Simulation-Based Development of Gradient Woven Fabrics

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Contributor: Tobias Georg Lang , Dominik Nuß , Thomas Gereke , Gerald Hoffmann , Michael Wöltje , Dilbar Aibibu , Chokri Cherif

Tendons and ligaments are complex tissues that are necessary for movement of the human body. Ligaments connect two bones, and serve to guide and support joints, while tendons realize the transmission of forces between soft muscles and hard bones. Injuries occur very commonly, and usually due to chronic abrasion or trauma, e.g., in sports accidents. The gold standard for the treatment of such defects is the use of the patient's own tissue, e.g., from the back muscle for shoulder tendons or from the thigh for the anterior cruciate ligament. However, autologous material is only available in limited quantities and harvesting is associated with an increased risk of complications (donor morbidity). Alternatives to autologous material are biological or synthetic implants, which, however, still have significant deficits. Thus, from a medical and economic point of view, there is a need to develop novel biomimetic (adapted to biological and structural properties of human tendons and ligaments) and long-term resorbable implants to cure defects.

finite element method (FEM) gradient structure open reed weaving

shuttle narrow weaving loom

1. General Considerations

Tendons and ligaments are primarily composed of collagen fibers embedded in an extracellular matrix. The fiber arrangement is subject to a complex hierarchical principle. They not only run parallel to the longitudinal axis, but also are diagonal as well as undulating and intersecting. The arrangement varies depending on the position. Thus, they form spiral-like, interwoven structures [1]. The undulation of fibers protects tendons and ligaments from injury, as the fibers first align themselves under load (structural elongation) before rupture because of excessive material stretching. The nonlinear deformation behavior of tendons and ligaments is realized by complex, graded structural zones. Deformation occurs initially by alignment of undulated collagen fibers and leads to complete failure through material stretching and initial fibril rupture. The tendon and ligament tissue first transitions into cartilage tissue and then into bone tissue. In tendons, a transition zone also forms between the tendon and muscle. In the three or five different tissue zones, different cell types and matrix compositions are found, which exhibit different stiffness and deformation behavior. It follows that implants must represent these different zones to ensure appropriate cell colonization and, thus, restoration of the ligament or tendon.

The use of degummed silk (silk fibroin) improves mechanical properties, biocompatibility, and long-term resorbability, compared to currently used resorbable polymers [2][3][4][5][6]. Furthermore, the formation of toxic degradation products is avoided. Silk fibroin is a natural protein with high bioactivity and good biocompatibility. It supports or promotes adhesion, proliferation, growth and differentiation of cells, which eventually lead to tissue regeneration [7][8][9][10][11][12][13][14]. Silk fibroin fibers have a strength of about 0.5 GPa and a breaking strain of around 15% [15]. Compared to other resorbable materials, such as collagen and poly-L-lactide acid (PLLA), silk fibroin fibers are thus highly resilient: they exhibit a strength more than three times higher than PLLA and 67 times higher than collagen [5]. Therefore, silk fibroin yarn is especially predestined for the reconstruction of tendons and ligaments in terms of structural mechanics.

2. Textile Materials for Use as Tendon or Ligament Implants

Textile technology is especially suited to fabricate graded and biomimetic tendon and ligament implants. Various technologies were investigated for that purpose: braiding [16][17][18][19][20][21][22], knitting [23][24][25], weaving [26][27][28][29], and embroidery [30][31].

Using braiding, adjustment of fabric properties is mainly limited to the variation of the braiding angle. While tendons and ligaments exhibit relatively small dimensions (up to 10 cm), structural adaptation to natural requirements of tendons and ligaments is, thus, only possible to a limited extent within the process. A change in geometry (e.g., from the ligamentous bone-tendon insertion to the round tendon center) requires special machines that can switch between flat and circular braids. The implementation of graded stiffness zones is also challenging, as stiffness differences homogenize in regular braids with recurrent cyclic loading.

Gereke et al. [21] have presented a possible range for tailoring the mechanical properties of braided ligament replacements by a variation of the braiding process parameters, together with an FEM (finite element method) model of the braiding process. They varied the braiding angle by applying different draw-off forces in the braiding process, which influenced the tensile properties of the braided structure.

Knitted fabrics for tendon/ligament implants have been prepared from silk fibroin [25], Poly(Lactic-co-Glycolic Acid) (PLGA) [23][24] and Poly-ε-Caprolactone (PCL) [24]. Even though cell reaction was positive, mechanical strength of native tendon/ligament could not be achieved, due to the fact that its textile structure and deformation behavior could not be reproduced. The commercially used knitted product Artelon® (Artelon, Marietta, GA, USA) is manufactured from fibers of polycaprolactone-based polyurethane urea (PUUR) [32][33]. However, it does not exhibit graded stiffness and, thus, does not support locally adapted cell differentiation.

Stitching of tendon and ligament replacements has also been investigated for the anterior cruciate ligament using absorbable lactic acid-based materials [30][31]. However, machine parameters, such as stitch length and needle diameter, limit the formation of graded features.

Woven implants are commercially available. The woven fabric X-Repair™ (Synthasome Inc., Del Mar, CA, USA) is manufactured from PLLA fibers and, thus, bears the risk of over-acidification of the defect site [29]. Due to the highly dense weave, there is only little space available for the formation of tendon cells from collagen fibers and supporting extracellular matrix. Another commercial product, Biofiber™ (Tornier Inc., Edina, MN, USA), is an open-pored leno weave from the degradable polymer prolyl 4-hydroxylase (P4HB) [29]. It is constructed from several textile layers that are sewn together [28]. It provides only a constant deformation behavior over the length, which means that the requirements for a biomimetic implant are not achieved.

The deformation behavior of a woven fabric is a result of fiber material properties and the weave pattern used. Selectively combining different weave patterns within one fabric enables locally different deformation behavior. This effect has been used to date to adjust the drape behavior of fabrics for composite reinforcements in a targeted manner [34][35]. The use of open reed weaving (ORW) technology (broad weaving technology) and variable-width reed (ribbon weaving technology), in combination with multilayer woven structures, represent promising approaches for realization of fabrics with locally adjustable deformation behavior (structural mechanical gradients), varying fabric width and porosity over the length (geometric gradients) for biomimetic tendons and ligaments.

A simulation approach for the generation of a unit cell has proven to be especially useful, since it results in a high accuracy in representation of yarn cross-sections and contact areas compared to a moderate computation time [36][37][38]. Finite elements, known as digital elements, are particularly suitable for modeling textile structures made of multifilament yarns [37][39][40][41][42]. In this micro-scale approach, the filaments are discretized by chains of truss or beam elements connected by frictionless links at their nodes. The only mechanical property of the yarn is the tensile modulus in the fiber direction.

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