Reenentrant tensegrity: A three-periodic, chiral, tensegrity structure that is auxetic

Mathias Oster⁠¹, Marcelo A. Dias², Timo de Wolff³, Myfanwy E. Evans⁴*

We present a three-periodic, chiral, tensegrity structure and demonstrate that it is auxetic. Our tensegrity structure is constructed using the chiral symmetry $D_2$ cylinder packing, transforming cylinders to elastic elements and cylinder contacts to incompressible rods. The resulting structure displays local reentrant geometry at its vertices and is shown to be auxetic when modeled as an equilibrium configuration of spatial constraints subject to a quasi-static deformation. When the structure is subsequently modeled as a lattice material with elastic elements, the auxetic behavior is again confirmed through finite element modeling. The cubic symmetry of the original structure means that the auxetic behavior is observed in both perpendicular directions and is close to isotropic in magnitude. This structure could be the simplest three-dimensional analog to the two-dimensional reentrant honeycomb. This, alongside the chirality of the structure, makes it an interesting design target for multifunctional materials.

INTRODUCTION

The geometric design of material microstructures allows specific material properties to be prescribed through particular motifs and mechanisms. Additive manufacturing has highlighted the potential for designed materials with targeted functionality. Auxetic structures, being those with a negative Poisson’s ratio, are an interesting target in the design of metamaterials. An auxetic material is most simply characterized by a perpendicular expansion on stretching the material in a chosen direction. The two-dimensional (2D) reentrant honeycomb pattern is the quintessential example of auxeticity from geometric design (1). Theoretically, some understanding and design principles exist for auxetic structures in $\mathbb{R}^2$ in terms of expansiveness and pseudo-triangulations (2); however, a three-periodic counterpart is notoriously hard, because the design rules of the 2D case are not easily generalized to the 3D case. The current breadth of examples using a reentrant vertex geometry involves only a limited number of structures (3, 4). Furthermore, many techniques focus on analyzing existing databases of lattices for possible interesting mechanisms (5), which is limited by the breadth of existing framework databases. Here, we propose a previously unknown 3D auxetic structure, alongside its construction technique, which has auxetic behavior both as an idealized geometric motif and a simulated elastic material.

We begin with the idea of a tensegrity, a term that comes from the notion of integrity under tension. Originating in the architectural work of Kenneth Snelson and Buckminster Fuller, tensegrity structures use a combination of tension and compression forces to give the illusion of floating rods in space (6, 7). A tensegrity combines strut elements and cable elements. The struts are extendable rigid bars with a prescribed minimum length, which are typically under a compression force. The cables are elements under tension connecting the rigid bars. The combination of these elements and their internal tension maintain the integrity of the structure. Instead of cable elements, elastic elements under tension could also be used to stabilize the structure.

A tensegrity can be described mathematically by a set of vertices that fulfill simple distance constraints. Struts prescribe that the vertices can never be closer than given distance but can be arbitrarily far apart. Vertices connected by a cable can be as close together as desired but not farther apart than the length of the cable. In the case of elastic elements rather than cables, a spring energy can be considered along each of the elements. The equilibrium configuration is then the minimization of the spring energy given the distance constraints of the struts. An interesting parallel to the spatial constraints of a tensegrity structure can be made to sphere packings, where the centers of spheres can never be closer than twice the radius, analogous to the strut constraint (7). This idea has also been used to explore configurations and stability of periodic sphere packings (8).

Similar to the description of sphere packing, symmetric, periodic packing of cylinders in 3D space is a useful technique in the description of crystalline materials. In the description of a crystal structure, the cylinders represent rods of strongly bonded atoms or groups of atoms. For example, the 3D structure of the mineral Garnet was well known for many years, but the subsequent use of cylinder packings provided a more simple description and understanding of the structure (9). More recently, cylinder packings have been used in the design and construction of metal-organic frameworks to achieve topologically robust structures (10).

Using the invariant axes of the crystallographic space groups allows the enumeration of the simplest and most symmetric cylinder packings (11). The restriction to cubic symmetry (which corresponds to a spatially isotropic material), as well as all rods being related to each other by a symmetry of the packing, yields precisely six distinct cylinder packings (11). Relaxing the requirement that the cylinders are straight allows the formation of a more general class of curvilinear cylinder packings, obviously with more geometric freedom. The central axes of the curvilinear cylinders are still along the original directions, but the cylinders can curve past, and weave through, their neighbors (12, 13). A particular set of these curvilinear cylinder packing structures were observed to have what was termed a dilatant property, where mutual straightening of the curvilinear cylinders leads to a homothetic expansion of the material (13). This structural mechanism can be used to explain the swelling of mammalian
skin cells on prolonged exposure to water, where the cylindrical packing describes the organization of keratin intermediate filaments in the cells (13, 14).

