Design methodology of the strength properties of medical knitted meshes

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Abstract. One of the most important utility properties of medical knitted meshes intended for hernia and urological treatment is their bidirectional strength along the courses and wales. The value of this parameter, expected by the manufacturers and surgeons, is estimated at 100 N per 5 cm of the sample width. The most frequently, these meshes are produced on the basis of single- or double-guide stitches. They are made of polypropylene and polyester monofilament yarns with the diameter in the range from 0.6 to 1.2 mm, characterized by a high medical purity. The aim of the study was to develop the design methodology of meshes strength based on the geometrical construction of the stitch and strength of yarn. In the environment of the ProCAD warpknit 5 software the simulated stretching process of meshes together with an analysis of their geometry changes was carried out. Simulations were made for four selected representative stitches. Both on a built, unique measuring position and on the tensile testing machine the real parameters of the loops geometry of meshes were measured. Model of mechanical stretching of warp-knitted meshes along the courses and wales was developed. The thesis argument was made, that the force that breaks the loop of warp-knitted fabric is the lowest value of breaking forces of loop link yarns or yarns that create straight sections of loop. This thesis was associate with the theory of strength that uses the “the weakest link concept”. Experimental verification of model was carried out for the basic structure of the single-guide mesh. It has been shown that the real, relative strength of the mesh related to one course is equal to the strength of the yarn breakage in a loop, while the strength along the wales is close to breaking strength of a single yarn. In relation to the specific construction of the medical mesh, based on the knowledge of the density of the loops structure, the a-jour mesh geometry and the yarns strength, it is possible, with high accuracy reaching up to 95 – 87 %, to determine the actual bidirectional strength of medical meshes.

1. Introduction
Warp knit fabrics are widely used, among others, in clothing, underwear production and hosiery, decorating industry, upholstery as technical products, including medical devices. The last group can include knitted medical mesh, among others, hernia mesh [1, 2, 3, 4]. Hernia surgeries are one of the most commonly performed medical procedures. It is worth noting that ignoring hernia may result in serious consequences, and even death.

Hernia (Lat. Hernia) is an undesirable exit of the whole or part of an organ or bulging of tissue beyond its anatomical location [6, 7, 8, 9]. In 1984, Irving Lichtenstein performed the first surgery using hernia mesh (Fig.1).
The basic performance parameter of knitted hernia mesh is its bi-directional tensile strength along courses and wales. In the process of designing knitted fabric, we should also take into account the need to reduce the weight of an implant, ensure a high porosity of the resulting structure and its elasticity as well as its biocompatibility with the body. The expected value of the strength of the hernia mesh is estimated by manufacturers and doctors at the level of 20÷30 cN/11 cm of the width of a sample [10]. Currently, the process of designing hernia mesh is a trial-and-error process, since structural parameters and strength are tested empirically, after the fabric has been manufactured. There is no logical and engineering methodology of designing bi- or multi-directional strength of medical mesh. Therefore, it was advisable to undertake research to develop the methodology to design strength properties of medical mesh in terms of the geometric structure of the weave and yarn properties.

2. **The mechanical model of the stretched warp knit fabric.**

An analysis of the forces acting in the elements of the structure of the mesh during the stretch of the fabric in static conditions has been performed. Considerations refer to stretching along courses and wales. Across the width S of the fabric stretched by force F there is n wales and m courses, each fabric is then stretched with a force $F_n$ and $F_m$. A serial arrangement of the structural elements of the fabric results in the stretching process which can be reduced to one mesh. This allows us to specify an absolute strength for the whole width of the sample, and a relative strength for a course or a wale of the mesh. For more complex structures the strength is referred to a repetitive element, for example, a slot (intersection of meshes) or a unit of the length and the width. Currently, manufacturers usually provide the absolute strength of the mesh in Newton, defined for a sample with the width equal to 5 cm. Looking at the problem from the viewpoint of the structure of the fabric, it is justified to use the concept of relative strength. This enables the design of the strength for similar structures of a greater or lesser density and of a comparable structure of repetitive elements of the knitted fabric.

