Spider Silk Violin Strings with a Unique Packing Structure Generate a Soft and Profound Timbre

Shigeyoshi Osaki
Department of Chemistry, Nara Medical University, Kashihara, Nara 634-8521, Japan
(Received 18 November 2011; published 11 April 2012)

We overcome the difficulties in pulling long draglines from spiders, twist bundles of dragline filaments, and succeed in preparing violin strings. The twisting is found to change the cross section shapes of filaments from circular to polygonal and to optimize the packing structure with no openings among filaments providing mechanically strong and elastic strings. The spider string signal peaks of overtones for the violin are relatively large at high frequencies, generating a soft and profound timbre. Such a preferable timbre is considered to be due to the unique polygonal packing structure which provides valuable knowledge for developing new types of materials.

DOI: 10.1103/PhysRevLett.108.154301 PACS numbers: 43.75.+a, 43.75.Zz, 61.41.+e, 82.35.Lr

Spider silk is expected to become a breakthrough textile of the 21st century for the production of items such as bulletproof jackets, sutures, and stockings, due to its functional characteristics, which include elasticity [1], high modulus [2–4], heat resistivity [5], and ultraviolet resistivity [6–8]. Large quantities of spider silk from captive-bred spiders are necessary to provide sufficient material for textile use; however, it is impossible to breed a large number of spiders within a small space as they prey on one another. Recently, researchers have attempted to use genetic engineering to assist in the mass production of spider silk [9–12], even though the mass production of genetically engineered silk has not been successful.

Previous studies on the physicochemical properties of spider silk revealed a safety law concerning the mechanical lifeline of spiders [13,14], and research showed that the collagen-fiber orientation in connective tissues is closely related to mechanical properties [15–17]. More recently, a short (13-cm-long) bundle consisting of ~190 000 dragline filaments collected from 300 spiders was successfully used to support the body weight of an adult human male [18], although the bulk density of the spider silk bundles was very low. If the bundles could be used to form a strand with a great mechanical strength and high elasticity, they may be effective as strings for musical instruments.

The crucial issue is the realization of homogeneous, elastic, and mechanically strong strings with a high density using long draglines, as inhomogeneous and low elastic strings show unfavorable vibration, while mechanically weak strings are easy to break when tuning or playing.

Bowed string instruments such as the violin have been the subject of many scientific studies [19–26]; however, not all of the details have been clarified, as most players have been interested in the violin body rather than the properties of the bow or strings [19–23]. Nevertheless, the importance of the quality of the bow and strings for the sound and tonal properties is generally recognized [24–26]. Conventional violin strings are made from steel, nylon, or gut. All strings require the physical properties of mechanical strength and elasticity.

Spider silk is considered to be an appropriate material for violin strings from the viewpoint of mechanical strength and elasticity, as the timbre of the violin is likely to reflect the characteristics of the materials used directly. Difficulties in collecting long draglines are often encountered because the spiders cut them when pulling [18]. These difficulties were recently overcome, allowing the collection of long draglines from more than 300 *Nephila maculata* spiders, which were subsequently made into long strings.

The present Letter therefore focused on the optimization of the packing structure of dragline filaments for preparing mechanically strong strings with a high density for violins, assuming the spider silk strings could generate a new type of thrilling timbre to contrast that of conventional strings, and considering the practical applications of spider silk in the form of high value-added goods.

Multiple draglines secreted from many female *N. maculata* spiders were in parallel aligned in rows consisting of ~3000, 4000, or 5000 filaments (90 cm in length) [Fig. 1(a)]. Each end of a row of dragline filaments was tied into a bundle (80 cm in length). Each bundle was twisted [27] to the left into a twisted bundle (73 cm in length), and three twisted bundles with similar numbers of filaments were furthermore twisted together to the right and then reformed as a raw string (55 cm in length). The total numbers of dragline filaments comprising the A, D, and G strings were ~9000, 12 000, and 15 000, respectively. Spider strings were prepared by treating the raw string with a dilute solution of gelatin [Fig. 1(b)].

The spider string was shown by using a scanning electron microscope JSM-6301F (JEOL, Japan) to be homogeneous and cylindrical [Fig. 2(a)]. Spiders secrete dragline filaments with cross section areas that depend on the spider's weight [14]. Even if cylindrical dragline filaments [Fig. 2(b)] are perfectly aligned in parallel as a bundle, many openings among the filaments can be observed.