We take here the dilatant $\Pi^+$ cylinder packing (11), as shown in Fig. 1. It is also referred to as the $\beta$-Mn rod packing, as it describes the chemical structure of $\beta$-Mn (15, 16). This packing has the chiral space group symmetry $P4_132$, with three distinct cylinder axes along $\{1,0,0\}$, $\{0,1,0\}$, and $\{0,0,1\}$. The $\Pi^+$ packing is described by the vectors

$$\left\{ \frac{1}{4}, 0, u \right\} \left\{ \frac{3}{4}, 1, u \right\} \left\{ u, \frac{1}{4}, 0 \right\} \left\{ u, \frac{3}{4}, 1 \right\} \left\{ 0, u, \frac{1}{4} \right\} \left\{ \frac{1}{2}, u, \frac{3}{4} \right\}$$

where $u$ is any real number, and the periodicity gives the parallel cylinders. When the straight cylinders of $\Pi^+$ are relaxed to a curvilinear form, the symmetry of the packing drops to the $I4_132$ space group (which is also chiral) and the packing becomes more dense. This curvilinear packing then displays the dilatant property on cooperative straightening of the curved cylinders (17). Figure 1 shows the transformation from an expanded structure with straight cylinders in contact to a compacted structure with helical cylinders.

Inspired by the parallel between tensegrities and sphere packings, we construct a tensegrity from the helical $\Pi^+$ cylinder packing by reimagining the structure as follows:

1) At all contacts between cylinders, rigid and incompressible bars are placed, connecting the central axes of the cylinders, with a length twice the cylinder radius. They represent the incompressibility of the cylinder at the contact.

2) Thin elastic elements are placed along the central axes of the cylinders in the packing. These elastic elements connect to the incompressible bars passing through the contact points. These elastic elements span the periodic boundary conditions.

3) The final constraint is that the periodicity of the structure remains, which, in this case, means that three orthonormal translation vectors of the same length remain fixed.

What results are a series of rigid rods suspended in space by a periodic web of elastic filaments. This is our periodic tensegery structure, as shown in Fig. 1.

The topology of the constructed network is known as bmn, as described in the Reticular Chemistry Structure Resource database (18): This terminology comes from the relation of the structure to the chemical structure of $\beta$-Mn. The structure has $I4_132$ space group symmetry, is embedded in a triply periodic unit cell, and has 24 vertices and 36 edges within each cubic unit cell. The vertices are degree 3, and all display the reentrant geometry characteristic of many auxetic materials, including the 2D reentrant honeycomb pattern. We note that there is a degree of freedom in the construction technique: Depending on the level of dilation/compaction of the starting rod packing (such as the two structures given in Fig. 1), we obtain different configurations of the bmn network, with different sized periodic unit cells of our periodic tensegery. These structures correspond to a variation of the angle of the reentrant vertices. The structure shown in Fig. 1 is one such structure in this family of structures. The reentrant geometry of the vertices is suggestive of auxetic behavior, and it is this hypothesized behavior that we now investigate more deeply.

**RESULTS AND DISCUSSION**

We investigate the equilibrium configurations and quasi-static deformations of the constructed periodic tensegery structure. As the starting point for our simulated deformations, we take the configuration shown in Fig. 1, which corresponds to the densest packing of the original cylinder packing, within a fixed unit cell. It can be confirmed numerically by Newton’s method that this structure is an equilibrium configuration, where the spring energy is at a minimum not assuming minimal spring lengths. We used several perturbed starting configurations to verify the minimization. The deformation process is then modeled by a quasi-static extension that assumes the springs to have length bounded from below by the configuration computed initially.

The behavior of the structure over an initial phase of deformation is dominated by a breaking of symmetry of the highly symmetric initial structure; all of the symmetries of the structure are lost, leaving just periodicity. On further extension, the structure reaches a more stable behavior, which sees an expansion of the structure in both of the perpendicular directions, indicating auxeticity. Figure 2 shows two configurations of the structure during the deformation process, both the starting equilibrium configuration and the maximally deformed, equilibrium structure. As a result of this process, we can measure the $y$- and $z$-direction lattice parameter lengths, as plotted in Fig. 3 (top).

