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A Comparative Mechanical Analysis of the Pointe Shoe Toe Box

An In Vitro Study

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ABSTRACT

Dancing en pointe requires the ballerina to stand on her toes, which are protected only by the pointe shoe toe box. This protection diminishes when the toe box loses its structural integrity. The objectives of this study were 1) to quantify the comparative structural static and fatigue properties of the pointe shoe toe box, and 2) to evaluate the preferred shoe characteristics as determined by a survey of local dancers. Five different pointe shoes (Capezio, Freed, Gaynor Minden, Leo's, and Grishko) were evaluated to quantify the static stiffness, static strength, and fatigue properties (cycles to failure) of the shoes. Under axial loading conditions, the Leo's shoe demonstrated the highest stiffness level, and the Freed shoe exhibited the least strength. Under vertical loading conditions, the Leo's and Freed shoes demonstrated the highest stiffness levels, and the Gaynor Minden and Freed shoes exhibited the highest strength. Fatigue testing highlighted the greatest differences among the five shoes, with the Gaynor Minden demonstrating the highest fatigue life. Dancers rated the top five shoe characteristics, in order of importance, as fit, comfort, box/platform shape, vamp shape, and durability and indicated that the "best" shoe is one that "feels right" and permits artistic maneuvers, not necessarily the strongest or most durable shoe.

Appreciated for the artistry, grace, and elegance of the dancers, ballet is an art form that makes immense physical demands on the body while requiring the production of aesthetic and graceful movements. From the 1581 introduction of ballet at the French Court (attributed to Catherine de Medici), the popularization of this art form by Louis XIV, and the 1661 creation of the Academie Royale de Danse,[2] the technique of ballet has become more demanding, requiring refinement of the dancer's strength, technique, and tools. This was highlighted by Marie Taglioni, who, in 1832, was the first to dance en pointe. This was originally done with soft satin slippers containing a leather sole. As pointe technique developed, the shoe also evolved to allow the ballerina to perform more exacting maneuvers. In time, the shanks became harder, the boxes became stronger, and the toe platform became wider.

When dancing en pointe, today's ballerina stands on her toes with little more than a papier-mâché or cardboard shell to protect her forefoot. The pointe shoe, made up of the toe box, shank, and the outer material, is one of the most important tools of the dancer. The outer material is usually a soft, cotton-backed cloth called corset satin. The pointe material provides a relatively low-friction surface to permit spins while allowing for sufficient "grip" during standing or jumping. Although it is fairly durable, this covering will wear out, usually over the toe platform, and replacement will be necessary. The conical toe box consists of layers of burlap, cardboard, or paper, or a combination thereof, that have been saturated with glue.[3] It tightly surrounds the toes so that the dancer's weight rests on the platform. The shank, made up of cardboard, leather, or a combination of the two, also helps to support the foot while en pointe by providing a certain degree of stiffness. The breaking-in process of the toe box softens the cardboard and conforms the shoe to the foot, but destroys the glue bonds. The optimum toe box shape lasts for only a short

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period because of the rigors of the performance. Once the toe box loses its structural integrity and becomes too soft to adequately support and protect the foot, the shoes are usually discarded.[4]

To date, most of the research interest surrounding the pointe shoe is directed toward the prevention of dance injuries[1,5] and augmentation of pointe shoes with shoe orthoses,[7] as well as determining the toe pressures generated while dancing en pointe.[9,10] However, no studies have quantitatively assessed the comparative intrinsic mechanical properties of different pointe shoes. Therefore, the objective of our current research project was twofold: 1) to compare and evaluate the structural static and fatigue properties of five different types of pointe shoes, and 2) to evaluate the preferred shoe characteristics as determined by a survey of the local dance population to compare the relationship between mechanical properties and choice of shoe.

