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Research on Footwear Laces with Respect to Abrasion Resistance and Spontaneous Untying

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Abstract

In this paper, two types of footwear laces research were undertaken. The first was connected with abrasion resistance and the second with the displacement force at the knot. The abrasion resistance was registered by the level of abrasion for standard eyelet. The displacement force was measured with the use of a tensile test machine, where the force and extension were registered. As a criterion of test evaluation, the maximum force was established when the knot was untied. The research was conducted for a set of different types of shoelaces (differing in shape, structure and raw materials). The evaluation criteria proposed can be used in order to determine the raw materials and optimal construction of shoelaces. From the user's point of view, the measures identified i. e. the displacement force in the knot (F_{pw}) and abrasion resistance (K_s) are the most important factors.

Key words: *footwear laces, testing methods, abrasion resistance, displacement force at the knot, shoe laces criteria quality.*

Introduction

The locomotion process is connected with the mechanical work of all segments of the human body. One of the biggest roles which is played by footwear is gait stabilisation. This function is provided by the spacer construction of laces, which is connected with the muscles and tendons of the dorsal foot surface. The foot stability provided by shoelaces, supports the natural processes of twisting the foot in perpendicular and lateral directions, which is important to create the ability to dynamically resist foot inversion of eversion. Moreover, using footwear is connected with muscle fatigue caused by the bending forces of soles and uppers, which are generated during walking. Inside a shoe volume, the footwear upper is lifted by the dorsal muscle effort. At the same time, the back of the torso is dragged in the same direction. Hence, the physiological effort which is necessary to overcome the material stiffness (lacings and connections between the footwear upper and bottom) is equal to the vertical forces beneath the foot. Laces decide about the fit of footwear to stay right on the feet [1], which is very important for the biomechanical factors of the gait, like velocity and rotation ability. When footwear is tightly laced, the foot pronation of the ankle joint is reduced and the load coefficient decreases. The negative effect of this is excessive pressure on the dorsal foot surface and straightening of the muscles of the ankle joint, which can cause an increase in injury probability. According to Polster [2], the six main lacing patterns are crisscross, zigzag, star, bowtie, serpent and s-zigzag (*Figure 1*).

The problem of the lacing pattern influencing the kinematic and dynamic parameters is intuitively known, but literature sources are very scarce. In papers [3-4] gait stability as a function of the lacing pattern of running shoes was examined. The undertaken analysis showed, that different lacing patterns can cause different shoe fit, which was perceived in terms of the comfort rating, like heel cup fitting and forefoot cushioning. It is one of the most important ways of reducing the probability of injury occurrence. Hagen and co-authors [5] showed the correlation between lacing patterns and the peak of dorsal pressures. From the user's point of view, the abrasion resistance of footwear laces is a very important factor, which decides about shoe fit and gait safety.

Czaplicki [6] showed that the type of fibre, structure and shape of laces is one of the factors which determine the abrasion resistance. Also, the width and diameter are not without significance. Material abrasion is also caused by the type of eyelet surface and the velocity of the laces' movement in the eyelet. Nowadays, abrasion resistance is measured according to the applicable standard [7], according to which, there are three methods of lace abrasion testing:
- **method 1:** lace on lace;
- **method 2:** lace on abrasive medium;
- **method 3:** lace on shoe eyelet.

The measurement device is shown in *Figure 2* [7].

In method 1, a footwear lace is threaded through a loop formed from the passage of a similar lace. In methods 2 and 3, a lace is threaded through a standard eyelet (method 2) and shoe eyelet (method 3). The abrasion resistance is measured as the number of cycles necessary for destruction of the lace or lace core.

Czaplicki and Serweta [8] carried out research on a new parameter – displacement force in a lace knot – F_{pw}, after which spontaneous untying takes place. This parameter is very important from the user's point of view because it determines the untying process during locomotion. It is very dangerous because when the lace of one foot is pinned to the ground by the second foot during a gait or run, the probability of falling increases. These events are often found amongst children and youths in preschools or schools. This problem also concerns runners or soldiers during military exercises.