The Poisson’s ratio is typically defined only for small strain linear elastic behavior. A more subtle formulation is required when considering highly nonlinear elastic materials over large strain intervals. We used two such formulations to analyze the deformation of the tensegery structure, the instantaneous Poisson’s function and the Poisson’s ratio using the log transform true strain (19). We can calculate the instantaneous Poisson’s ratio in terms of the engineering strain at time step $t$ as follows (19)

$$v_{yx} = \frac{-e_y}{e_x}$$

where $x$ is the direction of applied strain, $y$ is an orthogonal direction, and $e_y$ and $e_x$ are given by

$$e_y = \frac{(L_y)_{t+1} - (L_y)_{t-1}}{(L_y)_{t-1}}$$

$$e_x = \frac{(L_x)_{t+1} - (L_x)_{t-1}}{(L_x)_{t-1}}$$

**Fig. 1. The $\Pi^+$ cylinder packing in three different geometric incarnations. (Left) The $\Pi^+$ cylinder packing composed of straight cylinders, with chiral space group symmetry $P4_132$, and three distinct cylinder axes. (Centre) A compacted version of $\Pi^+$ where the cylinders become curvilinear, which now has the chiral space group $I4_132$. (Right) The bmn periodic tensegery structure, where the incompressible rods are shown in black and the elastic struts colored like the cylinder packing above. The periodic unit cell is outlined in the thick black lines.**
where $L_x$ and $L_y$ are the lattice parameter lengths in the $x$ and $y$ directions taken at time step ($t$) and the previous time step ($t-1$). The instantaneous Poisson’s function for the deformation of the tensegrity structure is shown in Fig. 3 (middle).

We can also calculate the Poisson’s ratio in terms of the log transform true strain at time step $t$ as follows (19)

$$v_{xy} = \frac{\eta_y}{\eta_x}$$

where, again, $x$ is the direction of applied strain, $y$ is an orthogonal direction, and $\eta_y$ and $\eta_x$ are given by

$$\eta_y = \ln \left( 1 + \frac{(L_y)_t - (L_y)_0}{(L_y)_0} \right)$$

$$\eta_x = \ln \left( 1 + \frac{(L_x)_t - (L_x)_0}{(L_x)_0} \right)$$

where $L_x$ and $L_y$ are the lattice parameter lengths in the $x$ and $y$ directions taken at time step ($t$) and the original configuration. The Poisson’s ratio calculated using the log transform true strain for the tensegrity structure is shown in Fig. 3 (bottom).

The magnitudes of the instantaneous Poisson’s function and the Poisson’s ratio using the log transform normal strain are both comparable, as expected from previous results comparing these formulations. The Poisson’s ratio is around $-1.1$ in the $y$ direction and $-0.75$ in the $z$ direction in the steady state. The cubic symmetry of the structure should imply that the Poisson’s ratio is the same in both the $y$ and $z$ directions; however, in this case, the complete loss of symmetry that occurs with the initial deformation results in these directions no longer being equivalent. The choice of which direction gives a larger or smaller Poisson’s ratio is also arbitrary and depends on the minimizing configuration found. Despite these differences arising from the symmetry breaking, the auxetic response of the structure stays close to isotropic in the $x$, $y$, and $z$ directions, which is a remarkable property for a 3D material.

The phase of deformation directly after the initial loss of symmetry of the structure is highly interesting from both a material science and numerical perspective. It is instructive to explore the stability of these minimizing configurations in more detail; however, the numerical tools are still under development.

We now turn our attention to the engineering potential of realizing these idealized geometric constructions. This is done by extending...
the concept of the auxetic periodic tensegrity structures to finite 3D lattices composed of elastic elements. For such more realistic situations, the driving principle toward auxeticity depends on the interplay between geometry and elasticity (20, 21)—by turning a mechanism into an actual structure, through locking of the hinge points, loading carrying will occur via axial stresses and bending moments.