In Figure 2 a model of the knitted fabric stretched along courses and along wales has been presented. A sample of the width S is gripped between two jaws, the upper one moves sliding up to the breaking point. The distribution of forces in the serially arranged mesh while stretching along the courses and wales has been presented in Fig. 3.

The following thesis has been put forward for research on modeling of the strength of knitted fabrics: The force breaking the mesh of a warp knit fabric is the lowest value of the force from among forces breaking the thread of the mesh chain or the force breaking thread of straight sections of the mesh.
This thesis, which is the foundation for the theoretical analysis of the strength of knitted fabric, refers to the theory of the strength and fatigue life using the concept of "the weakest link" (the weakest link concept) [6]. The defect of an elementary link in the described concepts of probability is understood as any object in the fabric, which generates heterogeneity of the fabric structure and accelerates the process of degradation. Therefore, a criterion of minimum force for all considerations concerning the determination of the mechanical strength of the mesh has been adopted:

\[ F_z = F_{\text{min.}} \]

where: \( F_z \) – the force breaking the mesh of the fabric, \( F_{\text{R min.}} \) – the minimum force breaking the threads in the mesh of the fabric stretched along the courses, \( F_{\text{K min.}} \) – the minimum force breaking the threads in the mesh of the fabric stretched along the wales.

The correctness of the presented thesis will be the answer to the question: "Which of the forces acting on the threads of the mesh with a specific strength of this thread is the lowest force that causes the damage to the mesh?"
2.1 Stretching the fabric along the courses.
An analysis of the forces acting in the mesh of a warp knit fabric has been performed subject to tensile force $F_R$. The distribution of forces in the components of the mesh, i.e. in the connector and straight sections of the loops of the mesh has been shown in Fig. 4.

Equilibrium conditions according to the reference system $XYO_1$:

\[-F_2 \cos \beta + 2F_1 \cos \alpha = 0 \quad (2.1-1)\]

If: \[F_R = F_2 \cos \beta \quad (2.1-2)\]

then: \[F_R = 2F_1 \cos \alpha \quad (2.1-3)\]

Equilibrium conditions according to the reference system $XYO_2$:

\[F_{2x} = F_2 \cdot \cos \beta \quad (2.1-4)\]

\[F_2 \cos \beta - F_R = 0 \quad (2.1-5)\]

Breaking forces:

\[F_{R1} = 2F_{ZN} \cos \alpha \quad (2.1-6)\]

\[F_{R2} = F_{ZN} \cos \beta \quad (2.1-7)\]

The force which will have a lower value according to formulas 2.1-6 and 2.1-7 is adopted as the force breaking the mesh while stretching the fabric along the courses:

\[F_{ZR} = F_{Rmin}.\]

2.2 Stretching the fabric along the wales.
An analysis of the forces acting in the mesh of a warp knit fabric subject to tensile force $F_K$ has been performed. Three variants of the geometry of the forces in the elements of the structure of the mesh have been adopted, i.e. in the connector and in straight sections of the mesh for the following relations of angles $\gamma$ and $\delta$:

I. where $\gamma = \delta$

II. where $\gamma > \delta$

III. where $\gamma < \delta$.

To solve the equations of equilibrium of forces in the elements of the mesh to force $F_K$ in the case of the relations of angles $\gamma > \gamma$ and $\delta < \delta$, the transformation of the reference system OXY has been adopted, so that one of the components of the force $F_K$ is equal to zero, i.e. $F_{1y} = 0$ then $F_K = f(F_2$ and trigonometric functions of angles $\gamma$ and $\delta$) and $F_{2y} = 0$ then $F_K = f(F_1$ and trigonometric functions of angles $\gamma$ and $\delta$).