The authors say that the spontaneous untying of laces is connected with the values of displacement forces in the knot. A positive correlation between the displacement force and resistance to spontaneous untying was found.
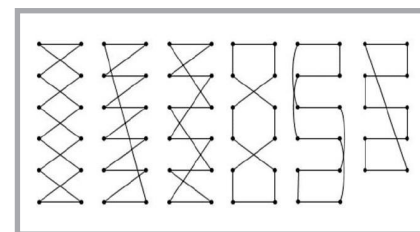

Figure 1. *Shoe lacing patterns: crisscross, zigzag, star, bowtie, serpent, s-zigzak lacings [2].*
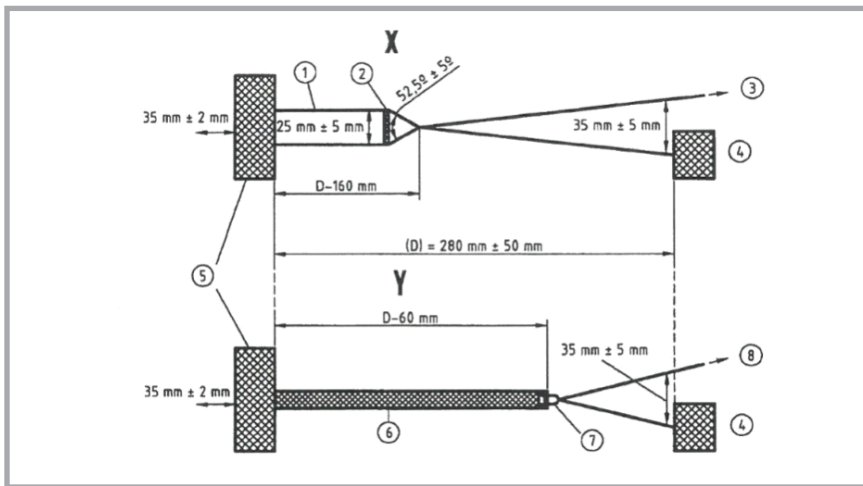
Figure 2. *Abrasion resistance device (view from above the abrasion geometry [7]) (X – method 1: abrasion between lace – lace, Y – methods 2 and 3: abrasion between lace – abrasive medium, 1 – lace's knot, 2 – strut, 3 – force (2.45N ± 0.03), 4 – stationary grip, 5 – non – stationary grip, 6 – the metal strip, 7 – abrasive medium of lace, 8 – force (2.45N ± 0.03)).*

The undertaken research was focused on the development of some parameters which are important from the footwear user's point of view:

■ lace abrasion, measured with an original device and proposing abrasion resistance as an indicator (instead of the number of cycles to lace destruction, according to standard [7]);

■ displacement force in the knot, measured as the minimal force necessary to induce the movement of the laces in the knot. This force is a resistance indicator for spontaneous lace untying.

■ Materials and method

Method for determining the shoelace force in a node

The method of determining the shoelace displacement force in a node is to determine the maximum force needed to cause movement of the shoelace tightened in

the node. Force measurements are carried out on a testing machine (ripper) with a range of 2 daN and working on the principle of a constant increase in elongation; it is also equipped with a device for the force diagram.

The length of the sample should be 500 ± 5 mm. The following test conditions were used to measure the travel force:
– 3 daN knot clamping force,
– node clamping time: 5 ± 1 s,
– the sample pre-load is assumed to be equal to 2% elongation,
– lower travel speed of the ripper: 1.67 mm/s,
– distance between clamps: 100 mm.

Figure 3 shows how to prepare a sample for measuring the sliding force in a node. Each of the samples to be tested immediately before the measurement should be prepared in accordance with *Figure 3.a-3.c*, with the node clamping

time after lifting the loaded sample being 5 ± 1 s. The sample prepared according to *Figure 3.c* is attached to the ripper clamps by pre-loading the bottom clamp with a weight causing 2% elongation of the sample. After attaching, the ripper is started and a graph of the sliding force F_{pw} of the shoelace sample over a length of 40 mm is obtained (*Figure 3.c*).

Based on measurements taken for 10 samples, the maximum force value F_{pw} should be read from the graphs in accordance with *Figure 4* with an accuracy of 0.5 divisions, and then converted to force values in cN. The average value of the sliding force F_{pw} in the node is calculated from the results obtained.

Method for determining the abrasion resistance of shoe laces (original)

The method of determining the abrasion resistance consists in determining the breaking force of the shoelace sample against abrasion, where the sample is subjected to cyclic abrasion in a shoe eye. and calculating the so-called coefficient of resistance K_s from *Equation (1)*:

$$K_s = \frac{F_s}{F_0} \qquad (1)$$

where F_s – mean value of the breaking force of 10 samples subjected to wear (daN), F_0 – average value of the breaking force of 10 samples not subjected to wear (daN).