The boundary conditions were enforced constraining the normal displacements of the elements for the lattice’s planes at $x = 0$, $y = 0$, and $z = 0$. A quasi-static and displacement controlled condition was applied to the end of the cable elements at the plane $x = n \times L$ (where $L$ is the length of the unit cell), thus imposing a stretch in the direction normal to the $yz$ plane. First, from Fig. 4, we look at the level of axial stresses $\sigma_{11}$ in each element. As expected, from a tensegrity structure, tension and compression will be carried by the cables and struts, respectively. By zooming in to a representative volume in the interior of the lattice, as shown in Fig. 4, we noticed that $\sigma_{11} > 0$ for the “cable” elements and $\sigma_{11} < 0$ for the struts. We further measure the effective structural Poisson’s ratio, as shown in Fig. 5, and we observe that $v_{xy}$ and $v_{xz}$ depend in a nonmonotonic manner with respect to the diameter ratio $d_c/d_s$, which is here seen as a design parameter. Notice that auxeticity can be maximized for $1 \lesssim d_c/d_s \lesssim 1.6$, depending on the direction of the deformation. In Fig. 6, we show two perspectives, $xy$ and $xz$, of center unit cells in $8 \times 8 \times 8$ lattices, in their rest and deformed configurations. To highlight the effect of curvature on each of the elements, we show two examples of aspect ratios $d_c/d_s = 0.6$ and $d_c/d_s = 1.2$, coloring the elements by the absolute value of the total curvature vector $\kappa$—here, its components in the moving frame parameterized by the arc length are two normal curvatures and one twist. Notice that the effect of auxeticity is derived from the fact that there is a local increase of voids’ size within the unit cell, which is the same phenomenon observed in the idealized mechanism seen in Fig. 2. However, given that, in the real structure where the hinges are locked, the moment balance at the nodes leads to an increase in the curvature of the cable elements, which results in less “free length” for the expansion in all directions. Hence, the difference in the Poisson’s ratio observed in Fig. 5 against the values $v_{xy} = -1.1$ and $v_{xz} = -0.75$ is computed for the idealized case, as shown in Fig. 2. We choose to demonstrate this effect from the curvature data because it gives us an intuitive geometric measure of the causal relationship between curvatures and the moments transferred by the joints via the bending rigidity of the element, i.e., the constitutive behavior of the elements.

To further extend these ideas to real materials, we explored 3D printing of a toy model of the structure. We printed in a single material, using rubber-like thermoplastic polyurethane, without differentiating between the rigid and elastic elements. The radius of the rigid and elastic in the printed is the same, which would correspond to the case of $d_c/d_s = 1$ in the simulations. Despite this simplification, we were able to observe mild auxetic behavior of the structure (Fig. 7). A full movie of the deformation is included in the Supplementary Materials.

Fig. 4. Tension and compression of the tensegrity elements. $8 \times 8 \times 8$ lattice for $d_c/d_s = 0.6$. The color map represents the level of axial stresses $\sigma_{11}$, normalized by the Young's modulus $E$, along the elements’ arc lengths. The inset shows a representative volume and further the dissection of the cable and the strut elements to show that they are subjected to tension and compression, respectively. The deformed configurations are shown at 0.025 strain.

Fig. 5. Poisson’s ratio of the structure. It shows the Poisson’s ratio $v_{xy}$ and $v_{xz}$, as a function of the diameter ratio $d_c/d_s$ between the of the cable and the strut elements. The results for lattice assemblies with different numbers of unit cells, $n$, are shown.

Fig. 6. The effect of curvature on each of the elements. Unit cell’s rest and deformed configurations for $d_c/d_s = 0.6$ and $d_c/d_s = 1.2$ from a $8 \times 8 \times 8$ lattice. The color map represents the norm of the curvature vector $\kappa$. Two different perspectives are presented, $xy$ and $xz$. The deformed configurations are shown at 0.75 strain.
The analysis of this structure instigated various explorations in the fields of algebraic geometry and optimization. It was apparent in most situations that the structure was too complicated for most of the available numerical tools, although from a materials science perspective, the tensegrity structure is relatively simple. This has already prompted the development of new numerical and symbolical approaches in these fields of mathematics (22–24), and we are optimistic about the use of these tools in further studies of this type.