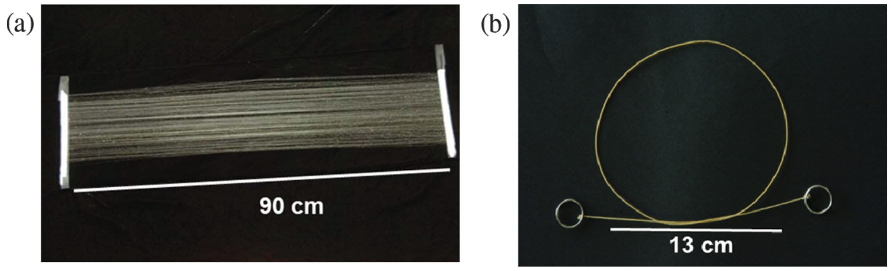

FIG. 1 (color). Photographs of spider strings. (a) About 3000 dragline filaments 90 cm in length collected from *N. maculata* spiders are aligned as a row. (b) Spider string prepared by furthermore twisting together three bundles prepared by twisting bundles with ∼3000 dragline filaments.

Since bundles with openings among filaments show low density, they are naturally easy to break when playing and are difficult to generate a favorable vibration. The cross section shapes of the filaments remained circular even after the small number of twists of the bundles. The author tried to prepare mechanically strong strings with high density by increasing the number of twists. Thus, the cross-sectional analysis by electron microscopy revealed a very intriguing fact as below. It was found that the cross section shapes of the dragline filaments constituting the strings were not circular, but polygonal, such as tetragonal, pentagonal, hexagonal, and heptagonal [Figs. 2(c) and 2(d)], and that the strings had no openings among these polygonal filaments. Tetragonal and heptagonal filaments were also observed for the strings consisting of many filaments with different thicknesses. To my knowledge, no one has observed such a change of cross section shapes of filaments from circular to polygonal in a two-dimensional plane. The sizes of the polygonal filaments were different, and the lengths of the sides of each polygonal filament were not equal [Fig. 2(c)]. The length of each side of the cross section of filaments matches that of the surrounding filaments. Each side plane of the polygonal filament also contacts with side planes of the surrounding polygonal filaments. Thus, the unique packing structure with no openings among filaments is produced even though the cross section shapes of filaments are nonequilateral polygonal. Such a packing structure indicates a high density string. Figure 2(d) shows the ratio of the cross section shapes shown in Fig. 2(c), indicating that hexagonal and pentagonal shapes accounted for most of the filaments.

It is likely that the dragline is relatively easy to deform by pressure, as it consists of a largely amorphous structure containing crystalline β sheets [28,29] and its elastic

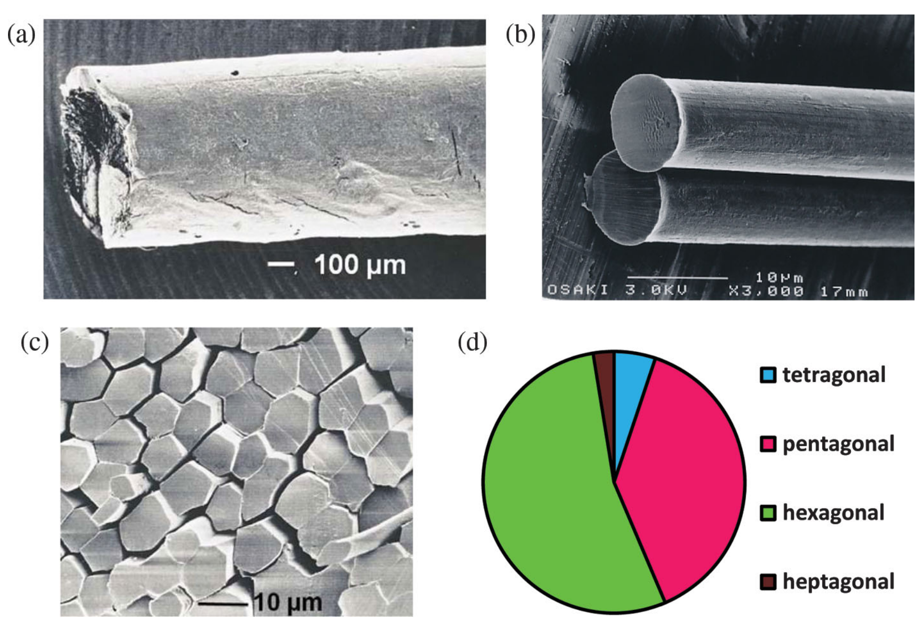

FIG. 2 (color). Electron microphotographs of spider string. (a) Side view of the string. (b) Cross section of the dragline filaments from a *N. maculata* spider. (c) Cross section of the dragline filaments constituting the string after a large number of twists. Openings observed in the photo are due to the release of pressure when cutting. (d) Ratio of cross section shapes of dragline filaments constituting the string.

