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The repeatability of testing with Semmes-Weinstein monofilaments

Forty-one filament kits were measured for filament application force, single and multitester application force repeatability, and comparison of filament repeatability with that of other hand held instruments. Results of this study show that if their lengths and diameters are correct, the filaments produce application forces that are repeatable within a predictable range. All hand held instruments vary in application force. The Semmes-Weinstein monofilaments vary relatively little and are a controlled reproducible force stimulus for use in clinical testing. (J HAND SURG 1987;12A:155-61.)

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Monofilament testing for peripheral nerve sensory function has been used more frequently and with renewed interest as the need for screening and monitoring peripheral nerve function has increased. Recent studies have shown the filaments to be a sensitive monitor of peripheral nerve function.[1, 2] However, the instrument originally described by von Frey[3] has undergone several changes in becoming the instrument available today, and the repeatability and reliability of the filament tests have fallen into question.

In the 1800's von Frey's focus was on the study of normal physiology; therefore, the horsehairs he used were designed to measure only light thresholds of touch recognition. It took the work of Semmes[4] and Weinstein[5] to develop the broad range of filament forces that are available today and the work of later investigators, beginning with von Prince,[6] to further refine the method for peripheral nerve testing.

Semmes and Weinstein needed a broader range of forces for their studies than those that were available with horsehairs. They designed and developed nylon monofilaments of increasing diameters set at right angles in acrylic resin (Lucite) rods (Research Designs, Inc., Houston, Texas, and North Coast Medical, Cambell, Calif.). They did not intend to provide specific measurable thresholds of force or stress but a relative range of progressive pressures. They described a relationship, as did von Frey, in which the ordinal rank of the filaments arranged according to their diameters resulted in progressive increases in pressure. To deal with the data statistically, they expressed the values as log (10 $\times$ force in mg) and indexed the filaments by numbers derived from this log scale.

When the filaments were used in subsequent studies by other investigators the index numbers became a source of confusion. Some authors reported the index numbers as forces in grams. While this error was beginning to be recognized, it was crystallized in a study by Levin, Pearsall, and Ruderman,[7] who republished the original forces calculated from the log formula, along with their measured forces from examining two filament kits. Having examined column buckling equations they suggested that stress, which is force/unit area, is the more appropriate variable for measuring pressure sensibility.

The study by Levin and associates[7] inadvertently led several clinical examiners to believe the results of filament use were not as accurate and repeatable as had originally been intended. This study has, in addition,

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Table I. Application force of filaments in three mini kit test groups

Filament index number		*Mean*	*Average standard deviation*	*Standard deviation expressed as % of mean*
2.83	Group I	70.93 mg	5.32 mg	8
	Group II	67.28 mg	5.26 mg	8
	Group III	91.53 mg	4.64 mg	6
Overall		70.92 mg	5.21 mg	7
Corrected overall		72.01 mg	5.31 mg	7
3.61	Group I	201.06 mg	19.72 mg	10
	Group II	177.66 mg	16.91 mg	10
	Group III	201.13 mg	11.95 mg	6
Overall		185.86 mg	17.18 mg	9
Corrected overall		205.39 mg	19.32 mg	9
4.31	Group I	2.45 gm	0.15 gm	6
	Group II	2.23 gm	0.21 gm	9
	Group III	2.78 gm	0.13 gm	5
Overall		2.35 gm	0.19 gm	8
Corrected overall		2.35 gm	0.17 gm	7
4.56	Group I	4.99 gm	0.22 gm	4
	Group II	4.91 gm	0.33 gm	4
	Group III	4.75 gm	0.24 gm	5
Overall		4.91 gm	0.29 gm	6
Corrected overall		4.91 gm	0.29 gm	6
6.65	Group I	189.83 gm	11.09 gm	6
	Group II	201.33 gm	9.54 gm	5
	Group III	204.67 gm	10.43 gm	5
Overall		192.47 gm	10.87 gm	6
Corrected overall		192.22 gm	11.38 gm	6

Twenty-eight kits; each filament was applied 10 times and results averaged for a total of 280 applications. The SD of each filament's application force was calculated and expressed as a % of the mean. Among groups tested there was no significant difference of application force at the 0.05 level for the 2.83 filament, and at the 0.01 level for the 3.61 filament. Some differences great enough to be significant were found among the larger filaments, suggesting for optimum repeatability in clinical testing the same kit should be used to test the same patient.

been quoted by some clinicians as an argument against using the filaments in peripheral nerve testing in preference to other testing methods. Such criticism of an instrument, which otherwise seems to produce reliable repeatable clinical data, led us to examine the filaments more closely.

