Measurements of Human Reaction to Hardness of Floor Covering

By R. SCHJÖDT

PEOPLE REACT to the hardness of a floor upon which they walk. The difference between a concrete or terrazzo floor, and a rubber or cork tile floor covering can be clearly felt. Those people, such as nurses and shop attendants, who are required to walk or stand much during their working hours, are quick to complain if the flooring is too hard. The hardness, or conversely, cushioning effect, of floors is an important part of our housing standards.

Earlier Work

When it comes to measuring the hardness of different floor surfaces and thus expressing in numbers the feeling mentioned above, difficulties appear. In spite of many attempts it has not been possible, as far as the author knows, to register in any measuring apparatus the difference felt between hard and cushioned floor surfaces. For instance, Holden and Muncey (1)[1] have measured the pressure on the foot by means of condensers placed between the foot and shoe. The electric capacity changes due to pressure were recorded. The results, however, show no variations from recordings made for concrete, timber, or cork tile floor. The conclusion reached in this and other tests is that variations due to changes in the floor surface are almost nonexistent.

Many writers on the subject of floor coverings have concluded that the feeling of relative softness or hardness of the coverings is an illusion resulting from the heat-insulation capacity of the floors (2). It is frequently maintained that it is wrong to speak of "soft" and "hard" floors; one ought to speak rather of "warm" and "cold" floors. The reason given is that the deformation of the shoes and of the flesh layer between the skin and the bones of the foot is so much greater than that of the floor covering, that the latter is of no importance.

As a result, any discussion of the softness—the degree of agreeable or nonagreeable walking on different flooring materials—is left out of the text books, and no attempt is made to decide upon specifications for softness which floor coverings in different rooms ought to satisfy.

The author does not agree with the point of view given above. When stepping from a hard to a soft floor, one feels the difference before any heat transport could possibly have made itself felt. But this opinion, to have any value, has to be backed by measurements that register the differences between floor coverings.

Possible Methods

It is evidently useless to repeat the measurements of the pressure on the foot. The feelings of hardness and tiredness occur in the muscles and in the nervous system, however, and therefore it appears natural to see whether it is possible to measure directly the work done by the muscles during walking.

Various methods of testing seem possible, apart from recording the pressure. Schwartz, Heath, Mizick, and Wright (3, 4), have measured the time spent on the heel, fifth metatarsal, and great toe of each foot. However, it does not seem likely that this will lead any further than the pressure measurements.

Fig. 1.—Showing (*left*) test subject with electrodes attached, and (*right*) electromyograph recorder.

The wires from the electrodes run to a cross-coupling panel, carried on the subject's back, and this is connected to the recorder. Concrete slabs with various floor coverings can be seen.

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[1] The boldface numbers in parentheses refer to the list of references appended to this paper.