MATERIALS AND METHODS

Shoe Types and Sizes

A total of five different brands of pointe shoes were evaluated: the Ariel (Capezio, Totowa, New Jersey), Chacott (Freed, New York, New York), Gaynor Minden (Gaynor Minden, Inc., New York, New York), Leo's (Leo Dancewear, Chicago, Illinois), and Fouetté (Grishko Ltd., Villanova, Pennsylvania). The shoes were obtained from local distributors with the understanding that they would be used for research purposes. The shoe size requested for testing was standardized and equal to a size 6½ to 7 street shoe (Fig. 1). The shoes were delivered in their normal packaging materials, and any shoes found damaged or defective on receipt were returned to the manufacturer with a request for replacement. The shoes were carefully removed from the packaging, separated, and randomly labeled according to the mechanical test to be performed.

Calculation of Toe Box Dimensions

Before mechanical testing, the toe box outer dimensions and inner volume were calculated for correlation to the mechanical properties of peak toe box stiffness (in kilonewtons per meter) and strength (in newtons). Using Vernier calipers, the outer dimensions of toe box depth, height, and width were measured as follows: depth, the distance from the vamp edge to the tip of the toe box; height, the distance from the sole of the toe box to the top of the vamp; width, the side-to-side distance across the toe box (Fig. 2). For toe box volume calculation, we poured a known quantity of polymethyl methacrylate beads (200-μm diameter, Polysciences, Inc., Warrington, Pennsylvania) from a 250-mm graduated cylinder into the pointe shoe, leveled the beads at the vamp edge, and calculated the difference in cylinder volume.

Mechanical Analysis

Mechanical analysis of the pointe shoes was performed using a servohydraulic MTS 858 Bionix testing device (MTS Systems Inc., Minneapolis, Minnesota). Using an MTS interface cable, load-displacement data acquisition was performed through an analog-to-digital DAS16G Metrabyte board (Metrabyte Corp., Taunton, Massachusetts) interfaced with an IBM 486 PS/2 (IBM Inc., Armonk, New York). All data files were downloaded into Lotus 1·2·3 (Lotus Development Corp., Cambridge, Massachusetts) for spreadsheet computational data analysis. Testing of the pointe shoes was performed under both static and dynamic testing conditions. All shoes were unused before testing and were not retested.

Static Testing Conditions

Static testing quantified the ultimate compressive strength and stiffness of the pointe shoe toe box with respect to the applied load under conditions of vertical and

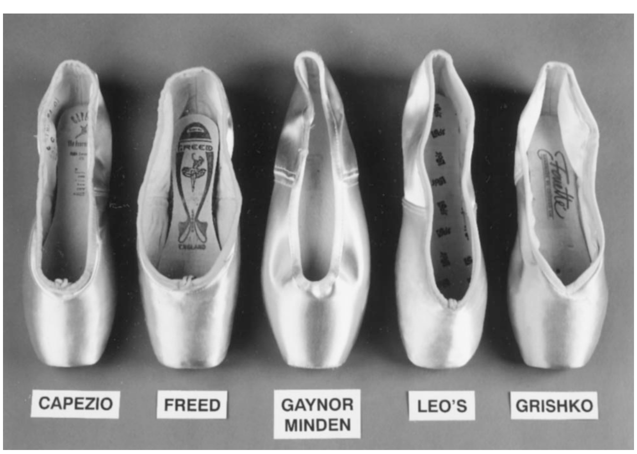

Figure 1. Five different brands of pointe shoes were evaluated: Capezio, Freed, Gaynor Minden, Leo's, and Grishko. All shoes were unused before mechanical testing and were not retested.

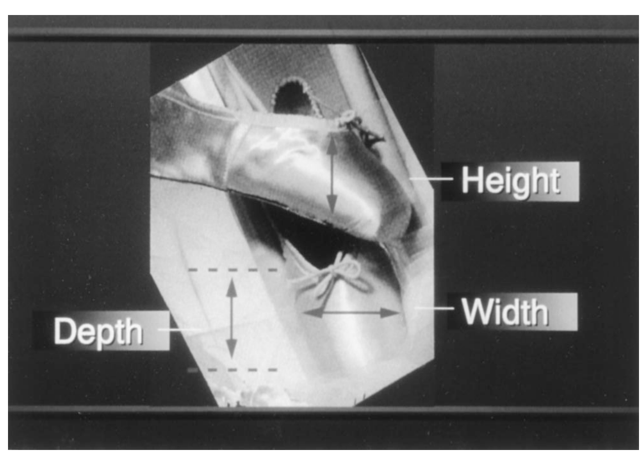

Figure 2. Before mechanical testing, the toe box outer dimensions and inner volume were calculated for relationship to the mechanical properties of peak toe box stiffness and strength.