The formula to determine the stress (force/unit area) seems more specific than its accuracy when one realizes the filaments bend as their force is applied. The full "area" of the filament tip is not in contact with the skin being tested, but only a crescent-shaped edge. To be specific in measurements of stress produced by the instrument one would have to then calculate the edge of an area of a specific diameter filament that is being exerted by a specific force (at a given amplitude). It is no more accurate to refer to calculated stress than it is to refer to a specific force exerted with a specific length and diameter filament. Forces are more understandable to the practicing clinician and give an understanding of the numerical value of a specific filament so long as the length is constant, and diameters are known.

Von Frey had put a single tip on his filaments, but Semmes and Weinstein realized this was not possible in a broader range of forces. With a constant tip, a small diameter filament cannot produce a large diameter filament force (by being shortened) without at some point losing its buckling capacity. On the other hand, a large diameter filament with a constant tip cannot buckle to produce a light force.

The design of the filaments of constant length but increasing diameters to bend when a specific value is reached provides unique control. This design helps control the variables that occur with any hand held instrument. Any hand held instrument, used as a stimulus, carries with it the vibration of the examiner's hand and the variable application amplitude of the examiner. These variables, independent of the stimulus, exceed the normal touch recognition resolution of the cutaneous end organs and bombard them with stimuli at multiple frequencies. The bend of the filaments provides some control of the application amplitude and vibration. Even though the diameters must change to produce heavier

Table II. Range of filament forces

Filament index number	*Low*	*High*	*Mean*	*Diameter in inches*
2.83	0.058	0.97 gm	0.072	0.005
3.61	0.155	0.252 gm	0.205	0.007
4.31	1.85	2.53 gm	2.35	0.012
4.56	3.66	6.13 gm	4.91	0.014
6.65*	151	212 gm	192.22	0.045

The range of filament forces for each mini kit filament diameter was established by recording the lowest and highest occurring application force.
*In this test the 6.65 filament was not applied to bending.

Table III. Multitester filament application force repeatability

Filament number tester	*2.83 *ASD*	*†POM*	*3.61 ASD*	*POM*	*4.31 ASD*	*POM*	*4.56 ASD*	*POM*	*6.65 ASD*	*POM*
1	5.91	7	22.79	8	0.22	7	0.38	6	24.21	9
2	6.11	7	10.99	4	0.23	7	0.37	6	20.14	7
3	9.96	11	37.24	14	0.29	9	0.44	8	22.44	9
4	6.22	6	10.91	4	0.17	5	0.36	6	10.87	6
5	10.29	11	27.62	11	0.25	8	0.35	6	19.57	9
Overall average SD	7.70 mg	8.5	21.91 mg	8.2	0.19 gm	8.2	0.28 gm	6.4	19.45 gm	8

Six mini kits were tested by five testers, each filament applied 15 times by each tester, and averaged for total 450 applications for each filament. While there were differences in filament application force large enough to be significant at the 0.01 level, suggesting for optumum repeatability the same tester should retest the same patient, the overall SD of the multitesters approached those of the single tester applications. It is possible for several examiners to test the same patient with repeatability of findings within the overall average SD shown for the multitester.
*Average standard deviation.
†Percent of mean.

forces, the filaments provide a relatively more controlled testing stimulus than other hand held instruments, which do not attempt to control these variables.[8]

Filament repeatability

Single tester. To determine the repeatability of the filaments as a force stimulus 28 unused mini kits containing the five filaments most often used in clinical testing were measured for their application force when applied in 1.5 seconds, held for 1.5 seconds, and lifted in 1.5 seconds. The kits were examined in groups as they had been received for clinical testing, with group I containing eight kits, group II containing 17 kits, and group III containing three kits. A single tester applied each filament of each kit 10 times, and the results were averaged, with each of the filaments having been applied a total of 280 times. Diameters of the filaments were measured with a micrometer and checked against their specified diameters. Filaments with diameter errors, or whose diameter when rounded approximated the diameter of its neighboring filament, were eliminated. A corrected average (mean) score was then calculated for each filament. The lengths of all filaments were 38 mm.