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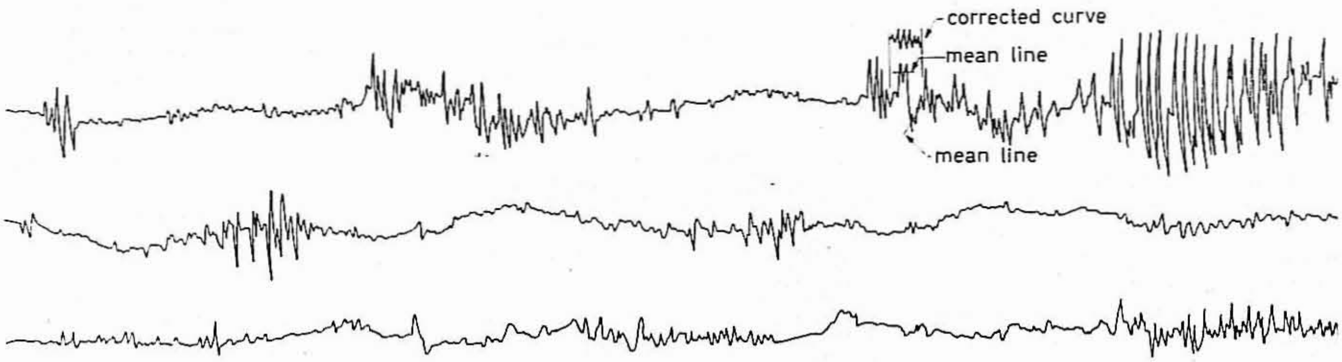
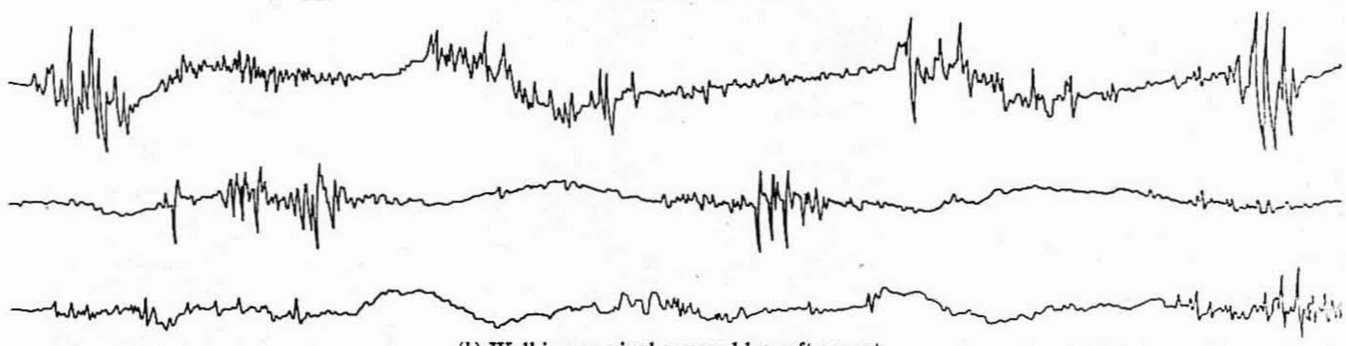
Electromyography, the recording of electric muscle-action potentials, has been extensively used in the last decade for analysis of muscle coordination. The potential changes travel along the muscle fibers, and cause activation of the contractible substance. The electric potentials in the muscles are recorded, through the electrodes fastened to the skin, by cathode-tube oscillographs. This method of recording the work of the muscles seems to have been used first by Erlanger and Gasser (5), and Lundervold (6) for measuring the muscular energy in typewriting.

The author awakened the interest of Lundervold in the present problem, and a collaboration was initiated, Lundervold seeing the problem from the physiological angle, and the author from the technical.



(*a*) **Walking on concrete.**



(*b*) **Walking on vinyl covered by soft carpet.**

Fig. 2.—Electromyograph curves for muscle action in left leg (Pre-tibial group, Calf group, and Quadriceps group).

The recorders have a tendency to continue a sideway movement once this has started, and thus break the mean line. In Fig. 2(*a*) is shown how this is corrected when the areas of activity are calculated.

The "long wavelength" oscillations seen on the diagrams have no significance.

Experimental Methods

The tests consisted in having various persons walk on different floor coverings, and recording the work performed by the muscles (Fig. 1). The electromyograph was an eight channel brass amplifier and recorder, with a sensibility of 500 μv per in. The results are as shown in Fig. 2.

The question whether there was any real difference registered in the muscle work when walking on different flooring materials was decided in the affirmative. (See Fig. 2). The differences are evident if one compares, for instance, the right-hand part of the first curve in Fig. 2(*a*) and 2(*b*), and it is still clearer where the person has walked from concrete to soft floor coverings, and the reverse. But this qualitative result is evidently not sufficient. It is still necessary to express the results in numbers that show clearly the degrees of hardness registered for various materials.

Discussion of Results

Lundervold has shown that tiredness results when two antagonist muscles are working simultaneously. It was therefore decided to register the lengths of time when two such muscles were working together. When using the curves shown in Fig. 2, only the periods were added where the muscles of the first and second electrode, and the second and third, were working together.

Only deviations from the mean line are recorded; the "long wavelength" oscillations seen on the curves are not considered. The recorders also have a tendency to continue a sideway movement once they are started, and thus break the mean line. This is illustrated in part of the first curve in Fig. 2 (*a*) where the mean line is indicated, and the corrected curve is drawn above.