The smallest value must be selected from the calculated values, which will determine the force breaking the wale:

\[F_{ZK} = F_{Kmin}.\]

Fig. 5 shows a generalized model of stretching the fabric along the wales taking into account the movement of threads between the loops and a connector of the mesh. In the course of further discussion this phenomenon has not been taken into account.
F₁ - forces acting in straight sections of the loop of the mesh
F₂ - a force acting in the connector of the mesh
F₁Δ - a component of forces acting in the threads of the loop in the direction of stretching the mesh
Fₖ - a force stretching (breaking) one wale
γ - an inclination angle of an axis of the loop from axis OY
δ - an inclination angle of the connector from axis OY
p₁, p₂, p₃ - expected displacement of threads

Fig. 5. A model of static stretching of the warp knit fabric along the wales

Table 1. Models used to determine the force breaking the mesh while stretching along the wales.

| Relation of angles γ = δ | Fᵏ₁ = 3FᴺCosγ |
|-------------------------|---------------|
| **Elimination of forces acting in the loop of the mesh** |
| Force F₂ to the left of axis y′ | Fᴷ² = \( \frac{FᴺCos\left(\frac{\pi}{2} - (γ + δ)\right)}{Cos\left(\frac{\pi}{2} - γ\right)} \) |
| Force F₂ to the right of axis y′ | Fᴷ³ = \( \frac{FᴺCos\left(δ - \left(\frac{\pi}{2} - γ\right)\right)}{Cos\left(\frac{π}{2} - γ\right)} \) |
| Force F₂ on axis y′ | Fᴷ⁴ = \( \frac{FᴺCos\left(\frac{π}{2} - γ\right)}{Cos\left(\frac{π}{2} - γ\right)} \) |
| **Elimination of a force acting in the connector of the mesh** |
| Force F₁ to the left of axis y′ | Fᴷ⁵ = \( \frac{2FᴺCos(δ - γ)}{Cos\left(\frac{π}{2} - δ\right)} \) |
| Force F₁ to the right of axis y′ | Fᴷ⁶ = \( \frac{2FᴺCos\left(\frac{π}{2} - (γ + δ)\right)}{Cos\left(\frac{π}{2} - δ\right)} \) |
| Force F₁ on axis y′ | Fᴷ⁷ = \( \frac{2FᴺCos\left(\frac{π}{2} - δ\right)}{Cos\left(\frac{π}{2} - δ\right)} \) |
| Relation of angles γ > δ | Relation of angles γ < δ |
|\( Fᴷ² = \frac{FᴺCos\left(\frac{π}{2} - (γ + δ)\right)}{Cos\left(\frac{π}{2} - γ\right)} \) | \( Fᴷ₁ = \frac{FᴺCos\left(\frac{π}{2} - (γ + δ)\right)}{Cos\left(\frac{π}{2} - γ\right)} \) |
| \( Fᴷ³ = \frac{FᴺCos\left(δ - \left(\frac{π}{2} - γ\right)\right)}{Cos\left(\frac{π}{2} - γ\right)} \) | \( Fᴷ₉ = \frac{FᴺCos\left(δ - \left(\frac{π}{2} - γ\right)\right)}{Cos\left(\frac{π}{2} - γ\right)} \) |
| \( Fᴷ⁴ = \frac{FᴺCos\left(\frac{π}{2} - γ\right)}{Cos\left(\frac{π}{2} - γ\right)} \) | \( Fᴷ₁₀ = \frac{FᴺCos\left(\frac{π}{2} - γ\right)}{Cos\left(\frac{π}{2} - γ\right)} \) |
| \( Fᴷ⁵ = \frac{2FᴺCos(δ - γ)}{Cos\left(\frac{π}{2} - δ\right)} \) | \( Fᴷ₁₁ = \frac{2FᴺCos\left(\frac{π}{2} - (γ - δ)\right)}{Cos\left(\frac{π}{2} - δ\right)} \) |
| \( Fᴷ⁶ = \frac{2FᴺCos\left(\frac{π}{2} - (γ + δ)\right)}{Cos\left(\frac{π}{2} - δ\right)} \) | \( Fᴷ₁₂ = \frac{2FᴺCos\left(\frac{π}{2} - (δ - γ)\right)}{Cos\left(\frac{π}{2} - δ\right)} \) |
| \( Fᴷ⁷ = \frac{2FᴺCos\left(\frac{π}{2} - δ\right)}{Cos\left(\frac{π}{2} - δ\right)} \) | \( Fᴷ₁₃ = \frac{2FᴺCos\left(\frac{π}{2} - δ\right)}{Cos\left(\frac{π}{2} - δ\right)} \) |
A collective presentation of equations to calculate breaking force $FK$ of the stretched knitted fabric along the wales for three variants of relations of angles $\gamma$ and $\delta$ and three cases of the location of forces $F_1$ and $F_2$ to the axis of $OY$ have been shown in Table 1. The listed relations to determine the breaking force are a function of the strength of the thread and geometric parameters of the mesh i.e. $FK = f(FZ; \gamma$ and $\delta)$. To model the strength of the knitted mesh the data is needed regarding the strength parameters and the geometry parameters of the structure of the knit in the process of stretching.

