WHITE PAPER

Mechanical Performance Analysis of 3D Printed and Traditionally Manufactured Rigid Insole Shells

This study explores the mechanical properties associated with three materials and manufacturing methods used to produce customized rigid shells for orthotic insoles: Formlabs Fuse 1+ 30W and Nylon 11 Powder, HP 3D High Reusability PA 11, and traditionally manufactured polypropylene.

The mechanical properties of these materials were tested through various experiments. External testing was conducted by the Orthopaedic Innovation Centre. Their testing involved Static and Dynamic 3-Point Bend tests and a Ross Flex test. Internal testing involved hand flexion to 180° of insole shells printed at various angles. The results were analyzed to assess the durability and performance of the insole shells.

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formlabs | healthcare

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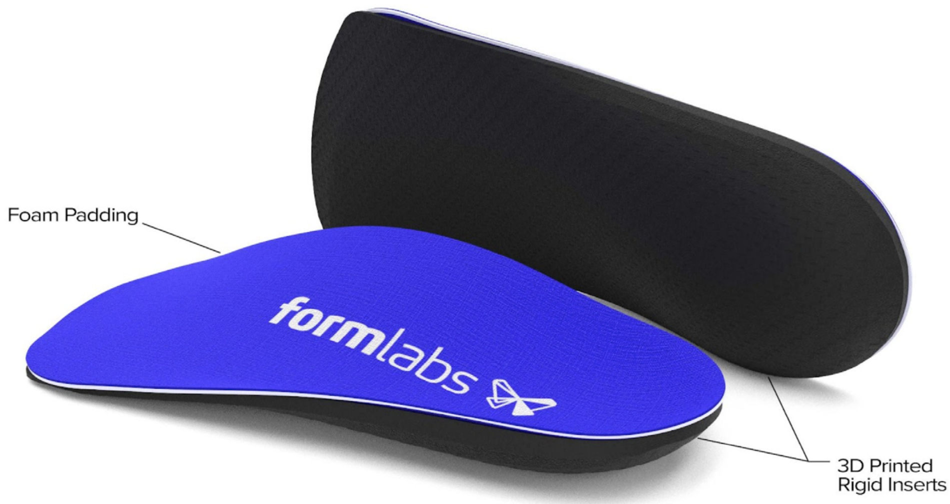
Background

A rigid insole is an orthotic device that is used to help the wearer correct abnormal foot posture or provide additional support. If not addressed, poor foot posture can cause foot, ankle, knee, or back pain, as well as more permanent issues. Customized insoles can be prescribed or recommended to a patient by a podiatrist, or another medical professional with proficiency in biomechanics. Generic versions can be purchased over the counter to address common self-diagnosable conditions.

Orthotic insoles are intended to be worn on top or in place of the soft inserts that most shoes come with. They are composed of multiple layers: a soft foam or fabric layer for comfort, a base for stability and additional comfort, and a customized rigid shell that serves as the main source of support and correction for the wearer.



A fully-assembled orthotic insole composed of a rigid insole shell for support (black) and a foam layer for comfort (blue)

Fuse 1+ 30W and Nylon 11 Powder are highly suitable for producing customized rigid shells for orthotic insoles. To evaluate our manufacturing method in comparison to other industry alternatives and ensure that our material surpasses the requirements of everyday use, we performed a series of tests to assess mechanical properties. The Orthopaedic Innovation Centre (OIC) conducted external tests, which included a Static 3-Point-Bending test, a Dynamic 3-Point-Bending test, and a Ross Flex test. We also subjected insole shells machined from polypropylene and 3D printed in PA 11 using an HP multi-jet fusion (MJF) machine to the same tests.

Internally at Formlabs, we rigorously tested the durability of our angled prints through a series of 180° hand flexion tests. This test was intended to challenge the mechanical properties of parts printed in a variety of printing orientations. SLS printing is not isotropic, but angled printing may be desired to accommodate larger sizes or optimize the build volume.