The proprietary device for testing the abrasion of shoelaces working on the principle of cyclical pulling of the shoelace through a shoe eyelet (30 ÷ 50 cycles/min) is shown in *Figure 5*. For measuring the breaking forces F_0 and F_s of shoelaces, a ripper with a range of 50, 100, 200 daN was used. The length of the samples was 500 ± 5 mm.
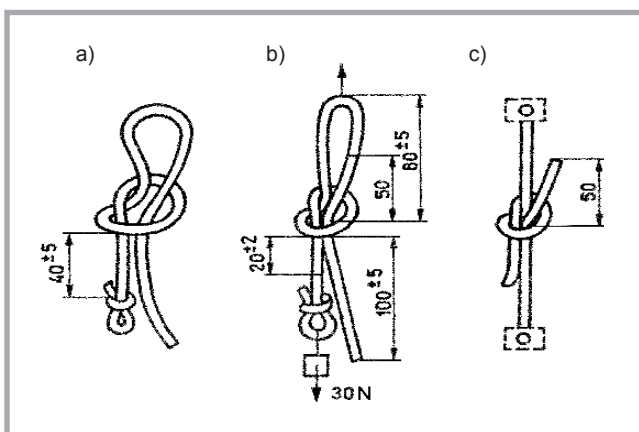

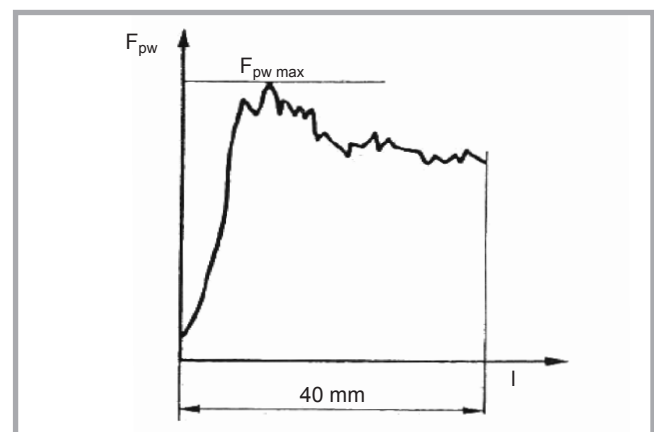**Figure 3.** *Lace sample preparation of displacement force in knot measurement.*

Figure 4. *Relationship between the force (F_{pw}) and displacement (l) of the lower clamp of the testing machine.*

The following test conditions were used for the measurements:
a) friction element – standard shoe eye with diameter d = 6.7 mm,
b) sample shoelace tension during wear: 0.5 daN,
c) length of the sample abrasive in a 30 mm mesh,
d) number of abrasion cycles: 1000,
e) wear intensity: 30 cycles/min,
f) the distance between the tensile clamps during the breaking force measurement before and after the 200 mm test,
g) the pre-load of the abrasive and non-abrasive samples was equal to 2% of the elongation of the non-abrasive sample.

Of the samples to be tested, half should be used for abrasion testing and the other half for determining the breaking strength of non-abrasive samples.
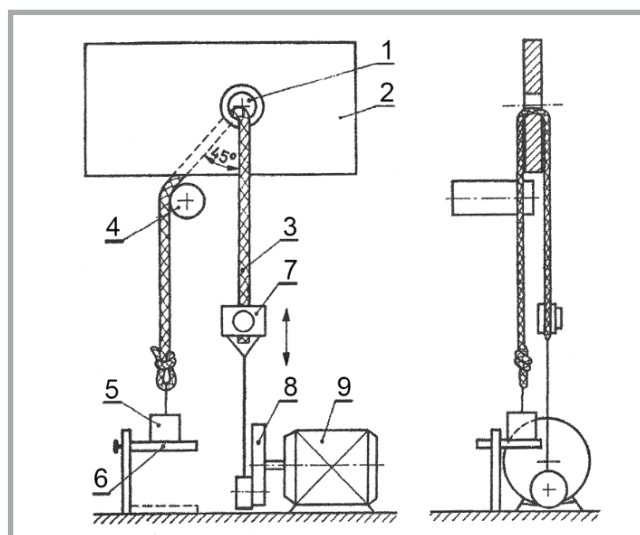
The method of performing abrasion measurements on the device is shown in **Figure 5**.