3. An analysis of the structure of the fabric while stretching.
An analysis of the geometry of the structure of a warp knit fabric focused on the determination of the following parameters:

- inclination angle $\alpha$, $\gamma$ of the loop of the mesh to axis $OX$ and $OY$,
- inclination angle $\beta$, $\sigma$ of the connector to axis $OX$ and $OY$,
- width of the wale, $A$
- height of the course, $B$
- width of the loop of the mesh, $c$
- height of the loop of the mesh, $d$
- size of satin area, $Pp$ (only in Pro Cad program for loosely structured variants)

The analysis was carried out on the basis of images of the stretched fabric on the tensile tester. For the purposes of empirical research six variants of the mesh weaves have been designed: symmetrical double course satin with cloth structure and mixed meshes for threadings 1/3, 2/2, 3/1, 1/1 (with shifted and identical threadings) and a weave of the cloth of threading 1/1. The knitted fabric was manufactured from polypropylene monofilament yarn having a diameter of 0.08 mm, on a warp HKS3 produced by K. Mayer, with a needling number E28. Photos have been taken of stretched fabrics on the tensile testing machine in two perpendicular directions (Fig. 7).

Fig. 6. Analyzed structures of knitted mesh

Fig. 7. The image of the fabric on the tensile tester stretched
a- along courses, b- along wales
On the basis of the photographs taken with the program GIMP basic geometrical parameters of the structure of the knitted fabric have been read. The results are shown in Table 2.

Stretching both along courses and wales causes a significant rapprochement of straight sections of the mesh and connectors to axis OY (a longitudinal axis of the stretched fabric), causing that inclination angles $\gamma$ and $\sigma$ at the breaking point are close to zero. The values of angles obtained in this method were used in the calculation of the critical values of forces breaking the fabric mesh.

4. The experimental analysis of the strength of warp knit fabrics

4.1 Testing the strength of yarn

The strength of single yarn and yarn in the loop has been tested. Polypropylene yarn with a linear density of 4.6 tex and a diameter of 0.08 mm was subject to the test. The test was conducted on the device manufactured by Hounsfield, setting the speed of the upper beam movement at 100 mm/min. The length in jaws was 500 mm. The study shows that the breaking strength of the monofilament in the loop is 3.72 N with elongation at the breaking point of 19.62 %, so per thread the force is 1.86 N. The average strength of a single thread stretch is 2.16 N with elongation $\varepsilon = 25.94 \%$.