Sample Sourcing

EXTERNAL TESTING SAMPLES

Three samples were used for each test; one from Formlabs, one from HP, and one traditionally manufactured from polypropylene. Details on each sample can be found in the table below. Each sample was created using the same model provided to us by Gespodo and shares the same dimensions (2 mm thickness from center to edge). That model can be found here.

	Material	Manufacturing Method
1	Formlabs Nylon 11 Powder	Fuse 1+ 30W
2	HP 3D High Reusability PA 11	HP Jet Fusion 5210 Pro
3	Homopolymer Polypropylene	Freedom Machine Tool Patriot CNC Router

Rigid insole shell samples used in external mechanical property testing. From left to right: Formlabs Nylon 11 Powder, HP PA 11, CNC machined polypropylene

INTERNAL TESTING SAMPLES

Twelve insole shells were used for hand flexion testing. Two were printed at each of the following angles from the build volume floor; 0°, 10°, 20°, 30°, 40°, 50°. These samples were printed at Formlabs Ohio according to this procedure. This model with a center thickness of 2.8 mm and edge thickness of 1.8 mm was used.

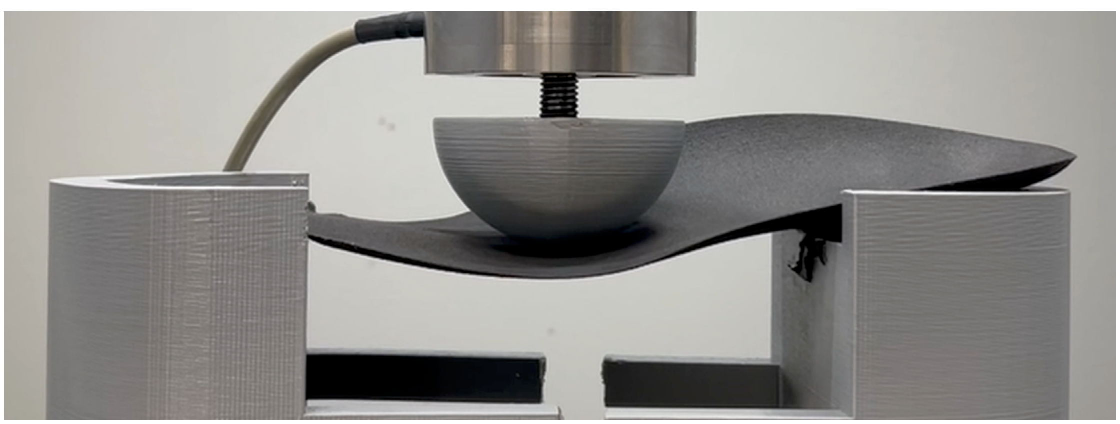
Insole shells angled from 0-50 from the floor of the build chamber in PreForm

Testing Procedures

STATIC 3-POINT BEND TEST

Static 3-Point Bend Testing was done using a fully-calibrated Thelkin load frame (SDL-M-010) with a load cell capacity of 1 kN and a displacement range of 100 mm. The load frame's associated software was used for controlling the system and acquiring data.

All samples were preconditioned in the testing environment for 24 hours prior to the start of testing (note: this is not required in normal production per our application guide). Samples were placed in a custom fixture to hold the center of the sample under the center of the load applicator. A compressive displacement of 40 mm (equivalent to approximately 60° of flexion) was applied to the insole at a rate of 40 mm/min, and then released at a rate of 240 mm/min. Each sample was then inspected for signs of fracture. The system was programmed to stop if the insole shell were to fail, as indicated by a drop in the applied load. Results were plotted as applied load in response to displacement over one minute.