axial shoe alignment. Static analysis for both axial and vertical tests was performed under displacement control at a constant rate of 0.5 mm/sec. Using a 2-inch-diameter cylindrical steel ram with a flattened bottom, the load was applied to the toe box until failure occurred. Peak failure was defined as a significant and consistent decrease in the registered load or collapse of the toe box by 7 mm (an arbitrarily chosen point), whichever came first. For axial loading conditions ($N = 5$), the toe box was positioned using C-clamps so that the applied load originated at the tip of the toe box and was directed along the shank axis, as occurs when the ballerina is en pointe. The cylindrical ram completely covered the tip of the toe box. For vertical loading ($N = 5$), the shoe was mounted on the MTS load cell horizontally so that the applied load was delivered to the distal plantar surface of the toe box, as occurs when the ballerina is in the demi-pointe position (Fig. 3).

Cyclical Fatigue Testing Conditions

Dynamic testing of the pointe shoes highlights the fatigue properties (cycles to failure) of the toe box under repetitive loading conditions. Setup of the pointe shoe toe box for fatigue testing was identical to that used for static axial loading conditions. Testing was performed using a cyclic loading rate of 10 Hz, a load level of 2 kN, and an R ratio (minimum stress:maximum stress)[6] of 0.1, so that the applied load cycled between −200 and −2000 N. Fatigue failure was defined as collapse of the toe box by 7 mm.

Pointe Shoe Cost Analysis and Dancer Questionnaire

The local suppliers of pointe shoes provided retail cost information for each of the five shoe types. A dancer questionnaire was distributed to 200 ballet dancers from nearby colleges and dance programs. Those participating in the study (average age, 19.3 ± 0.25 years) averaged 11.27 ± 0.66 years of ballet experience. Most of the students surveyed were primarily interested in ballet with secondary interests in jazz. The questionnaire was designed to evaluate the medical history of each dancer, the dancer's training in all forms of dance, and the preferred characteristics of the pointe shoe selected (Table 1).

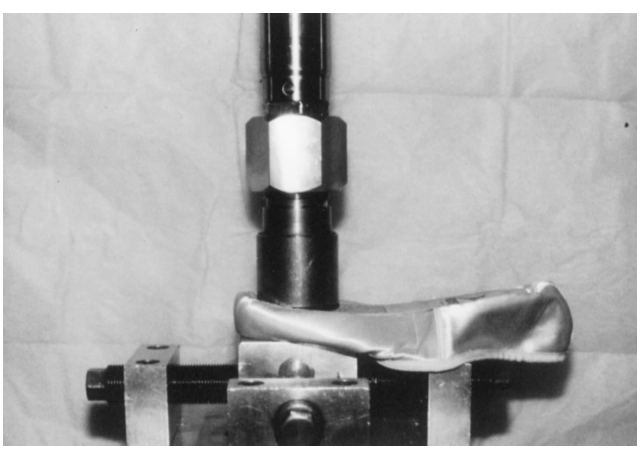

Figure 3. A view of the pointe shoe oriented for vertical compressive loading. The applied load was delivered to the distal plantar surface of the toe box.

Data and Statistical Analyses

Stiffness calculations represent the peak load divided by the corresponding displacement within the first 2 mm for axial loading and within the first 5 mm for vertical loading. Strength values represent the peak load (in newtons) within the first 7 mm of displacement for both axial and vertical loading. Statistical analyses of the mechanical data included descriptive statistics, a one-way analysis of variance (ANOVA), and a post hoc Student-Neuman-Keuls procedure for multiple comparisons between groups (statistical significance was indicated at $P < 0.05$). Unless otherwise noted, data are represented as mean values plus or minus the standard deviation. The pointe shoe toe box dimensions were considered in relation to the mechanical parameters using linear regression analysis.