In order to perform the measurement, one end of the sample 3 should be connected to the weight 5 located on the movable base 6. Then the sample is pulled through the roller 4 and the eyelet 1 fixed on the plate 2, leading to the clamp 7. The sample in the clamp should be tensioned with a force causing the weight 5 to lift from the plate 6 to a height of about 2 mm and fix. After mounting the sample, the movable stand 6 is lowered to its lower position and the instrument started. After 1000 cycles are registered on the meter, the device should be turned off. After the abrasion tests, the breaking force is determined for all samples, i.e. for abrasive and non-abrasive ones, and it must be ensured that when determining the breaking forces of abrasive samples, the abrasive section occurs in the middle of the distance between the clamps. From the results obtained after calculating the average breaking force F_0 for non-abrasive samples and the average breaking force F_s for abrasive samples, the value of the abrasion resistance coefficient K_s is calculated according to **Equation (1)**.

Research material

In accordance with the methods developed, tests were carried out to evaluate the sliding force in the node and abrasion resistance for shoe laces made of various raw materials (fibres) i.e. yarns. Shoelaces also differed in dimensions as well as in structure and shape. The research material and its characteristics are presented in **Table 1**. For each of the 23 samples, the type of raw material, yarn linear mass, type of weave and shape as well as the width or diameter of the shoelace are given. Individual items 1 ÷ 23 in **Table 1** include shoelaces made of: polypropylene (1 ÷ 8), elastil (9 ÷ 11), polynosic (12 ÷ 15), cotton (16 ÷ 18), textured polyester (19 ÷ 20), polyester (21 ÷ 22) and polyamide (23).

■ **Results and discussion**

Table 2 shows results of the displacement force in the node and the abrasion rate of shoe laces.

In **Table 2**, column 2 contains sample designations, column 3 – average values of the travel force in the node (F_{pw}) in cN, column 4 – the results of measurements of abrasion resistance coefficients Ks calculated from **Equation (1)**, column 5 – compliance with the requirements for the travel force in the node (F_{pw}), where the "+" sign means that the requirements are met, while the "–" sign that it does not satisfy the requirements, column 6 – the requirements for the abrasion resistance coefficient (K_s), where the "+" sign means that the requirements are met, while the "–" sign that it does not satisfy the requirements, and column 7 contains the quality assessment of the shoelace,

Figure 5. *Test rig for measurement of the abrasive coefficient: 1 – shoes, 2 – plate, 3 – specimen, 4 – roller, 5 – load, 6 – movable base, 7 – clamp, 8 – eccentric wheel, 9 – electric motor.*

Table 1. *Material characterisctics of shoelace samples.*

No	Sample name	Raw material	Linear mass	Weave type/shape	Width (diameter), mm
1.	PP/3	polypropylene	167 dtex, f 150	braided/flat	3.0
2.	PP/4.5	polypropylene	167 dtex, f 150	braided/ flat	4.5
3.	PP/6.5	polypropylene	167 dtex, f 150	braided/ flat	6.5
4.	PP/8.5	polypropylene	167 dtex, f 150	braided/ flat	8.5
5.	PP/5	polypropylene	167 dtex, f 150	braided/tape	5.0
6.	PP/8.5	polypropylene	167 dtex, f 150	braided / tape	8.5
7.	PP/10	polypropylene	167 dtex, f 150	braided / tape	10.0
8.	PP/11	polypropylene	167 dtex, f 150	braided/ tape	11.0
9.	El/4.0	elastil	110 dtex x 2	dziana/ flat	4.0
10.	El/6.0	elastil	110 dtex x 2	dziana/ flat	6.0
11.	El/4.0	elastil	110 dtex x 2	braided/ tape	4.0
12.	Pn/4.5	polynosic	40 tex x 1	braided / flat	4.5
13.	Pn/5.5	polynosic	40 tex x 1	braided / flat	5.5
14.	Pn/7.0	polynosic	40 tex x 1	braided / flat	7.0
15.	Pn/10.0	polynosic	40 tex x 1	braided/tape	10.0
16.	CO/2.5	cotton	25 tex x 2	braided /round	2.5
17.	CO/3.5	cotton	25 tex x 2	braided / round	3.5
18.	CO/4.0	cotton	25 tex x 2	braided / round	4.0
19.	TPE/3.0	textured polyester	200 dtex	knitted/ tape	3.0
20.	TPE/6.0	textured polyester	200 dtex	knitted / tape	6.0
21.	PE/6.0	polyester	19 tex x 2	braided / flat	6.0
22.	PE/11.0	polyester	56 tex x 1	braided / tape	11.0
23.	PA/4.0	polyamide	235 dtex	braided / round	4.0