Testing setup for the Static and Dynamic 3-Point Bend Tests indicating the placement of the sample and the location of the load application

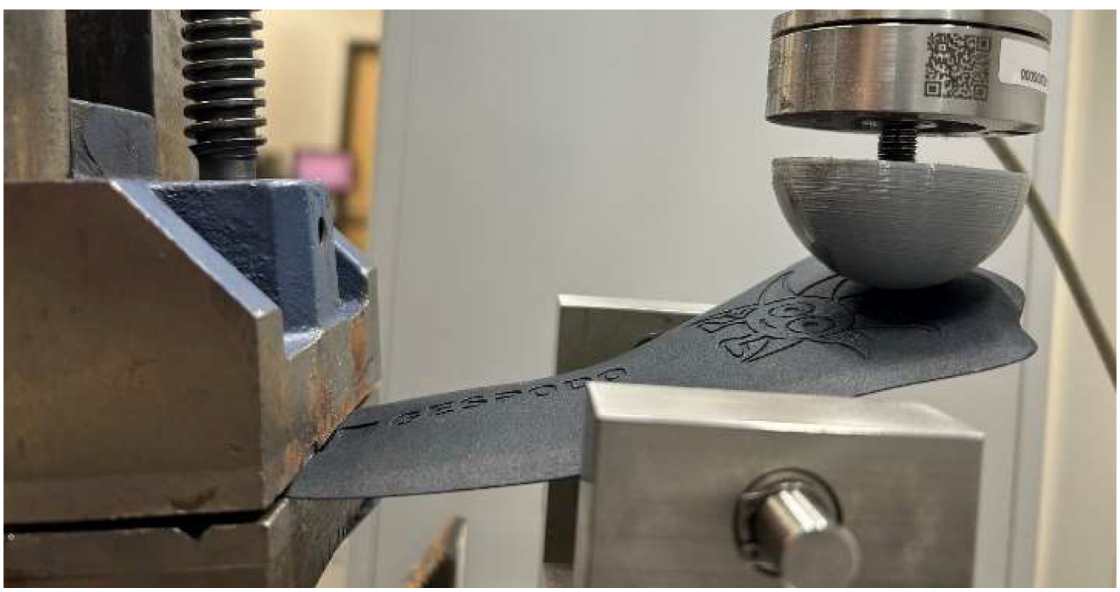
DYNAMIC 3-POINT BEND TEST

For the Dynamic 3-Point Bend Test, the samples were tested using the same load frame and software as the Static 3-Point Bend Test. All samples were preconditioned in the testing environment for 24 hours prior to the start of testing. Samples were placed in a custom fixture to hold the center of the sample under the center of the load applicator. A compressive sinusoidal displacement of 5 mm was applied to the insole shell at a rate of 5 Hz. The HP and PP samples were tested for up to 2 million cycles, and the Formlabs samples were tested for up to 4 million cycles. Each sample was then inspected for signs of fracture. The system was programmed to stop if the insole shell were to fail, as indicated by a drop in the applied load. Results were plotted as applied load in response to displacement up to 5 mm.

ROSS FLEX TEST

The Ross Flex test was conducted using the same load frame and software as the Static and Dynamic 3-Point Bend tests, but with a 100 mm diameter pin in place of the insole-holding fixture.

All samples were preconditioned in the testing environment for 24 hours prior to the start of testing. Samples were placed in a custom fixture to hold the center of the sample under the center of the load applicator. A compressive sinusoidal displacement was applied to the insole shell such that approximately 90° of flexion was achieved at a rate of 2.5 Hz up to 1.5 million cycles for all samples. The system was programmed to stop if the insole shell were to fail, as indicated by a drop in the applied load. Results were plotted as energy returned in response to the number of cycles flexed.



Testing setup for the Ross Flex Test indicating the position of the sample and the location of the load application

HAND-FLEX TEST

Six of the 12 hand-flex samples, one from every angle, was kept at 50-70% humidity for 24 hours prior to testing. This step was intended to simulate humid conditions within a shoe. Two samples from every angle, humidified and not humidified, were bent by hand to 180° and back. Parts were then visually inspected for signs of failure.