RESULTS

Pointe Shoe Dimensions

Area computations calculated from the toe box height, width, and depth of the five pointe shoes were similar, but volume computations were somewhat different, particularly when comparing the Gaynor Minden with the Leo's pointe shoes. The thickness of the layers in the toe box may contribute to the volume variation (Table 2).

Mechanical Analysis

Static Analysis. Axial compressive stiffness comparisons indicated that the Leo's pointe shoe was the stiffest and was statistically different ($P < 0.05$) compared with the four other shoes. There were no differences between the Capezio and Freed or the Gaynor Minden and Grishko ($P > 0.05$) pointe shoes in axial compressive stiffness, but the differences in all remaining comparisons were statistically significant (Fig. 4). The peak axial compressive strengths exhibited by the pointe shoes were not as sig-

TABLE 1
Pointe Shoe Selection Criteria: Top 12 Characteristics in Order of Preference Based on Dancer Questionnaire

Rank	Characteristic
1	Fit
2	Comfort
3	Box/platform shape
4	Vamp shape
5	Durability
6	Shank style
7	Breaks in quickly
8	Heel depth
9	Price
10	Availability
11	Drawstring location
12	Color

TABLE 2
Pointe Shoes: Area and Volume Calculations

Shoe type and size	Width (mm) (Mean ± SD)	Height (mm) (Mean ± SD)	Depth (mm) (Mean ± SD)	Volume (ml) (Mean ± SD)
Capezio 4-½ C	70.60 ± 0.55	51.68 ± 0.64	51.50 ± 0.87	69.20 ± 5.02
Freed 4 X	70.00 ± 2.45	49.55 ± 2.37	44.13 ± 5.02	52.75 ± 13.79
Gaynor Minden 7 W	77.00 ± 0.00	50.00 ± 1.41	60.00 ± 2.83	68.00 ± 0.00
Leo's 4-½ D	64.40 ± 1.34	53.54 ± 1.57	42.04 ± 2.67	45.80 ± 3.77
Grishko 4 M	73.80 ± 1.10	55.80 ± 0.84	52.80 ± 2.05	75.80 ± 2.86

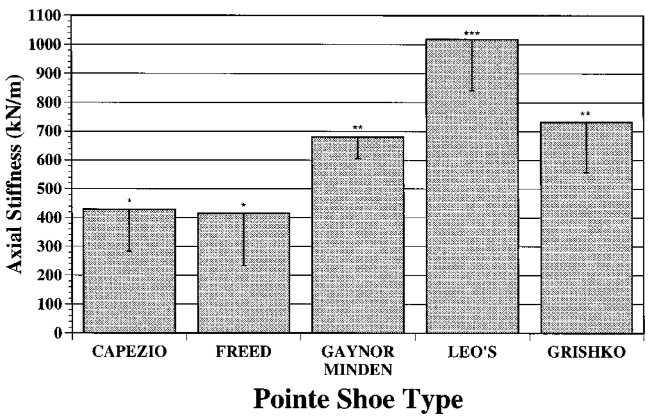

Figure 4. Axial compressive stiffness levels of the five toe boxes demonstrated that the Leo's shoe had the greatest stiffness and was significantly different from the other four shoes ($P < 0.05$). There was no statistically significant difference between bars with an equal number of asterisks (*). All other comparisons were statistically significant at $P < 0.05$ (one-way ANOVA, $F = 12.74$, $P < 0.001$). The error bar signifies 1 SD.