Furthermore, persons performing the test do not walk with exactly the same speed every time. To make the results more comparable, characteristic points on the curves were found, and the curves were redrawn so that the distances between these points were always the same.

Part of the first two curves in Fig. 2 are redrawn in Fig. 3 in the way described above. To determine the degree of tiring muscular activity, the areas of activity are shown in Fig. 3 Two muscles are always counted together, and only those parts are counted where both muscles are in activity. The stretches drawn as a wavy line (compare with Fig. 2 for their characteristics) are counted as active, but the area is zero. In other words, the activity of the other muscle is counted over these stretches.

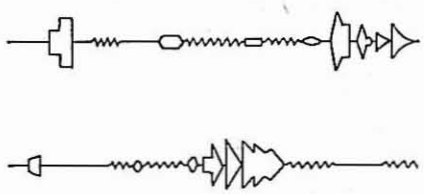


Fig. 3.—Extract from the first 4 in. of the first two curves of Fig. 2.

In calculating the areas of muscular activity, only the parts where both muscles are active simultaneously are counted.

Thus, for instance, the areas of activity appearing in the upper curve between 1 and 2 and between 8 and 9 cm are not counted, because the other muscle is inactive on these stretches.

The curves obtained have been analysed in this way. The results vary a good deal from individual to individual, and for the same individual from covering to covering. But the correlation of results for the different

TABLE I.—TEST RESULTS FOR SUBJECTS WALKING ON DIFFERENT FLOOR SURFACES.[a]

Subject	Concrete				0.05-in. Sheet Rubber plus 0.15-in. Foam Rubber				Rubber as Before Plus Carpet			
	With Shoes		Barefoot		With Shoes		Barefoot		With Shoes		Barefoot	
	Calculated	Average	Calculated	Average	Calculated	Average	Calculated	Average	Calculated	Average	Calculated	Average
No. 1	35	58	...	...	38	42	...	...	27	20	...	..
	80	...	...	...	42	...	...	...	13	...	...	...
	...	...	...	...	47	...	...	...	...	...	...	...
No. 2	171	173	253	222	123	117	151	149	74	82	...	..
	174	...	191	...	110	...	147	...	96	...	...	..
No. 3	124	138	151	140	...	...	...	...	100	103	98	91
	151	...	140	...	...	...	...	...	105	...	84	..
	...	...	129	...	...	...	...	...	...	...	...	..
No. 4	104	85	56	60	50	64	50	53	67	48	40	45
	69	...	48	...	77	...	55	...	31	...	52	...
	84	...	56	...	...	...	54	...	45	...	52	...
	81	...	54	...	...	...	...	...	...	...	34	...
	...	...	84	...	...	...	...	...	...	...	47	..
No. 5	85	82	84	99	46	61	81	58	50	47	101	95
	71	...	105	...	70	...	29	...	53	...	82	..
	83	...	161	...	67	...	65	...	38	...	102	..
	88	...	91	...	...	...	...	...	...	...	...	..
Average		107		130		71		87		64		77

[a] Areas of activity in square centimeters, for pre-tibial group plus calf group. One square centimeter represents 33.3 μv-sec.

TABLE II.—TEST RESULTS AS IN TABLE I BUT FOR CALF GROUP PLUS QUADRICEPS GROUP.[a]

Subject	Concrete				0.05-in. Sheet Rubber plus 0.15-in. Foam Rubber				Rubber as Before Plus Carpet			
	With Shoes		Barefoot		With Shoes		Barefoot		With Shoes		Barefoot	
	Calculated	Average	Calculated	Average	Calculated	Average	Calculated	Average	Calculated	Average	Calculated	Average
No. 1	37	39	...	...	21	30	..	...	24	22	...	..
	41	...	...	...	16	...	..	..	20	..	...	..
	...	...	...	...	19	...	..	..	...	..	...	..
No. 2	80	75	149	148	54	47	94	92	20	24	...	..
	69	...	147	...	40	...	89	..	8	..	...	..
No. 3	17	12	32	21	...	...	..	..	10	7	6	9
	7	...	20	...	...	...	..	..	3	..	12	..
	...	...	12	...	...	...	..	..	...	..	...	..
No. 4	193	155	96	111	90	114	80	87	108	91	101	97
	130	...	118	...	137	...	85	..	77	..	97	..
	165	...	111	...	...	...	96	..	86	..	100	..
	135	...	119	...	...	...	..	..	...	..	91	..
No. 5	79	38	24	39	10	12	6	14	34	25	32	27
	30	...	15	...	18	...	19	..	29	..	18	..
	31	...	72	...	9	...	17	..	13	..	30	..
	12	...	44	...	...	...	..	..	...	..	...	..
Average		64		80		40		64		34		44