Table 2. The values of the basic parameters of the structure of the mesh while stretching along courses and wales

| STRETCHING ON TENSILE TESTER ALONG COURSES | STRETCHING ON TENSILE TESTER ALONG WALES B |
|-------------------------------------------|------------------------------------------|
| Elongation: initial | maximum | initial | maximum |
| inclination angle of the connector to axis OX, degrees | 59.22 | 85.91 | 21.25 | 85.25 |
| inclination angle of the loop to axis OX, degrees | 66.85 | 88.28 | 17.36 | 85.68 |
| inclination angle of the connector to axis OY, degrees | 30.78 | 4.09 | 68.75 | 4.75 |
| inclination angle of the loop to axis OY, degrees | 23.15 | 1.72 | 72.64 | 4.32 |
| width of two loops and the connector, mm | 4.03 | 4.64 | 4.32 | 0.72 |
| width of a wale, mm | 2.262 | 2.41 | too close arrangement of elements of the mesh |
| height of a course, mm | 0.41 | 0.89 | too close arrangement of elements of the mesh |
| width of a loop, mm | 0.42 | 0.54 | 0.18 |
| height of a loop, mm | 1.47 | 1.15 | 1.54 | 1.54 |
4.2 Testing the strength of the knitted fabric
The study was conducted on two strength testing machines: HOUNFIELD and Instron 3345. The samples used for testing the strength of knitted fabrics have dimensions 5x20 cm, the distance in the jaws of the tensile machine is 10cm. Knitted mesh with the weave of satin and cloth were subject to the test. Only the basic weave of cloth of threading 1/1 was further analyzed. The big problem for both tensile machines while stretching was breaking at the jaws.

The measurement results of stretched knitted fabrics:
The average absolute strength of the fabric while stretching along wcourses was 150.25 N, elongation at the breaking point of 108.1 %. The absolute strength along the wales: 89.78 N, elongation at the breaking point of 316.9 %. Referring the above values to a single course and single wale we receive, respectively:
the relative strength along the courses: 1.67 N / 1 course,
the relative strength along the wales: 2.24 N / 1 wale.

5. Verification of methodology of designing the strength of knitted medical mesh
Calculations have been made of the theoretical strength of the knitted mesh with a cloth weave, based on the models identified in Chapter 2. These values were determined depending on the inclination angles of the elements of the mesh, i.e., the connector and straight sections of the loop to axis OY and the strength of single yarn and yarn in the loop. The calculation algorithm was created in Excel. It consists of three blocks:
- input data: the strength of thread $F_{ZN}$, the angles $\alpha, \beta, \gamma, \delta$
- computing, which recorded fifteen formulas determining the breaking forces of knitted fabric
- results of the calculation: the value of the minimum force of all calculated values in the calculation block ($F_{R_{\text{min}}}$, $F_{K_{\text{min}}}$).

5.1 The computing strength of the knitted fabric stretched along the courses
Since a criterion $F_{ZR} = F_{R_{\text{min}}}$ was established as the force breaking the mesh, a smaller force is accepted from the obtained calculations, i.e. $F_{R2}$ which equals to 1.86 N/wale.
Also, calculations of the strength of yarn broken individually were performed giving the result $F_Z = 2.15\ \text{N/cm}$. The relative strength of the fabric stretched along the courses, referred to one mesh can be determined by means of the strength of the yarn in the loop. It equals $1.86\ \text{N}$. The absolute strength of the fabric is then determined as the product of the force and the number of courses in the sample.

5.2 The computing strength of the knitted fabric stretched along the wales

To determine a theoretical force breaking the mesh of the fabric stretched along the wales, it was necessary to determine the relationship between the angles $\gamma$ and $\delta$, and perform appropriate calculations. In the studied weave of cloth a relation $\gamma<\delta$ occurs between the angles, so the formulas FK8-FK13 were used. According to the criterion of a minimum force, the smallest force $F_{K_{\text{min}}}$ is considered to be a value breaking the mesh.