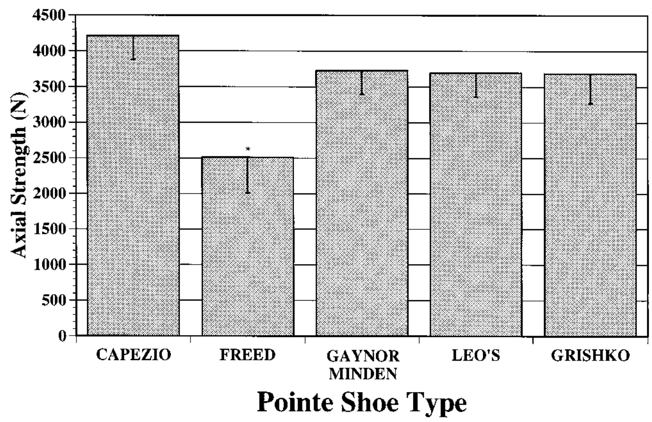

Figure 5. The axial compressive strength levels of the five shoe types were compared. The Freed shoe demonstrated significantly lower strength levels than the other four shoes ($P < 0.05$). The Capezio demonstrated the greatest axial strength, but it was not significantly different from that of the Gaynor Minden, Leo's, or Grishko shoes (one-way ANOVA, $F = 17.90$, $P < 0.001$). The error bar signifies 1 SD. An asterisk (*) indicates statistical significance ($P < 0.05$).

nificantly different as the peak axial compressive stiffnesses. The Freed shoe demonstrated strength levels that were significantly less than the four remaining shoes (Fig. 5). The Capezio demonstrated the highest level of axial strength, but the difference compared with the Gaynor Minden, Leo's, or Grishko shoe was not significant.

Vertical loading of the pointe shoes resulted in stiffnesses and strength levels much lower than the corresponding axial tests. The Freed shoe exhibited the highest vertical stiffness level, and was significantly different from the remaining four shoes ($P < 0.05$). The Leo's shoe was significantly different from the Gaynor Minden, but neither was significantly different from the Grishko or Capezio (Fig. 6). Peak vertical strengths exhibited by the five shoes demonstrated trends opposite to those in the stiffness levels. For example, the Gaynor Minden, which had the lowest vertical stiffness, demonstrated the highest level of vertical strength. Both the Freed and Gaynor Minden shoes, although not significantly different from each other, were significantly different from the Capezio, Leo's, and Grishko pointe shoes ($P < 0.05$), which demonstrated similar peak strengths under this vertical loading condition (Fig. 7).

The predominant failure mechanism, exhibited by all pointe shoes under both axial and vertical static testing, was buckling of the toe box tip in on itself (Fig. 8). When compared with pointe shoe failure mechanisms observed in actual ballet shoes, the failure patterns generated under benchtop laboratory conditions appeared grossly similar, despite the in vitro loading condition.

Cyclical Fatigue Analysis. Fatigue testing of the pointe shoes at the 2-kN load level demonstrated highly significant differences among the five shoe types, particularly when comparing the Gaynor Minden with the remaining shoes ($P < 0.05$). As indicated by the number of cycles required for shoe failure, the Gaynor Minden demonstrated more resiliency under conditions of repetitive loading; the Capezio, Freed, Leo's and Grishko shoes exhibited lower thresholds of elastic deformation, resulting in relatively quick plastic (permanent) shoe deformation under the applied load. The mean cycles at failure for the Gaynor Minden was statistically higher ($P < 0.05$) than those for the other shoes, which were not different from each other (Fig. 9).

Regression Analysis. The purpose of the volume and stiffness calculations was to relate the dimensional and mechanical properties of the shoes with the peak failure strengths exhibited by the different shoes. For axial loading, significant predictive value was found when the Leo's