Table I shows the mean, average standard deviation (SD) and the SD as percent (%) of mean for each filament. The SD as % of mean shows there is relatively little change in the SD statistics for the small filaments through the larger filaments.

An F test of significance, comparing filaments received in the three groups, showed no significant differences at the 0.05 level for the 2.83 filament and at the 0.01 level for the 3.61 filament. Some test kit group differences substantial enough to be significant were found among the larger filaments, suggesting for optimum repeatability in clinical testing the same kit should be used to test the same patient.

Table II shows the specific range of force that occurred with each filament (listed by index number) and the mean force for each filament in the 28 kits. The specific diameter in inches for each filament in the mini kit is also shown. The range of filament forces for mini kit filament diameters was established by recording the lowest and highest occurring application force.

Multitester. To determine the repeatability of the filaments among multiple testers, six mini kits of five filaments were tested for their application force by five testers. Each filament was applied 15 times by each

Table IV. Comparison of single tester filament and multitester application forces: standard deviations

	Single tester		*Multitester*	
	*ASD**	*POM†*	*ASD*	*POM*
Filament index numbers				
2.83	5.31 mg	7	7.70 mg	8
3.61	19.32 mg	9	21.91 mg	8
4.31	0.17	7	0.19 gm	6
4.56	0.29 gm	6	0.28	5
6.65	11.38	6	19.45	8

There is less difference than was expected in these SD. Only the 2.83 and 6.65 (index numbers) filament application forces were different enough to be significant (0.01 level). In a subsequent comparison of the multitester SD with single tester mini kit filament from seven standard (long) kits, there were no significant differences in the standard SD at the 0.05 level.
*Average standard deviation.
†Percent of mean.

tester and results were averaged for a total of 450 applications for each filament. Table III shows the multitester application force average SD. Calculations of the SD % of mean showed little change overall in the % of mean for the various filaments. While an F test of significance among the various testers showed some differences great enough to be significant at the 0.01 level, the SD among the several testers were surprisingly small, and although slightly broader, compared closely to the multiple applications by only one tester.

A comparison of the single tester force average SD and multitester force average SD can be seen in Table IV. Only the 2.83 and 6.65 (index numbers) filament application force differences were great enough to be significant. These were significant at the 0.01 level. The difference of the 2.83 SD in the two tests was 2.39 mg. In a subsequent comparison of the multitester standard deviations with mini kit filaments from seven standard (long kits) there was no significant difference in the SD values at the 0.05 level with any of the filaments. These data suggest that it is possible for several examiners to test the same patient with repeatability of findings within the SD specified for the multitester. For optimum accuracy it remains a good idea for the same examiner to test the same patient when possible.

Single tester—complete set repeatability

To determine the range of force for each filament in the standard (long) kit, filaments in seven complete testing kits were measured by one tester. Each filament of each kit was applied 15 times and averaged for a total of 105 applications/filament. The resulting means and SD are shown in Table V. For reference purposes they are compared with the Semmes-Weinstein published forces;[5] the Levin and associates[7] measured forces, the calculated forces based on the original buckling equation $M = \log(10 \times F \text{ mg})$, and the filament diameters.

Inspection of the testing data shows that the range of force of some filaments overlaps with those of others, and as Levin and colleagues[7] suggested, not all of the filaments are necessary. This gives support to the use of a reduced number of filaments, as in the mini kit, which is now being used with increasing frequency in clinical testing. There is no overlap of application force in mini kit filaments if their diameters are correct.

The offset shows a comparison of the forces of the mini kit filaments found in the standard kit with the mini kit measurements from Table II. Note there is little difference in the measurements of mini kit filaments in the seven standard kits and the previously measured 28 mini kits except for the 6.65 filament.

The heavier force of the 6.65 filament in the standard kit results from the application of this filament to buckling. (The 6.65 filament is usually applied just before buckling in clinical testing.) This filament buckles at a ceiling of 300 gm and cannot reach the 447 gm originally reported in the literature based on the buckling equation.

The range of forces established for all of the filaments can be read in Table V as the mean plus or minus the SD value. Diameters are included on this table for calibration reference.