[a] Areas of activity in square centimeters, for calf group plus quadriceps group. One square centimeter represents 33.3 μv-sec.

TABLE III.—AVERAGE VALUES OF AREAS OF ACTIVITY FOR MUSCLES IN PRE-TIBIAL GROUP PLUS CALF GROUP. TEST PERSONS WERE USING SHOES. FOR COMPARISON, VALUES OF SHORE AND INDENTATION TESTS.

Materia	Areas of Activity, sq cm	Shore Hardness "Durometer" Type "D"	Indentation Tests
Concrete	107	100	..
Vinyl asbestos tile, 0.08 in.			
On concrete	81	77	9.5[a]
On wood	46	77	4.3
Linoleum, 0.10 in. on concrete	70	65	6.5[b]
0.05-in. sheet rubber on 0.15-in. foam rubber on concrete	71	19	0.6
Same, with $^1/_8$-in. woolen carpet, on concrete	64	...	...
Cork tiles, $^5/_{16}$ in., on concrete	59	38	3.8
Sheet vinyl $^1/_{32}$ in., felt base $^1/_{16}$ in., on concrete	48	25	2.4
Norway spruce	57	40–50	2.6

[a] For test floor. Indentation tests for different vinyl floors give values from 2.9 to 12.0.
[b] For test floor. Indentation tests for different linoleum floors give values from 2.5 to 6.6.

floor coverings was good. Results are shown in Tables I and II.

The kind of shoes used, thickness of soles, height of heels are all important. Therefore experiments were carried out with the subjects walking barefoot and in high-heeled shoes. The results with the high-heeled shoes were in good agreement as far as muscle work was concerned, but showed that other muscles were used. Lundervold will publish an account in which this will be discussed.

The results for subjects walking barefoot are also shown in the tables. The agreement with the tests with shoes is good. The work of the muscles in Table I increases about 20 per cent when walking barefoot; for the muscles in Table II the increase is about 40 per cent.

The work in muscles higher up in the body (hamstrings group, erector spinae, and gluteus maximus) was in good agreement with the results shown.

The results grouped according to floor materials are shown in Table III. These electromyograph results are from the calf group and pre-tibial muscle group with the subject wearing shoes. Any muscles other than those registered, could have been used without changing the relationships. The difference in registered muscle work is very pronounced, and agrees very well with the feeling of "cushioned" effect of the floor coverings.

Electromyograph tests cannot be made easily every time it is desired to examine the qualities of a floor covering. The importance of the test lies primarily in establishing the actual reality behind the feeling of hard or soft floors, and in giving a basis for comparison.

TABLE IV.—FRICTION COEFFICIENTS OF VARIOUS FLOORING MATERIALS

Material	Leather Sole				Rubber Sole			
	Dry		Wet		Dry		Wet	
	Static	Kinetic	Static	Kinetic	Static	Kinetic	Static	Kinetic
Concrete	0.54	0.45	..	..	0.74	0.71	..	..
Vinyl tile	0.46	0.39	0.30	0.11	0.58	0.54	0.63	0.47
Rubber	0.45	0.63	0.43	0.27	0.44	0.63	0.87	0.50
Sheet vinyl	0.43	0.39	0.78	0.29	0.48	0.67	0.82	0.61
Cork tiles	0.42	0.34	0.78	0.55	0.53	0.50	1.00	0.98
Linoleum	0.27	0.25	..	..	0.42	0.36	..	..
Norway spruce, varnished	0.31	0.25	..	..	0.50	0.40	..	..
Terrazzo	0.25	0.22	..	..	0.38	0.34	..	..
Limestone, honed	0.27	0.21	..	..	0.38	0.27	..	..
With fine sand on the soles:								
Terrazzo	0.26	0.26	..	..	0.31	0.29	..	..
Limestone, honed	0.10	0.10	..	..	0.15	0.13	..	..