modulus [2–4] was between the crystalline and amorphous regions. Pressure from twisting is therefore expected to change the cross section from circular to polygonal such as pentagonal and hexagonal, which reduces the openings among filaments and optimizes the packing of strings consisting of many circular filaments with different thicknesses. This also maximizes the density and mechanical strength of spider strings. Such close packing with no openings may be related to Penrose tilings [30], where tiles with fixed sizes are arranged so that openings among tiles do not need to be prepared, being related to the aperiodic tilings of quasicrystals [31–33]. However, the present packing structure consists of several types of polygonal shapes with different lengths of sides, while Penrose tilings consist of two types of symmetrical polygonal shapes with an equal length of sides [30].

Hertzian [34,35] and Phoenix-type theories [36,37] are, respectively, related to the deformation related to the contact stress problem between circular filaments within the elastic limit and to the statistical mechanical strength of a twisted fiber bundle. Such theories may be applicable to the present case even though the imposed pressure is beyond the elastic limit.

Spider strings are required to enlarge the elastic limit strength for preparing mechanically strong strings and to lengthen the elastic region for generating favorable vibration. The force-elongation curves were measured by using a Universal Testing Instrument RTC-1150A (Orientech. Corp., Japan). The elastic limit and breaking strengths were 4.16 and 15.4 kg wt, respectively, for the spider string of a linear density (σ) of 5.60×10^{-4} kg/m (560 tex), 3.68 and 20.9 kg wt, respectively, for an A gut string (Chorda, Pirastro) of $\sigma = 5.81 \times 10^{-4}$ kg/m (581 tex), and 3.12 and 13.8 kg wt, respectively, for a nylon-core A string wrapped with aluminum (Tonica, Pirastro) of $\sigma = 7.00 \times 10^{-4}$ kg/m (700 tex). The elastic limit strength of spider strings was about 27% of the mechanical breaking strength, while that of dragline filaments was about 22% of the mechanical breaking strength. Thus, sufficient twisting increased the elastic limit strength and lengthened the elastic region.

The similarities between the elastic limit and breaking strengths of the three kinds of strings prompted the author to establish spider strings for use as an A string for the violin. The frequency (f) of vibration for the stationary wave of the violin is given by [23]

$$f = (1/2L)(T/\sigma)^{1/2} \quad (1)$$

for strings, where L is the length of the string, T is the applied tension, and σ is the linear density.

The L of the open string of the Hofner violin (Germany) used here was 0.324 m. By using Eq. (1), the tension for the open A spider string ($f = 440$ Hz) was estimated to be 4.64 kg wt, which was a little higher than the elastic limit strength of 4.16 kg wt. As the tension was above the elastic limit strength, mechanical hysteresis was expected to be observed. Therefore, the spider string is predicted to require regular tuning from the viewpoint of stress relaxation. This is also true for gut and nylon-core strings, because the elastic limit strengths are much smaller than the estimated tensions of 4.81 kg wt for the gut string and 5.80 kg wt for the nylon-core string. However, tuning a violin with spider strings is easier than with gut or nylon-core strings, since the elastic limit strength of the spider string is close to the estimated tension, unlike the gut and nylon-core strings. An increase in the elastic limit strength for the spider strings may come from sufficient twisting, which lengthens the elastic region related to the vibration and tuning. If the frequency used is lower, the elastic limit strength of spider string becomes greater than the estimated tension. In such a situation, the spider string is applicable to the violin. On the other hand, the elastic limit and breaking strengths were 10.2 and 13.3 kg wt, respectively, for an A steel string (Chromcor, Pirastro) of $\sigma = 7.20 \times 10^{-4}$ kg/m (720 tex). Tuning a violin with metal strings is thus more straightforward, as the elastic limit strength of the string is much larger than the estimated tension of 5.97 kg wt. By enlarging the elastic limit strength of the spider string as much as possible, the tuning time can be reduced.

