noise test comparison result

The European-style chair was pushed along the same floor (tile floor) in a straight line for 20 cm, at a speed of 10 cm/s. The decibel tester (TA650A, TASI, Suzhou, China) was used to measure the decibel value of the noise with and without the foot covers, and three groups of tests were carried out. The maximum decibel value was taken from each group of tests to make comparisons, and the results are shown in Fig. 9. The maximum decibel average value of the European-style chair installed with protective foot covers decreased by 51.03% during the horizontal pushing process, indicating that the protective foot covers effectively reduce the noise and have obvious quiet effect.

CONCLUSIONS

1. This study combined reverse design and additive manufacturing technology, using flexible PLA filament to rapidly develop furniture protective foot covers that fit the shape of chair feet and provide a cushioning effect.
2. The protective foot covers have a certain cushioning effect, avoiding the damage caused by the collision of furniture feet with the ground when moving furniture; at the same time, the noise generated by the friction between the furniture feet and the ground is reduced, creating a quiet and comfortable home environment.
3. This case provides a reference for the rapid development of other customised protective products.

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