Results

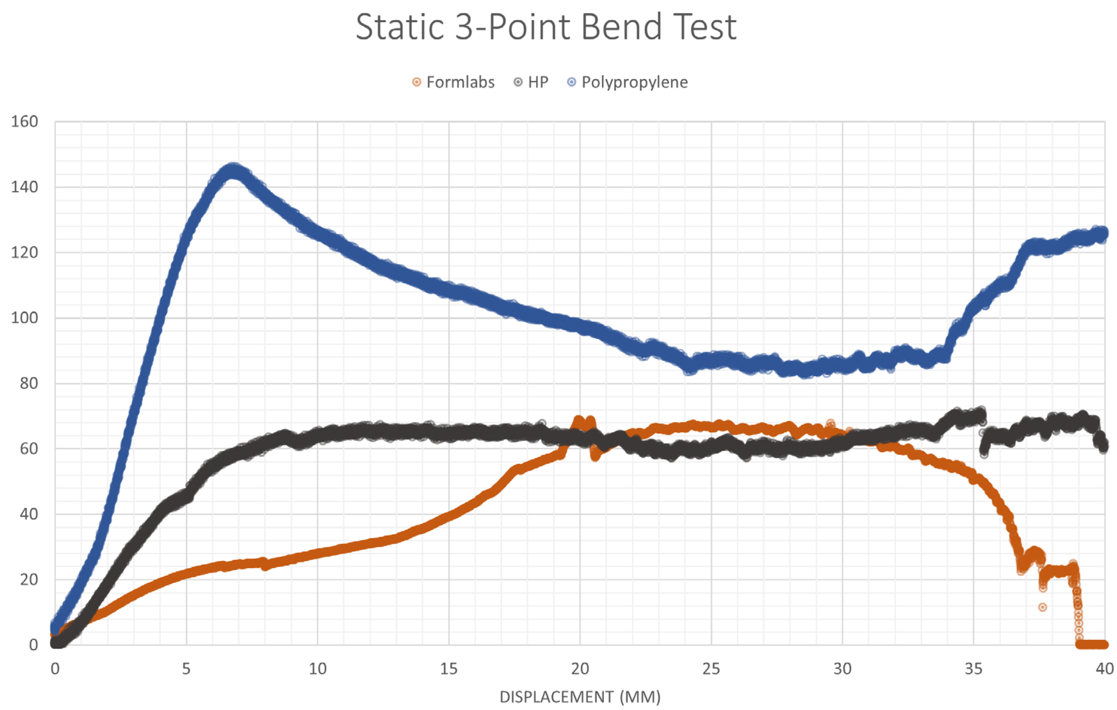
STATIC 3-POINT BEND TEST

No insoles failed upon displacing 40 mm. The ranking of most to least stiff was as follows: polypropylene, HP, and Formlabs. The ranking of most flexible to least flexible is as follows: Formlabs, HP, polypropylene. Relative stiffness and flexibility were determined using the following flexural modulus calculation:

$$E_{flex} = (L^3F)/(4wh^3d)$$

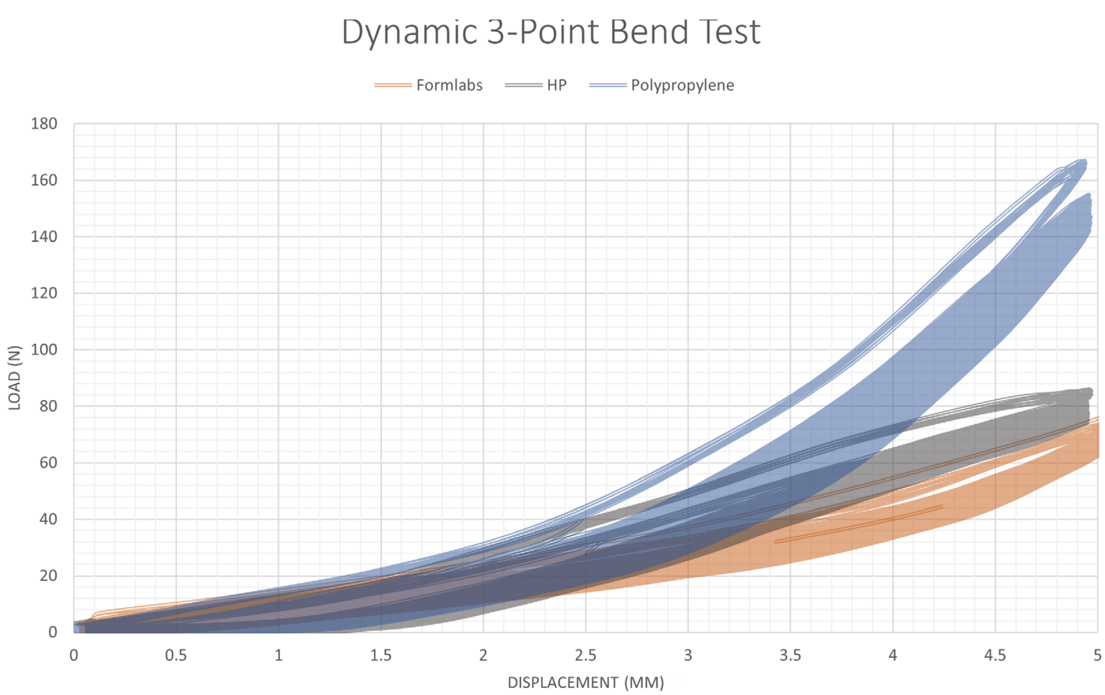
Where L is the distance between the tester's supporting pins, F is the force applied to the sample, w and h are the width and height of the sample respectively, and d is the sample's vertical displacement.

The Formlabs sample maintained a consistent stiffness up to approximately 30 mm displacement whereas the HP and polypropylene samples were stiffer initially, then became easier to deform further after about 10 mm of displacement.



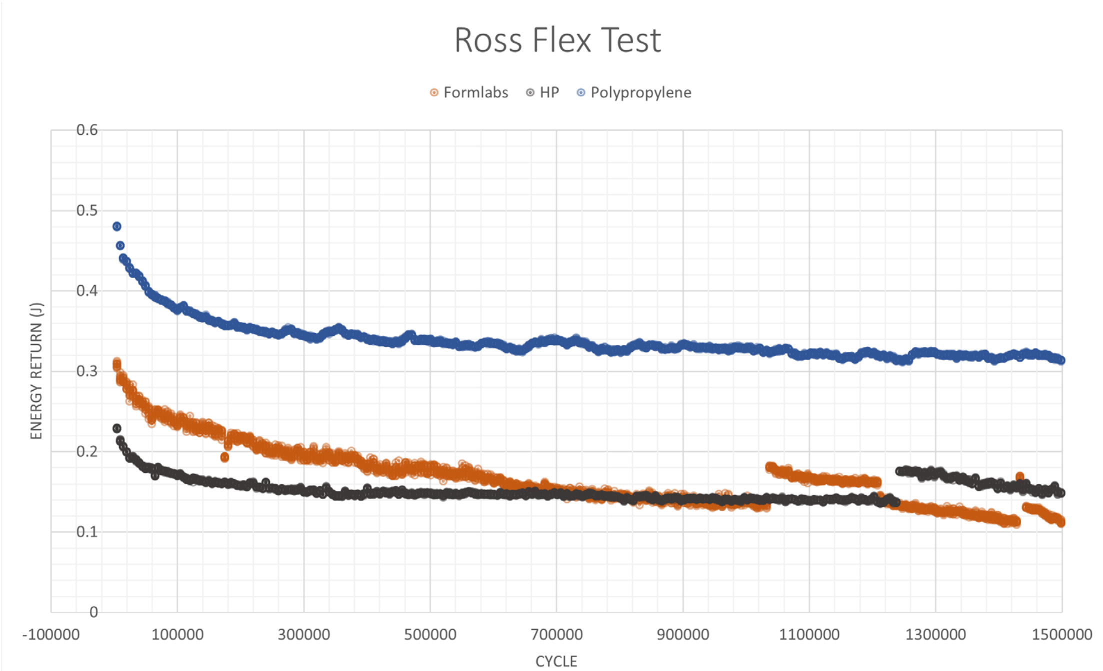
DYNAMIC 3-POINT BEND TEST

All samples survived displacement of 5 mm 2 million times with no signs of damage. The Formlabs sample survived an additional 2 million cycles, resulting in 4 million cycles total with no signs of damage.