Table 2. *Results of displacement force at the knot and abrasion resistance coefficient for examined footwear laces ((+): $F_{pw} \geq 490\,cN$, (-): $F_{pw} < 490\,cN$, (+): $K_s \geq 0.85$, (-): $K_s < 0.85$).*

No	Sample name	Displacement force in the knot F_{pw}, cN	Abrasion resistance coefficient Ks	Requirements F_{pw}	Requirements K_s	Quality evaluation
1.	PP/3	490	0.96	+	+	+
2.	PP/4.5	495	0.97	+	+	+
3.	PP/6.5	505	0.98	+	+	+
4.	PP/8.5	510	0.96	+	+	+
5.	PP/5	482	0.97	–	+	–
6.	PP/8.5	490	0.98	+	+	+
7.	PP/10	490	0.99	+	+	+
8.	PP/11	485	0.98	–	+	–
9.	EI/4.0	580	0.94	+	+	+
10.	EI/6.0	510	0.99	+	+	+
11.	EI/4.0	545	0.95	+	+	+
12.	Pn/4.5	535	0.60	+	–	–
13.	Pn/5.5	515	0.42	+	–	–
14.	Pn/7.0	440	0.50	–	–	–
15.	Pn/10.0	570	0.85	+	+	+
16.	CO/2.5	530	0.91	+	+	+
17.	CO/3.5	556	0.90	+	+	+
18.	CO/4.0	665	0.92	+	+	+
19.	TPE/3.0	525	0.99	+	+	+
20.	TPE /6.0	510	0.98	+	+	+
21.	PE/6.0	498	0.88	+	+	+
22.	PE/11.0	570	0.92	+	+	+
23.	PA/4.0	380	0.82	–	–	–

where "+" indicates a positive rating, while "–" shows a negative one.

Based on the results of tests from 23 samples of shoe laces, acceptable indicators for the shoelace force in the node $F_{pw} \geq 490$ cN and the wear resistance factor Ks ≥ 0.85 were adopted.

A positive assessment of shoelaces is taken if both indicators are at least equal to the minimum values of F_{pw} and K_s.

As a result of tests of shoelaces, both woven and knitted, made of various raw materials in terms of abrasion resistance and sliding forces in the node, various results were obtained, which may be influenced by factors such as the type of raw material, the structure of the shoelace (braided or knitted) and its width.

Analysing the abrasion coefficients, it was found that values above 0.9 definitely occur. Of the factors mentioned above, the shape of the shoelace has a clear impact on the abrasion of the laces. In the case of shoelaces made of polynosic, the braided shoelace in the shape of a ribbon has a coefficient $K_s = 0.94$, and the remaining shoelaces made of this material in the shape of a flattened T-shirt have low abrasion coefficients in the range of 0.30 ÷ 0.60. Shoelaces for which coefficients K_s were less than 0.70 were worn in places of abrasion, as a result of partial wiping of the yarn forming the shoelace. Considering the force of travel in the node, it should be stated that for round braided cotton laces, the lacing force increases along with the width of the laces. For polypropylene woven laces with a ribbon shape and flattened jersey, the sliding force values in the node are similar. No influence was observed here for either the shoelace width or shape. For shoelaces made of polynosic, the braided shoelace in the shape of a ribbon has the highest sliding force in relation to that made in the shape of a T-shirt.

■ Summary

Based on the results obtained, it is proposed to adopt for all braided and knitted shoelaces made of various raw materials the following required values of indicators: sliding force in the node $F_{pw} \geq 490$ cN, and coefficient of abrasion resistance $K_s \geq 0.85$. Due to the simultaneous validity of both the F_{pw} indicator and K_s, shoelaces for which at least one of these indicators does not meet the above requirements should be considered as low quality.

In the light of the requirements set out above for the laces in the criteria presented for their assessment, polyamide shoelaces with the symbol PA/4 and braided laces in the shape of a T-shirt with symbols Pn/4.5, Pn/5.5 and Pn/7 made of polynosic should be qualified as low quality. From the laces made of polynosic, only the shoelace with the symbol Pn/10, made in the shape of a ribbon is of good quality ($K_s = 0.85$ and $F_{pw} = 570$ cN). It follows the very important conclusion that when using polynosic as a raw material for shoelaces, only braided ones should be produced.

To sum up, it should be stated that the criteria presented for assessing shoelaces allow for economically justified use of the raw material, choosing the structure and shape of the shoelace in such a way as to ensure the quality parameters required on the one hand, and use the cheapest technological process on the other.

The test methods presented may form the basis for the development of new standards in the quality testing of shoelaces.

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