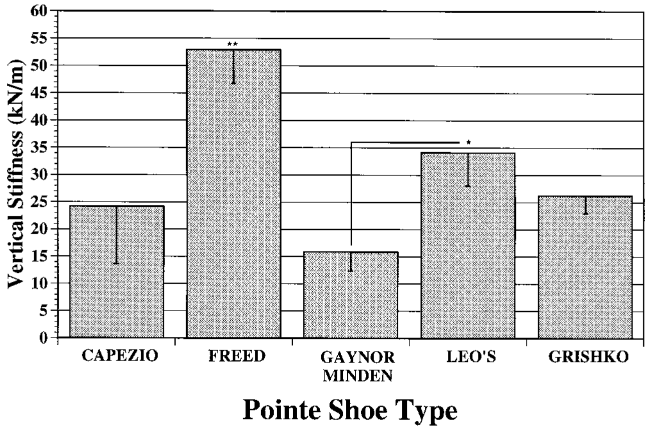

Figure 6. The Freed shoe demonstrated greater vertical compressive stiffness levels than the other four shoes ($P < 0.05$). The Leo's shoe was significantly different from the Gaynor Minden ($P < 0.05$), but neither was significantly different from the Grishko or Capezio (one-way ANOVA, $F = 21.46$, $P < 0.001$). The error bar signifies 1 SD. The double asterisk (**) indicates a statistically significant difference in comparison with all the other shoe types. The single asterisk (*) indicates statistical significance ($P < 0.05$) in comparison of the Leo's shoe with the Gaynor Minden shoe.

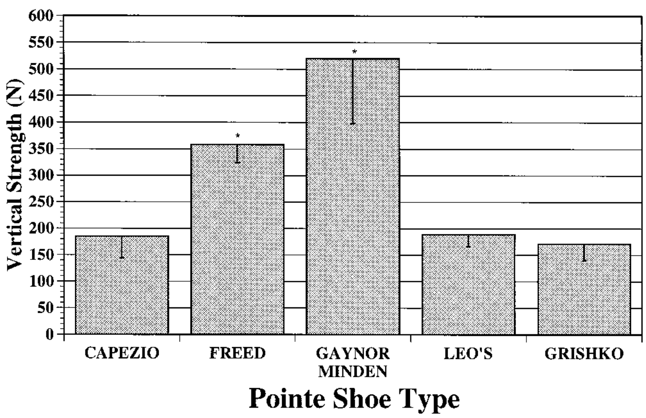

Figure 7. Vertical strength levels for the five shoes demonstrated trends opposite to those for stiffness levels. The Gaynor Minden and Freed shoes demonstrated the greatest vertical strength and were significantly different from the Capezio, Leo's, and Grishko shoes ($P < 0.05$; one-way ANOVA, $F = 26.49$, $P < 0.001$). The error bar signifies 1 SD. An asterisk (*) indicates statistical significance ($P < 0.05$).

peak strengths (failure loads) were compared with the stiffnesses exhibited by the same toe box ($r^2 = 0.94$) (Table 3). This significance in predictive value was found only in the Leo's shoe under axial loading conditions.

Dancer Questionnaire

According to questionnaire responses, ballet training averaged 11 ± 0.66 years with an average of 6 ± 0.44 years

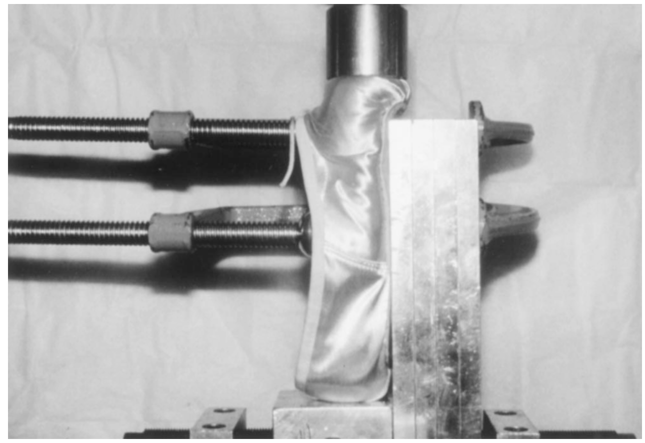

Figure 8. A lateral view of the secured pointe shoe toe box at the endpoint of the destructive axial compressive loading test using a cylindrical steel ram.