Sound-wave signals for a second spider string prepared in a similar way were recorded at 293 Hz, corresponding to the D string. The tension estimated by using Eq. (1) was 2.06 kg wt, which was much smaller than the elastic limit strength of 4.16 kg wt, indicating that the spider string is applicable to the violin. The sound-wave signals for steel and gut strings were also measured. Next, the spectra of the tone magnitude were obtained by Fourier transformation of the sound-wave signals and compared among spider, gut, and steel strings [Figs. 3(a)–3(c)]. The signal peaks of the spider string were relatively high at high frequencies, particularly at the eighth and ninth overtones, and intermediate at the third, fourth, and fifth overtones, compared with the peak of the fundamental tone [Fig. 3(a)]. On the other hand, the signal peaks of steel strings were relatively low at high frequencies [Fig. 3(b)] except for the first overtone. The signal peaks of gut strings were also relatively low at high frequencies [Fig. 3(c)] except for the first and second overtones. Thus, the spider string signal peaks of the overtones were relatively high at high frequencies, compared with those of the steel and gut strings. This indicates that the combinations of different overtones generated by the spider strings are unique. Moreover, several professional violinists evaluated the timbre generated by these spider strings as relatively soft and profound, being able to acoustically recognize a thrilling timbre due to the existence of many overtones while they were playing. The famous violin, Dancing Master's Violin 1720 "Gillott" made by Antonio Stradivari, was used for comparison of timbre [38]. Several professional violinists evaluated that

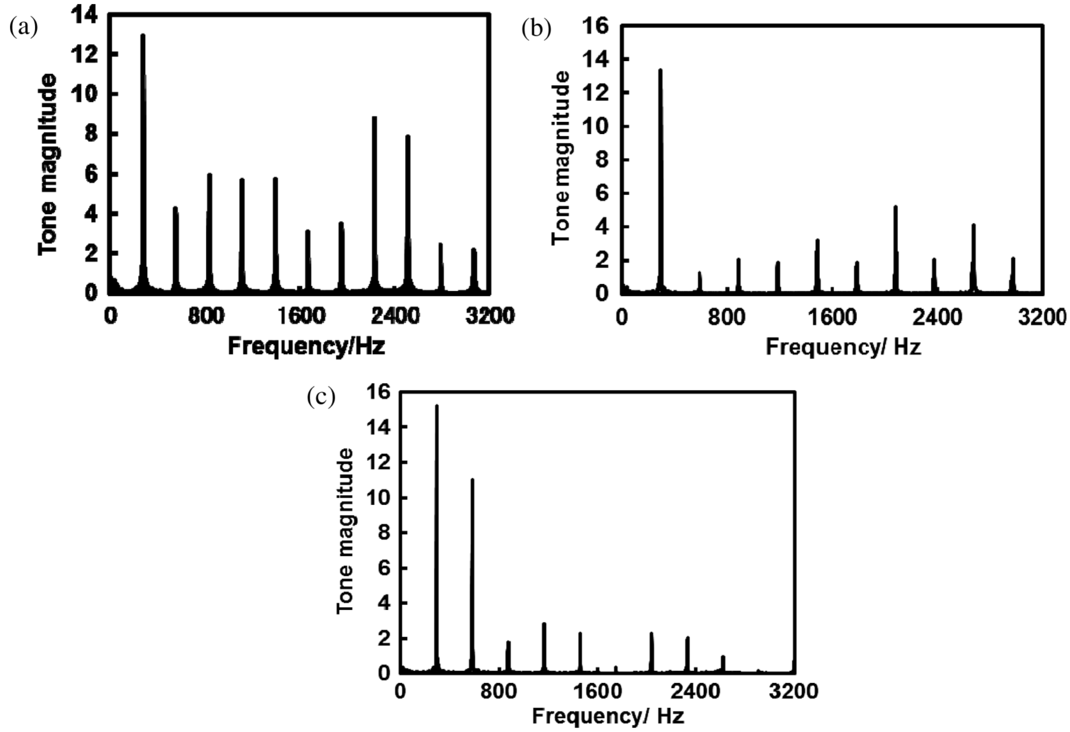

FIG. 3. Power spectrum reflecting the tone magnitude obtained by a Fourier transformation of the sound-wave signals. The frequency of the fundamental tone was 293 Hz. (a) Spider string. (b) Steel string. (c) Gut string.

the sounds ascribed to spider silk strings were the fittest among the four kinds of strings for the Gillott. On the other hand, it was found that the timbre of the common violin using spider strings was in no way inferior to that of the violin by Antonio Stradivari using conventional strings and also suggested that using spider strings could change not only the timbre but also the music itself.