After rounding measurements of angles $\gamma$ and $\delta$ to the nearest unit, 4 degrees were obtained for both angles. Thus it is reasonable to use the following formula:

$$F_K = 3F_Z \cos \gamma = 3 \cdot 2.16\ \text{N} \cdot \cos 4^\circ = 3 \cdot 2.16\ \text{N} \cdot 0.99 = 6.42\ \text{N/cm}$$

Table 3. Computing strengths

| Determining the strength of the mesh while stretching along wales | unit   |
|---------------------------------------------------------------|--------|
| For mean values                                               |        |
| Force breaking yarn in the loop                               | 1.86000 \text{N} |
| Average inclination angle of the loop to axis OY, $\gamma$    | 4.31800 \text{degrees} |
| $\gamma$, rad                                                 | 0.07536 \text{radians} |
| Average inclination angle of the connector to axis OY, $\delta$ | 4.75200 \text{degrees} |
| Force FK8, breaking a wale                                    | 3.89434 \text{N} |
| Force FK9, breaking a wale                                    | 3.89434 \text{N} |
| Force FK10, breaking a wale                                   | 24.70382 \text{N} |
| Force FK11, breaking a wale                                   | 7.07875 \text{N} |
| Force FK12, breaking a wale                                   | 7.07875 \text{N} |
| Force FK13, breaking a wale                                   | 44.04222 \text{N} |
| Minimal force determining the strength of warp knit fabric while stretching along wales | 3.89434 \text{N} |

This result differs significantly from the actual value of the force breaking one mesh, which is equal to $2.24\ \text{N/cm}$. The following is a calculation algorithm of forces along the wales for the case $\gamma<\delta$, adopting the force breaking the thread in the loop (Table 3).

The minimum value of $F_{K_{\text{min}}} = 3.89\ \text{N/wale}$ was obtained. Calculations taking into account a force breaking a single yarn were performed. For this case, the theoretical strength of the mesh is $F_{K_{\text{min}}} = 4.52\ \text{N/wale}$.

From this comparison it follows that experimental and theoretical values of the strength along the courses are close, however, while stretching along wales they are significantly different. Noteworthy is
a large convergence of the fabric strength to the strength of threads. Attention should also be given to
the problems of measuring the angles necessary to determine the designed strength. This applies to the
place of measurement of angles and a big discrepancy between the measurement results. It seems
legitimate for practical reasons to estimate the relative strength of the fabric on the basis of the
strength of the yarn used.

| Experimental strength of yarn | Theoretical strength of knitted mesh |
|-------------------------------|-------------------------------------|
| - single thread              | 2,16 N                              |
| - thread broken in yarn       | 1,86 N                              |
| - along courses               | 1,67 N/1 course                     |
| - along wales                 | 2,24 N/1 wale                       |
| - along courses               | 2,15 N/1 course                     |
| - along wales                 | 4,52 N/1 wale                       |
| - along courses               | 1,86 N/1 course                     |
| - along wales                 | 3,89 N/1 wale                       |

**Fig. 9** Verification of simulations of the strength of knitted mesh

6. Conclusions

1. In the absence of logical and engineering method of designing single- or multi-directional
   strength of medical mesh, it was expedient to develop theoretical assumptions to identify
   strength properties of medical mesh in terms of the geometry of the weave and properties
   of yarn.
2. The mechanical model of the strength of knitted mesh was based on the thesis that a force
   breaking the mesh of a warp knit fabric is the lowest value of the force from among
   forces breaking the thread of the mesh chain or a force breaking the thread of straight
   sections of the mesh. This thesis refers to the theory of strength and fatigue life based on
   the probabilistic concept of the “weakest link”.
3. On the basis of the presented models of two-way process of stretching fifteen calculation
   relations of a critical value of a breaking force were introduced. The strength of the mesh
   is a function of the strength of yarn and an inclination angle of the sections of the mesh to
   the axis of stretching.
4. Calculated values of the force breaking the mesh of knitted fabric are close to the
   experimental strength.
5. The actual strength of the cloth weave mesh related to one course is equal to the strength
   of yarn broken in the loop. The strength of the fabric stretched along the wales, however,
   is close to the force breaking a single yarn. The following statement can be used in a
   practical approach to estimate the approximate strength of knitted mesh.
6. The absolute strength breaking the warp knit fabric subject to stretching is directly
   proportional to the strength of yarn and closeness of courses and wales.
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