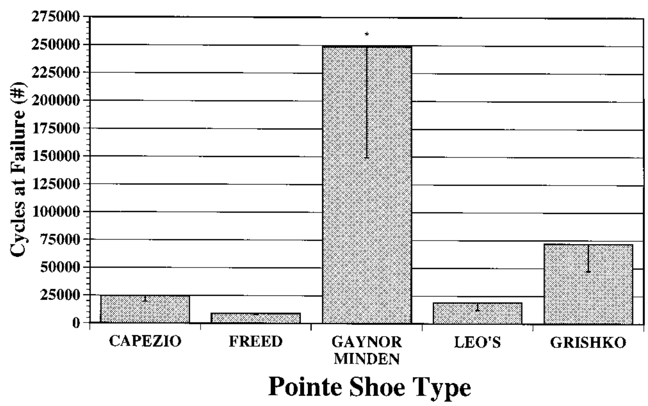

Figure 9. Cyclical fatigue testing at the 2-kN load level demonstrated differences between one shoe type and the other four. The mean number of cycles to failure for the Gaynor Minden shoe was significantly higher ($P < 0.05$) than for the other four types, which were not significantly different from each other (one-way ANOVA, $F = 14.30$, $P < 0.001$). The error bar signifies 1 SD. An asterisk (*) indicates statistical significance ($P < 0.05$).

of pointe work, jazz training averaged 4.5 ± 0.64 years, and modern dance training averaged 3.5 ± 0.48 years. The dancers spent an average of 59% (±0.035 SEM) of their training time in ballet, 31% (±3.5 SEM) in modern dance, and 4% (±1.4 SEM) in jazz. The pointe shoes worn included Capezio (33%), Chacott (32%), Bloch (26.5%), Freed (10%), and Gaynor Minden (6%). The top five preferred characteristics of pointe shoes selected were fit, comfort, box/platform shape, vamp shape, and durability (Table 1).

DISCUSSION

The modern pointe toe shoe must be able to provide support and protection whether the dancer is en pointe, in a demi-pointe position, or performing a jump.[2] The shoe

TABLE 3
Linear Regression Analysis (r^2) Comparing Pointe Shoe Dimensional and Mechanical Properties with Peak Failure Strengths

Shoe type	Loading mode			
	Axial		Vertical	
	Volume vs strength	Stiffness vs strength	Volume vs strength	Stiffness vs strength
Capezio	0.35	0.02	0.27	0.71
Freed	0.41	0.43	0.12	0.61
Gaynor Minden	0.59	0.34	0.54	0.73
Leo's	0.62	0.94[a]	0.82	0.67
Grishko	0.59	0.60	0.71	0.91

[a] Significant predictive value.

must add to the aesthetics of dance by enhancing the conical shape of the leg while providing for a quiet landing. The distal portion of the pointe shoe box, composed of layers of burlap, cardboard, or papier-mâché, contains the toes by bunching them into an oval platform. The hard material in the box also functions to absorb the forces to which the foot is subjected. A stiff shank, or insole, supports the arch while the outer sole allows for flexibility. Recently, shoe manufacturers have been developing composite toe boxes in an attempt to improve the mechanical properties of the shoes. An ideal shoe material would preserve the appropriate properties of the shoe while promoting the proper "feel"—the proprioceptive relationship between the foot and the floor.

The current study sought to define the intrinsic mechanical properties of various pointe shoes and relate these results to the actual physical characteristics of the shoe as well as to those identified as important by the local dance population. The mechanical testing methodology, using both static and dynamic testing conditions to assess these properties, represents a best- and worst-case scenario for the pointe shoes tested: the shoes were unused (that is, not deformed) before testing, and they remained empty (that is, they received none of the internal support normally provided by the foot and toes). In addition, C-clamps were used for stabilization, and the shoes were deformed using a steel ram.

In lieu of testing every shoe size, we selected size 6½ to 7 as a representative size, assuming that the results obtained with this size would accurately represent the mechanical trends produced across the board, despite shoe size. The shoe dimensions were similar, although the toe box volumes were not. The variation in shoe volume is most likely attributable to the material type, thickness, and layering within the inner regions of the toe box. Despite these intrinsic variations, there was no demonstrable relationship between toe box geometric/dimensional characteristics and mechanical performance under in vitro loading conditions. Of the four parameters studied for axial and vertical testing conditions among the five different pointe shoes, only the difference between shoe stiffness and failure strength under axial loading in the Leo's shoe was significant (Table 3).