**MATERIALS AND METHODS**

We investigated the equilibrium configurations and quasi-static deformations of the constructed periodic tensegrity structure. For any of our constructed tensegrity structures with different degrees of compression, we calculated the equilibrium configuration (6). If we place springs along each of the elastic cables, then these will each have an energy proportional to the square of their length. If we minimize this collectively while maintaining all of the length conditions of the tensegrity, then the equilibrium configuration can be found. The periodicity of the structure for a fixed unit cell size is incorporated through additional constraints keeping vertices related to copies of themselves by the orthonormal periodicity vectors. Noticing that the discrete Laplacian (25) fulfills Hooke’s law at each vertex of the structure, we interpret the spring energy of the tensegrity as the discrete Dirichlet energy $E$ on the vertex set $V$ and edge set $E$ of the unit cell. Using this idea, one gets

$$\frac{\partial}{\partial f_i} E(f) = \frac{\partial}{\partial f_i} \left( \frac{1}{2} \sum_{ij} \mu_{ij} \| f_i - f_j \|^2 \right) = \sum_{j \in E} \mu_{ij} (f_i - f_j)$$

where $ij \in E$ is an edge between vertices $i$ and $j$, and $j : ij \in E$ are all vertices that share an edge with vertex $i$. Furthermore, $\mu_{ij} > 0$ is the spring constant, $\| \cdot \|$ denotes the Euclidean norm, and $f : V \to \mathbb{R}^3$ is a realization of the network, i.e., $f_i$ are the Euclidean coordinates of a vertex $i$ for the actual configuration.

As an alternative approach, we can interpret the incompressible bars as springs with fixed lengths and assume a momenta and torque-free equilibrium, and the following optimization problem arises

$$\min_{f : V \to \mathbb{R}^3} \frac{1}{2} \sum_{ij \in E} \| f_i - f_j \|^2$$

under the constraints

1) $\| f_i - f_j \|^2 = \text{length (bars)} = \text{constant if } ij \text{ is an incompressible bar}$
2) $\| f_i - f_j \|^2 \geq \ell_{ij}^{\text{min}}$ if $ij$ is a spring of minimal length $\ell_{ij}^{\text{min}}$
3) $\sum_{f \in E} (f_i \times (f_j - f_i)) = 0$

where $\times$ denotes the cross product in three dimensions. This amounts to a polynomial optimization problem over semialgebraic sets. However, the number of variables in the problem is too high for the usual sums of squares/semidefinite programming–based approach in polynomial optimization [implemented in the packages like GloptiPoly (26)], resulting in memory overflow. Thus, we used the solvers of constrained optimization preimplemented in MATLAB. These solvers cannot guarantee to find a globally optimal solution; however, they will find local equilibrium configurations. MATLAB provides multiple solvers (27) that give consistent results for our problem. Here, we use the results obtained by the interior point algorithm (28), which replaces the inequality constraints by a sequence of equality constrained minimization problems involving logarithmic barrier functions that are solved either by Newton’s method or conjugate gradient steps.

We perform the quasi-static extension (and then subsequent compression) of the structure with small step sizes (0.0025) by changing the lattice parameter length of the structure in one direction (in this
Supplementary Material

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.ajb6737

References and Notes

1. R. S. Lakes, Response: Negative poisson’s ratio materials. Science 238, 551 (1987).

2. C. S. Borcea, I. Streinu, Geometric auxetics. Proc. R. Soc. A 471, 20150033 (2015).

3. R. F. Almgren, An isotropic three-dimensional structure with Poisson’s ratio \(\nu = -1.1\). J. Elast. 15, 427–430 (1985).

4. T. Bückmann, N. Stenger, M. Kadic, J. Kaschke, A. Frölich, T. Kennerknecht, C. Eberl, M. Thiel, M. Wegener, Tailored 3d mechanical metamaterials made by dip-in direct-laser-writing optical lithography. Adv. Mater. 24, 2710–2714 (2012).

5. C. Körner, Y. Liebold-Ribeiro, A systematic approach to identify cellular auxetic materials. Smart Mater. Struct. 24, 025013 (2015).

6. B. Roth, W. Whiteley, Tensegrity frameworks. Trans. Am. Math. Soc. 265, 419–446 (1981).

7. R. Connelly, A. Back, Mathematics and tensegrity. Am. Sci. 86, 142–151 (1998).

8. R. Connelly, J. D. Shen, A. D. Smith, Ball packings with periodic constraints. Discrete Comput. Geom. 52, 754–779 (2014).