The properties of spider violin strings can be ascribed to their elasticity, high modulus, and mechanically high strength that are characteristic of spider silk. It is necessary to lengthen the elastic region, since the elasticity is closely related to the favorable vibration. It is preferable that the tensile strength should be within the elastic limit in order to avoid the breaking of strings when playing. Thus, it is necessary to increase the elastic limit strength of strings as much as possible. In the present study, an increase in the elastic limit strength and the elastic region was accomplished by twisting for maximizing the density of strings.

It is possible to enlarge the elastic limit strength and elastic modulus of the strings if openings among filaments could be reduced by optimizing the packing structure of the filaments. Spider strings with a number of openings are mechanically weak, since thin filaments among a number of filaments are apt to break in succession. Even if several filaments of 9000 filaments constituting spider strings with no openings are broken down, on the other hand, the other filaments constituting the strings are mechanically strong [13], since the strings, as a whole, are able to resist against the stretching force. Especially, spider strings are very strong for slip of filaments, since the planes of polygonal filaments contact each other. Moreover, the softer and profound timbre of spider strings may be due to the inharmonicity at high frequencies, which depends not only on the elasticity and high modulus but also on the dense polygonal packing of a number of fine filaments. Thus, spider strings appropriate for the violin may be due to the pressure depending on the number of twists of bundles.

Sound-wave signals are affected by a combination of factors such as bow pressure, bow velocity, and distance from the bridge [39]. Since overtones were observed when the string was bowed, it was necessary in the present experiments to draw the bow under fixed conditions. It has been reported that inharmonicity related to the overtone magnitude is preferable for players [29], indicating that a number of overtones at high frequencies is optimal.

The inharmonicity f_n/nf_1 of the nth harmonic f_n is given by the following equation [21]:

$$f_n/nf_1 = (1 + Bn^2)/(1 + B). \tag{2}$$

Here, $B = 8\pi^3 Ed^4/TL^2$, d is the diameter of the string, L is the effective length, E is the elastic modulus, and T is the applied tension. The inharmonicity was evaluated by comparing the value of Ed^4 when T and L were the same for all strings. The elastic modulus was determined as 2.16 GPa for an A gut string of 740 μm thickness and 5.9 GPa for a spider string of 700 μm thickness. As a result, the inharmonicity of spider strings was much larger than that of gut strings.

In summary, it is considered that spider strings are appropriate materials for the violin because of their excellent mechanical properties. In the present study, several professional violinists reported that spider strings which showed high signal peaks of many overtones at high frequencies generated a preferable timbre, being able to create new music. This evaluation may be ascribed to the twisting of bundles which provides a unique packing structure of the dragline filaments constituting the strings, even though the mechanism for nonlinear deformation ascribed to the twisting is not clear and the relationship between the packing structure and acoustic properties is not also established scientifically. Future work will focus on making clear the mechanism for the polygonal packing and the details of the relationship between the timbre and the polygonal packing.

Finally, spider draglines may be appropriate materials that are sensitive to the vibrations related to music, since spiders are able to notice the presence of insects by their vibrations when captured on orb webs [40]. Violin strings are a novel practical use for spider silk as a kind of high value-added product and offer a distinctive type of timbre for both violin players and music lovers worldwide. To date, on the other hand, it has been impossible to change the cross section shapes of filaments except for a plastic cast at high temperatures. Here, the main point is that it was possible to change the cross section shape of dragline filaments by using pressure and also to achieve a unique packing structure. This result provides valuable knowledge for developing new types of materials, including composites with a unique packing structure.

I thank the violinist J-I. Matsuda (Osaka College of Music, Osaka, Japan), for comments on evaluating the timbre from a musical point of view.

