Introduction

Impotence is defined as the inability to achieve and maintain an erection adequate for satisfactory intercourse. It is a common problem for approximately 50% of men between the ages of 40 and 70. Impotence not only creates mental stresses in both the patient and his partner, but also can negatively affect self-esteem. In this study, computational biomechanical modeling tools have been developed to analyze the structural factors involved in normal, pathological (e.g. Peyronie’s disease) and artificial (prosthesis-aided) erection conditions.

Structural Analysis of the Normal Erect Penis

A biomechanical model of the normal human penis was developed to simulate the cross-sectional stress distribution during normal erection and to analyze the contribution of tissue characteristics to the erectile process. The model included the tunica albuginea, the skin, the dorsal blood vessels and the urethral channel (Fig. 1). The symmetrical two-dimensional (2D) geometry of the model was extracted from an anatomical schematic section through the middle of the penis and scaled to conform averaged dimensions. The model was solved for the structural stress distributions using commercial finite element software. The boundary conditions included 4 constraints on the lateral and dorsal-plantar aspects of the penis, allowing its expansion due to inflation by an equivalent erectile pressure \( P_e = P_a - \sigma_{cc} \). The erectile pressure \( P_e \) reflected the resistance stress \( \sigma_{cc} \) of the spongy corpus cavernosa tissue to inflation pressure \( P_a = 100 \) mmHg due to arterial blood flow into the penis cavities. As the penis becomes erect, blood is supplied to the corpus cavernosa until the corporal volume reaches \( V_E = 100\% \) of the total corporal capacity (TCC). When blood drains and the penis becomes flaccid, the corporal volume reduces up to \( V_F = 35\% \) TCC (Pescatory et al., 1994). Assuming that the corpus cavernosal tissue is unstressed at \( V_F \), the characteristic stretch ratio \( \lambda_{max} \) from flaccid to full erection is given by the generally accepted relationship \( \lambda = (V_E/V_F)^{1/3} \) and equals 1.42. In the absence of literature data describing the constitutive law of the corpus cavernosa tissue, the resistant stress \( \sigma_{cc} \) at the above stretch ratio was estimated as 7 KPa from the mechanical behavior of the lung parenchyma which is of a similar microstructure. The penile soft tissues in the model were assumed to be made of homogenous, isotropic, linear-elastic materials, whose mechanical properties are detailed elsewhere (Gefen et al., 1999; Gefen et al., 2001).

The simulation of stress distribution in the normal penis indicated that most of the load bearing during inflation is carried by the dorsal part of the tunica albuginea, where stresses are in the range of 5-30 KPa. This site contains several nerves and thus it is most vulnerable to intensified mechanical stresses. The skin appeared to bear a negligible load. Inflation of the neutral, elliptical cross-sectional shape of the cavernosum during erection yielded a more circular corporal profile, and lateral expansion of the penis cross-sectional shape (Fig. 1). This modeling approach allows simulation of stress distributions in various pathologic conditions of the penis by altering the geometry and material properties of its components, as demonstrated in the following sections.
Fig. 1. The normal penis model cross-sectional geometry, loading and boundary conditions (left) and the resulted von Mises stress distribution during full erection (right).

Fig. 2. Configuration of the penis model (left) and distribution of von Mises stresses during erection (right) in a representative condition of asymmetric Peyronie's plaque in the dorsal and middle parts of the tunica albuginea.

Fig. 3. Configuration of the human penis/IPP complex model (left) and the von Mises stress distribution resulting from its adaptation to representative circular prosthesis designs and positioning (right). IPP = inflatable penile prosthesis.
Application to Treatment Planning of Peyronie’s Disease

Peyronie’s disease is a pathological condition of the penis which is characterized by inflammation and ossification of the tunica albuginea that leads to penile deformities during erection, pain and erectile dysfunction. The above-described 2D biomechanical model of the penis was utilized to study the mechanical stress distribution during the development phases of Peyronie’s disease (Fig. 2) due to the mechanical interaction of ossified and normal penile tissues (Gefen et al., 2000a). The results demonstrate that Peyronie’s plaques may induce intensified stresses around penile nerves and blood vessels. These elevated stresses, which are more than double of those in a normal penis, may cause a painful sensation of neural origin or ischemia in regions of compressed vascular tissue. When the plaques cover only one of the corpora cavernosa, severe penile deformities have been shown to develop due to the non-homogeneous resistance of the tunica to expansion during erection (Fig. 2). The present model can be clinically applied for both analysis of the etiology of the disease and determination of the optimal timing for therapeutic interventions, such as a reconstructive surgery or insertion of a prosthesis.

Optimization of Design and Positioning of Penile Prosthesis

When conservative treatment of impotence fails, implantation of an inflatable penile prosthesis (IPP) can be carried out to restore erectile function. The interaction between the cylinders of the IPP and the surrounding tissues during IPP-aided erection may result in local elevated stresses. These stresses may reach values that can obstruct penile blood vessels and cause ischemia and/or stimulate nerves around the operation site, thereby inducing sensations of pain. The penis model was used to analyze penile stresses post-implantation of different IPP types, in order to optimize prosthesis design and surgical positioning by enabling minimal stress transfer to dorsal blood vessels and nerves (Gefen et al., 2000b). The results suggest that intralumenal pressures should be maintained at low levels (about 80 KPa) while cylinder thickness and stiffness should be kept just high enough (approximately 15% of the radius and 1000 MPa respectively) to eliminate deleterious cylinder-tissue contact stresses. Smaller prosthetic cylinders, i.e., occupying about 45% of the cavernosal space, may be advantageous in terms of reducing dorsal stresses, but lower penile rigidity should be expected (Fig. 3). A significant decrease of dorsal stresses can also be achieved by encouraging the surgeon to position the cylinders toward the lower part of the corpora. The computational simulations indicate that circular cylinders may allow greater biomechanical compatibility of the IPP with the penis structure than elliptic ones, and this should be a subject for clinical investigations.

Conclusions

The biomechanical model of the penis presented in this study is capable of predicting the distribution of stresses within its different tissue components. The ability to acquire data characterizing the internal stress state in the penis during erection makes this model a basic clinical tool, as it offers a new point of view on the mechanical factors that are active during erection and enables to relate these data with different penile pathologies. Being able to identify highly-loaded soft tissue regions of the penis, the model can be used not only for understanding the development mechanisms of some common erectile disorders (e.g. Peyronie’s disease), but also to be applied for development of novel clinical decision making and penile treatment approaches.

References