In this study, we began the process of defining the mechanical characteristics of some of the major brands of pointe shoes. The toe box, which plays an important role in protecting the toes—a common site of injury and deformity in dancers[4]—was mechanically evaluated under both static and dynamic conditions. Static testing yielded significant differences among the various shoes tested. The stiffness calculation represents the initial rigidity of the box; strength represents the overall toe box stability. The axial loading parameter represented the mechanical condition to which the shoe is subjected when en pointe, whereas vertical loading reproduced that in the demi-pointe position. A limitation to the axial loading parameter is that it is constrained to one axis—the long axis of the shank. As previously determined, the loads generated are multiple and in many directions as the ballerina works through the toe box to rise en pointe.[10]

The static testing demonstrated large variations when comparing the axial and vertical results. The shoes were significantly stiffer and stronger under axial loading than under vertical loading conditions (Figs. 5 to 8), highlighting the importance of foot and ankle support when en pointe versus when standing in demi-pointe. The plantar surface of the foot inherently allows for greater distribution of the pressure encountered; consequently, increased shoe flexibility is necessary. However, when en pointe, more support (that is, higher stiffness and strength) is required. All of the shoes tested demonstrated their peak stiffnesses and strengths within the 7-mm displacement range. This arbitrarily chosen peak-displacement end point represented what we considered failure of the toe box in the dance environment.

Fatigue testing of the shoes demonstrated one highly significant difference. The Gaynor Minden pointe shoe exhibited a fatigue range approximately 10 times higher than that of the other shoes tested. The static properties of the Gaynor Minden shoe were not so inordinately high as to predict the correspondingly high fatigue properties. The Gaynor Minden uses a patented design in the shank and toe box. The toe box is formed from an elastomeric material sandwiched between layers of shock-absorbing foam. In contrast, the Capezio, Freed, Leo's, and Grishko toe boxes are composed of materials such as burlap, cardboard, or paper— or some combination thereof—saturated with glue. The high threshold of elastic limitation, evident by the long fatigue life, presents itself as the distinguishing mechanical characteristic of the Gaynor Minden pointe shoe.

All pointe shoes demonstrated compressive strengths less than 4300 N. Based on theoretical applications using the impulse-momentum method, it is estimated that a

60-kg ballerina landing en pointe from a height of 1 meter generates an impact force of approximately 4950 N, with impact pressures exceeding 700 psi.[8] Therefore, in and of itself, the pointe shoe toe box is not able to protect the toes when en pointe, regardless of the shoe type. This emphasizes the existence of a load-sharing relationship between foot mechanics and strength and the intrinsic mechanical properties of the pointe shoe.

Based on the dancer questionnaire, the most durable or mechanically sound pointe shoe is not always the preferred shoe (Table 1) — despite the fact that a ballerina at the height of her career might wear out 65 pairs of pointe shoes a month.[4] However, the ideal shoe must first address the issues of fit and comfort. In effect, the durability factor is correctly positioned as the fifth most important requirement because all shoes evaluated in the current study were mechanically inadequate to fully endure the stresses engendered during dance. Hence, there must exist a load-sharing relationship between the foot and shoe, and this relationship appears best optimized with a shoe that simply offers the best fit and comfort. The combined aspects of an uninjured, strong foot and form-fitting shoe provide the best ingredients for success of both the dancer and shoe.

This study provides an objective assessment of the mechanical performance of pointe shoes and how this relates to the needs of the dancers. Moreover, this serves as a first step in evaluating pointe shoes, providing the dancer with an understanding of the comparative mechanical properties of the shoes and, most important, emphasizes that the best shoe is not always the strongest. In conclusion, this investigation establishes a consistent, necessary methodology for the mechanical evaluation of the pointe shoe toe box. Based on the current study, the intrinsic mechanical properties of stiffness, strength, and fatigue life are variable, depending on shoe type, and there exists no reliable predictive relationship between shoe dimensional and mechanical properties. Most important, the results of this study indicate the need for an optimal load-sharing environment between pointe shoe and the foot and ankle, regardless of the pointe shoe used.

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