9. S. Andersson, M. O’Keefe, Body-centred cubic cylinder packing and the garnet structure. Nature 267, 605–606 (1977).

10. N. L. Rossi, J. Kim, M. Eddaudou, B. Chen, M. O’Keefe, O. M. Yaghi, Rod packings and metal-organic frameworks constructed from rod-shaped secondary building units. J. Am. Chem. Soc. 127, 1504–1518 (2005).

11. M. O’Keefe, J. Plevert, Y. Teshima, Y. Watanabe, T. Ogama, The invariant cubic rod (cylinder) packings: Symmetries and coordinates. Acta Crystallogr. A 57, 110–111 (2001).

12. M. E. Evans, V. Robins, S. T. Hyde, Periodic entanglement II: Weavings from hyperbolic line patterns. Acta Crystallogr. A 69, 262–275 (2013).

13. M. E. Evans, S. T. Hyde, From three-dimensional weavings to swollen corneocytes. J. R. Soc. Interface 8, 1274–1280 (2011).

14. M. E. Evans, R. Roth, Shaping the skin: The interplay of mesoscale geometry and corneocyte swelling. Phys. Rev. Lett. 112, 038102 (2014).

15. H. Nyman, C. E. Carroll, B. G. Hyde, Rectilinear rods of face-sharing tetrahedra and the structure on \(\beta\)-mn. Z. Krist. 196, 39–46 (1991).

16. S. Lidin, S. Andersson, Regular polyhedra helices. Z. Anorg. Allg. Chem. 622, 164–166 (1996).

17. M. E. Evans, V. Robins, S. T. Hyde, Ideal geometry of periodic entanglements. Proc. R. Soc. A 471, 20150254 (2015).

18. M. O’Keefe, M. A. Peskov, S. J. Ramsden, O. M. Yaghi, The reticulic chemistry structure resource (RCSR) database of, and symbols for, crystal nets. Accts Chem Res 41, 1782–1789 (2008).

19. C. W. Smith, R. J. Wootton, K. E. Evans, Interpretation of experimental data for poisson’s ratio of highly nonlinear materials. Exp. Mech. 39, 356–362 (1999).

20. D. J. Rayneau-Kirkhope, M. A. Dias, Recipes for selecting failure modes in 2-d lattices. Extreme Mech. Lett. 9, 11–20 (2016).

21. D. J. Rayneau-Kirkhope, C. Zhang, L. Tharan, M. A. Dias, Analytic analysis of auxetic metamaterials through analogy with rigid link systems. Proc. R. Soc. A 474, 20170753 (2018).

22. A. Heaton, S. Timme, Catastrophe in elastic tensegrity frameworks (2020); arXiv:2009.13408.

23. H. P. Le, M. Safey El Din, T. de Wolff, ISSAC ’20: International Symposium on Symbolic and Algebraic Computation, Kalamata, Greece, July 20–23, 2020, I. Z. Emiris, L. Zhi, Eds. (ACM, 2020), pp. 297–304.

24. H. P. Le, M. Safey El Din, Solving parametric systems of polynomial equations over the reals through hermite matrices (2020); arXiv:2011.14136.

25. A. I. Bobenko, B. A. Springborn, A discrete laplace-beltrami operator for simplicial surfaces. Discrete Comput. Geom. 38, 740–756 (2007).

26. D. Henrion, J.-B. Lasserre, J. Löfberg, Gloptipoly 3: Moments, optimization and semidefinite programming. Optim. Methods Softw. 24, 761–779 (2009).

27. MATLAB and Optimization Toolbox (The MathWorks, Inc, 2018).

28. R. Byrd, M. Hribar, J. Nocedal, An interior point algorithm for large-scale nonlinear programming. SIAM J. Optim. 9, 877–900 (1999).

Acknowledgments

Funding: M.E.E. and T.d.W. thank the DFG Emmy Noether Program for support. M.E.E. and T.d.W. were supported by the projects EV 210/1-1 and WO 2206/1-1, respectively. M.E.E. also thanks the DFG Cluster of Excellence “Matters of Activity” for support. Author contributions: M.E.E., M.A.D., and T.d.W. designed the research. M.O., M.A.D., and M.E.E. performed the research. M.O., M.A.D., T.d.W., and M.E.E. analyzed the methodologies and results. M.A.D. and M.E.E. wrote the paper. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Submitted 25 May 2021
Accepted 22 October 2021
Published 10 December 2021
10.1126/sciadv.ajb6737