ROSS FLEX TEST

All samples exceeded 1.5 million cycles of 90° displacement. The highest energy return value between 0 and 1.5 million cycles was seen by the polypropylene sample, followed by Formlabs, and then HP.



HAND-FLEX TEST

All 12 samples printed from 0° - 50° from the bottom of the build volume survived bending to 180° and back. Humidifying samples to 50-70% humidity for 24 hours had no noticeable effect on mechanical properties.

Discussion

STATIC 3-POINT BEND TEST

Having the highest ranking of flexibility means that the Formlabs samples are the most durable of those tested, and the least likely to be damaged by heavy use. Of all three samples, Formlabs had the most linear response within the range of displacement associated with normal insole shell use. The HP and polypropylene samples were stiffer initially, then became easier to deform further after about 10 mm of displacement, whereas the Formlabs sample maintained a consistent stiffness up to approximately 30 mm displacement. It's unlikely that either the 10 mm or 30 mm of displacement would occur during normal use, but 10 mm is more likely to be surpassed than 30 mm.

DYNAMIC 3-POINT BEND TEST

All three of the samples survived testing, and softened somewhat over the course of the test. The polypropylene sample started out the stiffest and stayed the stiffest, but also changed the most over the course of the test. The Formlabs and HP samples start less stiff than the polypropylene sample, but change less over the course of the test.

By surviving 4 million cycles of 5 mm displacement total, the Formlabs sample withstood cycle testing equivalent to 10,959 steps a day for 365 days, which far exceeds the steps taken by the average adult.

ROSS FLEX TEST

By surviving a 90° bend more than 1.5 million times over a 100 mm pin, the samples demonstrated the ability to exceed the demand of normal patient use. By demonstrating an energy return greater than that of the HP sample, the Formlabs SLS sample is understood to have superior comfort in comparison to the sample produced with MJF.

HAND-FLEX TEST

All samples tested survived flex testing by hand to 180°. This result indicates that insole shells with these dimensions (1.8 mm at the edge, 2.8 mm at the center) printed within 0° - 50° from the bottom of the build volume have the ability to withstand angled displacement far exceeding those associated with daily use.

The humidified samples did not perform any differently than the samples that were not exposed to increased humidity, indicating that the humid atmosphere within a shoe does not pose a negative effect on the insole shells' mechanical properties.

Conclusion

Overall, the Formlabs sample demonstrated outstanding durability and resistance to heavy use, while maintaining consistent stiffness. They also exhibited high endurance during fatigue testing. The hand flexion test indicated that the insole shells could withstand angled displacement beyond daily use requirements, and humidity did not affect their performance. Rigid shells up to 270 mm can be printed in the orientations tested and deliver desired mechanical performance.

Limitations

These tests are designed to closely mimic or exceed common insole shell use, but do not necessarily address all real loading cases. The samples used for these tests represent common insole shell geometry and may not apply to all cases. Generalizations about sample geometry were used for the flexural modulus calculation, but were kept consistent across samples and therefore do not affect the comparative analysis.

There may be small variations in test setup between samples, and small errors in cyclical loading as disclosed by The Orthopaedic Innovation Center, which believes these factors have a negligible effect on the outcome of the tests. Similarly, variability in the load applied to the samples by hand is expected, but negligible to our qualitative observations.

Get Started With 3D Printed Insoles

Do you have any questions about this study or about 3D printing insoles using Formlabs' 3D printing solutions? Get in touch with our medical expert team directly.

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