[1] F. Vollrath, Int. J. Biol. Macromol. **24**, 81 (1999).
[2] D. Kaplan, W. W. Adams, B. Farmer, and C. Viney, *Silk Polymers*, ACS Symposium Series 544 (American Chemical Society, Washington, DC, 1994).
[3] J. Perez-Rigueiro, M. Elices, J. Llorca, and C. Viney, J. Appl. Polym. Sci. **82**, 2245 (2001).
[4] S. Osaki and R. Ishikawa, Polym. J. **34**, 25 (2002).
[5] S. Osaki, Acta Arachnol. **37**, 69 (1989).
[6] S. Osaki, K. Yamamoto, A. Kajiwara, and M. Murata, Polym. J. **36**, 623 (2004).
[7] S. Osaki, Polym. J. **36**, 657 (2004).
[8] S. Osaki and M. Osaki, Polym. J. **43**, 200 (2011).
[9] M. B. Hinman, J. A. Jones, and R. V. Lewis, Trends Biotechnol. **18**, 374 (2000).
[10] A. Lazaris, S. Arcidiacono, Y. Huang, J.-F. Zhou, F. Duguay, N. Chretien, E. A. Welsh, J. W. Soares, and C. N. Karatzas, Science **295**, 472 (2002).
[11] C. W. P. Foo and D. L. Kaplan, Adv. Drug Delivery Rev. **54**, 1131 (2002).
[12] T. Scheibel, Microb. Cell Fact. **3**, 14 (2004).
[13] S. Osaki, Nature (London) **384**, 419 (1996).
[14] S. Osaki, Polym. J. **35**, 261 (2003).
[15] S. Osaki, Nature (London) **347**, 132 (1990).
[16] S. Osaki, Rev. Sci. Instrum. **68**, 2518 (1997).
[17] S. Osaki, Anat. Rec. **254**, 147 (1999).
[18] S. Osaki, Polymer Preprints, Japan **55**, 1844 (2006).
[19] N. C. Pickering, J. Catgut Acoust. Soc. **44**, 6 (1985).
[20] N. C. Pickering, J. Catgut Acoust. Soc. **46**, 2 (1986).
[21] I. Firth, J. Catgut Acoust. Soc. **47**, 17 (1987).
[22] C. V. Raman, Philos. Mag. **32**, 391 (1916).
[23] N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments: Bowed STRING Instruments* (Springer, New York, 1988).
[24] H. L. F. Helmholtz, *On the Sensations of Tone (1877)*, translated by A. J. Ellis (Dover, New York, 1954).
[25] K. N. Goydke, E. Altenmüller, J. Möller, and T. F. Münte, Cogn. Brain Res. **21**, 351 (2004).
[26] T. Meyer, in *Proceedings of SMAC 83* (Royal Swedish Academy of Music, Stockholm, 1983).
[27] J. W. S. Hearle, P. Grosberg, and S. Backer, *Structural Mechanics of Fibers, Yarns, and Fabrics* (Wiley-Interscience, New York, 1969), Vol. 1.
[28] A. D. Parkh, S. K. Seeley, K. Gardner, L. Thompson, and R. V. Lewis, J. Mol. Recognit. **10**, 1 (1997).
[29] J. D. Beek, S. Hess, F. Vollrath, and B. H. Meier, Proc. Natl. Acad. Sci. U.S.A. **99**, 10 266 (2002).
[30] M. Gardner, *Penrose Tiles to Trapdoor Ciphers* (Freeman, New York, 1989).
[31] D. Shechtman, I. Blech, D. Gratias, and J. W. Cahn, Phys. Rev. Lett. **53**, 1951 (1984).
[32] J. L. Peter and P. J. Steinhardt, Science **315**, 1106 (2007).
[33] S. Torquato and Y. Jiao, Nature (London) **460**, 876 (2009).
[34] H. Hertz, J. Reine Angew. Math. **92**, 156 (1881).
[35] J. E. Shigley and C. R. Mischke, *Mechanical Engineering Design* (McGraw-Hill, New York, 1989), 5th ed., Chap. 2.
[36] S. L. Phoenix, Tex. Res. J. **49**, 407 (1979).
[37] P. K. Porwal, I. J. Beyerlein, and S. L. Phoenix, J. Mech. Mater. Struct. **1**, 1425 (2006).
[38] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.108.154301 for audio files of a program (Tchaikovsky's Violin Concerto in D-major, from the second movement) played by using Dancing Master's Violin 1720 "Gillott" in which steel, nylon, gut, or spider silk strings for A, D, and G were set.
[39] A. Askenfelt, STL-QPSR **36**, 23 (1995).
[40] W. A. Shear, *SPIDERS Webs, Behavior, and Evolution* (Stanford University, Stanford, CA, 1986).