Repeatability comparison with application force of other hand held tests

To compare the Semmes-Weinstein application force repeatability with that of other hand held instruments, the mini kit filament application force results from the mini kit and standard kit tests were averaged. These

Table V. Force comparisons and diameters*

MN	CF gm	S-WF gm	LMF gm	B-TMMAF gm	ASD gm	Diameters In	Diameters mm
1.65	0.0045	0.0045	0.0040	0.0081	0.000	0.0025	0.064
2.36	0.0229	0.0230	0.0094	0.0146	0.002	0.003	0.076
2.44	0.0276	0.0275	0.034	0.0346	0.004	0.004	0.102
−2.83	0.068	0.0677	0.091	0.0798	0.007	0.005	0.127
3.22	0.166	0.1660	0.112	0.1722	0.012	0.006	0.152
−3.61	0.408	0.4082	0.213	0.2171	0.025	0.007	0.178
3.84	0.693	0.6968	0.562	0.4449	0.030	0.008	0.203
4.08	1.20	1.194	0.977	0.7450	0.060	0.009	0.229
4.17	1.48	1.494	1.58	0.9765	0.082	0.010	0.254
−4.31	2.05	2.062	1.85	2.35	0.16	0.012	0.305
−4.56	3.64	3.632	2.81	4.19	0.33	0.014	0.356
4.74	5.51	5.500	3.14	4.64	0.62	0.015	0.381
4.93	8.53	8.650	10.60	5.16	0.81	0.016	0.406
5.07	11.80	11.7	17.0	7.37	0.86	0.017	6.432
5.18	15.20	15.0	18.6	12.50	1.17	0.019	0.483
5.46	28.90	29.0	22.3	20.90	1.68	0.022	0.559
5.88	76.00	75.0	73.2	46.54	3.67	0.029	0.711
6.10	126.00	127.0	86.5	84.96	7.92	0.032	0.813
6.45	283.00	281.5	—	164.32	15.33	0.040	1.016
−6.65	448.00	447.0	—	279.40	21.75	0.045	1.143

	Filament index	Application force mean, mini kit filaments from standard kit gm	Application force mean, previous mini kit test results (from Table II) gm
Mini kit filaments	−2.83	0.080	0.072
	−3.61	0.213	0.205
	−4.31	2.35	2.35
	−4.56	4.19	4.91
	−6.65†	*279.00	192.22

†Filament 6.65, heavier force in the long kits results from filaments applied to buckling.

One tester, seven complete testing kits.
The range of forces for all filaments can be read as the mean plus or minus the SD value. Note in offset the comparison of means of means of filaments in the mini kits and mini kit filaments tested in the long kits.
MN; marking number derived from log scale, CF; calculated force based on buckling equation, S-WF; Semmes-Weinstein force, LMF; Levin Pearshall, and Ruderman. Measured force, B-TMMAF; Bell-Tomancik measured mean application force, ASD; average standard deviation.

filament application force results were compared with the application force results from repeated applications of a two-point testing instrument, of a pin (pinprick exam), and a ballpoint pen (probe exam). Table VI compares the relative range of forces for each instrument and their SD. The two-point test had nine testers and 168 applications, and the ballpoint pen test had five testers and 150 applications. The test for pinprick had five testers and 75 applications.

On inspection of these data the range of forces produced by individual testers with these latter instruments varied broadly in gram range, which was several orders of magnitude higher than the lightest filaments and specfically the 2.83 filament (index number), which screens normal touch recognition. The broad range of force variation, as would be expected, most closely compared with the 6.65 filament that does not bend on normal application in clinical testing. The application force of any probe that is not controlled would be expected to vary in a large range.

Of interest, although it has been believed that the 6.65 filament was uncontrolled, it did consistently buckle at or below 300 gm. Although this force is not usually reached in testing it does represent more control of application force than the other instruments because it will bend (and return to a straight position) when its peak force is reached.

Stress measurements (force/unit area) are provided

Table VI. Comparison of filament application force repeatability with other hand held instruments

	Range gm	Mean gm	ASD* gm	POM†	Average	
					Diameter mm	Approximate stress gm/sq mm
Two point	19.39 -103.75	33.36	11.78	35	0.762	73.
Ballpoint	39.40 -368.67	251.68	28.71	11	1.219	216.
Pinprick	20.23 -335.	167.04	23.52	14	0.254	3.297.
Filaments						
2.83	0.058- 0.102	0.076	0.0061	8	0.127	6.
3.61	0.155- 0.252	0.209	0.023	11	0.178	8.
4.31	1.85 - 2.66	2.35	0.17	7	0.305	32.
4.56	3.66 - 6.13	4.55	0.31	7	0.356	46.
6.65	151. -298.4	235.61	16.57	7	1.143	230.