Practical Tests for Floor Surfaces

For a more practical way of testing the floor hardness, results of Shore tests and indentation tests are shown in Table III. The Shore test consists of introducing a spike in the material, and registering the resistance to penetration. The indentation test is made with an indentation tester (7, 8). The indenting tool consists of a flat-ended cylindrical steel rod $^1/_4$-in. in diameter, carrying a load of 29 lb. The values given in Table III are the inverse of the indentation in millimeters after 30 sec.

The Shore tests give a useful idea of the cushioning effect of a flooring material, rubber excepted. But they do not give any information about the floor as a whole, as they indicate only the characteristics of the surface material. Comparison between vinyl tile on concrete and on wood illustrates this.

In Table III the agreement between electromyograph and indentation tests is excellent, with the exception of the results for rubber. The Shore and indentation tests give very low, that is, "good" results for rubber, whereas the electromyograph places rubber far higher on the scale. Again, this agrees with "feeling." Rubber feels soft, but in spite of this, walking on rubber is not as agreeable as might be expected.

Friction Coefficients for Floors

To clear up this point, if possible, the friction coefficients of the materials were measured (9). Table IV gives the results for tests made by pulling a weighted sole along the floor (10). In some cases special test floors (Fig. 1) could be tilted so that the friction angle could also be measured directly.

The last two tests were included to establish the minimum safe value of the friction coefficient. In the lobby of a research institute, it was found necessary to put up warnings, "Take care, the floor is slippery." When this floor (limestone) was tested in the usual way, it gave practically the same results as terrazzo. However, when the tests were repeated with fine sand on the soles, this did not make much difference for the terrazzo, but lowered the friction coefficient to less than half of its former value for the limestone.

The results indicate that the friction coefficient for a floor material, tested as above for kinetic friction, ought to be not less than 0.20, and not more than 0.40, for leather soles.

It will be seen that rubber behaves differently from the other materials. It is well known that the static friction coefficient is higher for other materials but for rubber the kinetic coefficient is higher. The same result is found for sheet plastic with rubber sole, probably because the sole has decided the issue here. It is thus easy to explain why the electromyograph places rubber in a more disadvantageous situation than the Shore and indentation tests. The foot slides along the floor before being lifted. Then the kinetic friction coefficient comes into play, giving, for rubber, an increased resistance to motion, and causing increased muscle work.

Hardness Scale for Floors

It is tempting, on the basis of what was found above, to propose a hardness scale for floor surfaces, similar to the Mohs hardness scale. An approximate scale is given in Table V.

TABLE V.—HARDNESS SCALE FOR FLOOR SURFACES.

Relative Hardness	Material
10	Concrete, terrazzo, stone
7	Vinyl asbestos tiles
6	Linoleum, soft rubber
5	Cork tiles, soft wood, cork linoleum, high-grade vinyl
4	Sheet vinyl on felt base

Even though this Table V is far from exact, it gives the relative hardness of the flooring materials, and also a basis for indicating in building specifications the flooring wanted.

Which floor will be felt to be satisfactory in the different rooms and corridors depends very much on the standard of comfort in the locality. The author has come across a typical example of this.

The small Norwegian town, Steinkjer, was destroyed by fire during the war. Like all Norwegian small towns, it was formerly built of wood, but was rebuilt in concrete. During the first two years after reconstruction, nearly the entire population complained that their feet hurt. Later the complaints died down. The town had become accustomed to a lower standard of comfort.

Summary

Tests were carried out to see what differences can be recorded between the hardnesses of different flooring materials felt when walking. Since direct pressure recording by various methods has given no results, the author used the electromyograph tests. A clear difference in the reactions was found—in agreement with "feeling," and with Shore tests and indentation tests. The importance of friction in the effect of softness of floor surfaces is considered, and a hardness scale is proposed.

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