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 \( K_w \), are the most important factors.

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

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**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 stabilization. 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 foot 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 (laces 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 forefront 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.

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**Figure 1.** Shoe lacing patterns: crisscross, zigzag, star, bowtie, serpent, s-zigzag laccings [2].

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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 displacement force in the 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)**:

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

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 $F_s$ and $F_0$ of shoelaces, a ripper with a range of 50, 100, 200 daN was used. The length of the samples was 500 ± 5 mm.
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 \( F_b \) for non-abrasive samples and the average breaking force \( F_a \) for abrasive samples, the value of the abrasion resistance coefficient \( K_a \) is calculated according to Equation (1).

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K_a = \frac{F_b}{F_a}
\]

### Results and discussion

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

| 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/10       | polypropylene| 167 dtex, f 150 | braided/tape     | 10.0                |
| 6.  | PP/11       | polypropylene| 167 dtex, f 150 | braided/tape     | 11.0                |
| 7.  | PP/12       | elastil      | 110 dtex x 2   | dziana/flat      | 4.0                 |
| 8.  | PP/13       | elastil      | 110 dtex x 2   | dziana/flat      | 6.0                 |
| 9.  | PP/14       | elastil      | 110 dtex x 2   | braided/tape     | 4.0                 |
| 10. | PP/15       | polypropylene| 40 tex x 1     | braided/flat     | 4.5                 |
| 11. | PP/16       | polypropylene| 40 tex x 1     | braided/flat     | 5.5                 |
| 12. | PP/17       | polypropylene| 40 tex x 1     | braided/flat     | 7.0                 |
| 13. | PP/18       | polypropylene| 40 tex x 1     | braided/flat     | 10.0                |
| 14. | PP/19       | cotton       | 25 tex x 2     | braided/round    | 2.5                 |
| 15. | PP/20       | cotton       | 25 tex x 2     | braided/round    | 3.5                 |
| 16. | PP/21       | cotton       | 25 tex x 2     | braided/round    | 4.0                 |
| 17. | PP/22       | textured polyester | 200 dtex | knitted/tape    | 3.0                 |
| 18. | PP/23       | textured polyester | 200 dtex | knitted/tape    | 5.0                 |
| 19. | PP/24       | polyester    | 19 tex x 2     | braided/flat     | 6.0                 |
| 20. | PP/25       | polyester    | 56 tex x 1     | braided/late     | 11.0                |
| 21. | PP/26       | polyamide    | 235 dtex       | braided/round    | 4.0                 |

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 \( K_a \) 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 \( K_a \), 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,
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 $F_{pw}$ ≥ 490 cN and the wear resistance factor $K_s$ ≥ 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 polymeric, 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 polymeric, 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 $F_{pw}$ ≥ 490 cN, and coefficient of abrasion resistance $K_s$ ≥ 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 polymeric should be qualified as low quality. From the laces made of polymeric, 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 polymeric 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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