Two point, 9 testers, 168 applications; ballpoint, 5 testers, 150 applications; pinprick, 5 testers, 75 applications. Note the broad average SD in the two-point, ballpoint, and pinprick measurements, compared with the monofilaments (except 6.65 filament).
*Average standard deviation.
†Percent of mean.

in Table VI for reference with other literature. Most significant in this comparison is that the application force SD of the filaments are at the milligram level (except for the 6.65 filament), while the application force SD of the other hand held instruments occurs in grams.

Instrumentation used for force measurements

Filaments 1.65 to 4.56 (marking numbers). An instrument testing system consisting of four tiny strain gauges set on a platform and connected to an oscilloscope and digital panel meter was specifically designed to measure the lightest filaments by William L. Buford, Ph.D., Biomedical Engineer, in a previous study of filament dynamic properties by Bell and Buford.[8] A more sensitive measure was desired than that provided by top loading Mettler-type balances used in earlier studies of the filament forces. Top loading balances are difficult to read precisely when a filament is applied. The oscilloscope used in our testing can be frozen at a precise force reading as the filament is applied to the platform. Since the scope can be frozen the measurement can be analyzed as to its force and time.

Filaments 4.74 to 6.65: two point, pinprick, ballpoint tests. The larger filaments and all of the other hand held instruments tested produced forces too large (greater than 4 gm) to be measured on the above system. They were measured on an arm strain gauge, connected to a digital panel meter, to which a platform had been mounted. This strain gauge was also designed for force measurements by engineers in our Rehabilitation Research Department.

Discussion of overall testing

Errors in filament diameters were found and occurred most frequently in the standard (long) kits. Although diameter errors were sometimes within the force range established (with errors eliminated) they would fall in the ends of ranges and in some cases reproduce the force of another filament. This underlines the need to check the filament diameters in kits being used for clinical testing. If the diameters and lengths are correct the force is predictable within the specified range (See Table VI). Inch and millimeter micrometers are available from many sources. A Craftsman model (Sears Roebuck and Co.) is available at a reasonable price. Diameters can be measured against those as shown in Table V. Small variations in diameter may occur, but when rounded they should not reach the diameter of another filament.

Slight variations in the lengths of the filaments also occur, but they will produce heavier or lighter forces if they vary a few millimeters. They should be 38 mm in length from the point they leave the rod. Filaments that are too long can easily be cut with a scalpel to the correct length. Filaments that are too short should be replaced. Filaments from six kits, which had inadvertently been cut 10 mm shorter than the standard length, were measured before the error was discovered. These produced application forces that were much heavier than those filaments of the correct length. This underlines the need to check filament lengths of filaments in kits being used for clinical testing.

If the lengths are constant and diameters correct, the filaments do produce application forces that are repeatable within a predictable range, in milligrams for the lightest filaments and in grams for the heavier filaments. Within the limits of their tip geometry, they are a controlled, objective, reproducible force stimulus available for use in clinical testing of peripheral nerve function.

Conclusions

1. If the length and diameter are correct the application forces of the filaments are repeatable within a predictable range.
2. Results of test applications by multitesters are slightly broader than repeated test applications by only one examiner. It is possible for several examiners to test the same patient with repeatability of findings within the standard deviation specified for multitester.
3. Filament force calibration can be checked by: (1) assuring that the filament length is 38 mm (from the point it leaves the rod), and (2) measuring the filament diameter with a commercially available micrometer. If the length and diameters are correct, the filament application force should fall within the established range.
4. The heaviest and lightest application forces of some filaments overlapped with those of their neighbors, lending support to the concept that the use of fewer filaments does not necessarily result in loss of test sensitivity, and, in fact, can make the test more reproducible.
5. The filament application force SD occur in milligrams (except for the 6.65 filament), while those of other hand held instruments that do not control application force occur in grams (several orders of magnitude higher).
6. Within the limits of their tip geometry (diameters, edge contact on application) the filaments are a controlled, objective, reproducible force stimulus available for use in clinical testing of peripheral nerve function.

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