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Hair, Cloth and Soft Tissues: The Influence of Mechanical Properties on the Real-Time Dynamics of Deformable Objects

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Abstract

In spite of the impressive advancements achieved during the last years in the domain of interactive physically based simulation, the real-time animation of complex deformable objects still represents a challenge. In order to cope with the resulting computational complexity, researchers continue seeking adequate trade-offs between simulation accuracy and computing performance. One compromise allowing to gain processing power without loosing physical plausibility is selective physically based optimization, i.e. reducing the computations to a predictable amount based on the influence of physical material properties on the mechanical behavior of soft bodies. In this paper, we analyze simulation approaches for structurally different objects and discuss both their specificities and commonalities. We focus on the contribution of physical parameters in the real-time simulation of 1D rods, 2D surfaces and 3D volumes, taking as examples hair, cloth and soft tissues.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically-Based Modeling;

1. Introduction

Virtual reality interaction and physical simulation are computationally intensive tasks which aim at replicating real world phenomena with ever-improving realism. In this context, the interaction with virtual rigid objects has been studied for several decades and is now well understood. Interactive physically based simulation of complex deformable objects in real-time, however, still represents a challenge because of its high computational requirements.

The pursuit of an adequate trade-off between simulation accuracy and computing performance has lead to two major directions in the computer graphics community. On one hand, highly optimized simulation frameworks provide adhoc solutions which are confined to very specific problems and environments, such as e.g. the haptics-based incision of liver models or the tactile perception of textile surfaces. On the other hand, generic simulation frameworks tackle the representation of a broader variety of deformable objects, but achieve interactive rates at the cost of physical accuracy. As a result, simulation and interaction in digital environments are often artificially segregated. But in the physical world we can at the same time see and touch surrounding objects, with the same laws of physics universally governing all deformations of materials. As a corollary in the virtual world, a simulation framework is required which can easily animate a variety of elements and support multimodal interaction, without being too optimized for one specific simulation scenario, nor too generic to neglect physically plausible behavior.

In this paper, we analyze approaches for the physically based simulation of structurally different deformable objects and discuss both their possible specific optimizations and their generalities. We divide the general class of solid deformable objects into three geometric categories: 1D rods, 2D surfaces and 3D volumes. Analyzing the existing variety of simulation methods can provide important insights into the design of a model for real-time simulation of all categories of deformable objects. After a survey of the state of the art in physically based simulation (Sec. 2), we discuss the role of physical parameters in the real-time simulation of hair (Sec. 3), clothes (Sec. 4) and soft tissues (Sec. 5). We conclude the paper with an outlook on a unified simulation approach and prospects for future work (Sec. 6).

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2. Physical Models for Deformable Objects

During the past decades, many researchers have tackled the challenge of achieving visually and physically plausible animation of deformable objects within virtual environments with increasing success. A thorough overview of physically based modeling approaches can be found in [NMK*06]. Different simulation models have been designed and implemented for solving specific problems arising in various contexts such as animation of hair strands, simulation of clothes, or representation of deformable volumes. Remarkably, the underlying physical models have been mostly tailor-made for a particular application and a particular mode of interaction with little regard to the common footing they may share with other objects.

2.1. One-dimensional Objects: Rods

Deformable one-dimensional objects simulated in computer graphics are typically slender structures which are represented as generic rods [ST07, BWR*08] and used for a variety of purposes, ranging from knot-tying simulations [ST08] to the simulation of grass blades [BW06]. Threads [LMGC04] or catheters [DCLN06] are typically used in virtual surgery simulators. Furthermore, other virtual prototyping applications in engineering and design make use of wires and cables [SL08]. In the video game industry, 1D-elements are typically used for simulating hair strands and fur [HCL*07].

While the structural properties of these objects are very similar, the physically based simulation of hair in real-time probably represents one of the most demanding research topics. Around 150000 individual hair strands populate the human scalp, and reproducing realistic hair dynamics taking into account individual hair structure and physical properties is an extremely complex and expensive task in terms of computing resources. Therefore, the reproduction of hair behavior poses the highest requirements to a real-time simulation model for one-dimensional objects.

Different models have been used to simulate the behavior of hair. A comprehensive survey on hair styling, simulation and rendering has been given by [WBK*07]. Methods modeling individual hair strand dynamics include explicit representation schemes (based on spring-mass models [RCT91], [SLF08] or one-dimensional projective differential equation of angular momentum [AUK92]), chains of rigid bodies [HMT01] and physically based models relying on the Cosserat theory of elastic rods [BAC*06]. The latter approach offers a good framework for tuning physical parameters of inextensible, unshearable rods, providing an intrinsic definition of bending and twisting rigidity within the model. Recent research contributions also reported significant performance improvements through appropriate optimizations [KBMT09, Ber09].

Other recent approaches for efficient real-time simulation of hair are based on particle systems. Among these, promising results were given by FFD-based animation methods [VMT06a], as well as spring-mass simulation of one-dimensional object modeling torsion through altitude springs [SLF08].

2.2. Two-dimensional Objects: Surfaces

Clothes are probably the most frequently reproduced deformable surfaces in virtual environments. Exhaustive overviews of the main topics in cloth animation research are given in [MTCK*04] and [BMF05]. The field of physically based cloth simulation has witnessed a vast research activity during the last two decades [MTV05] and different techniques for animating cloth-like materials have been proposed.

Among the most efficient cloth simulation methods, particle systems represent the cloth surface as a set of particle masses. The surface strain is approximated through geometrical relationships between neighboring particles, and corresponding particle forces approximate the stress. Particle acceleration is obtained from these forces, and the resulting ordinary differential system is integrated using adequate numerical methods, leading to the evolution of the particle positions along time.

The major issue with simple spring-mass models is their lack of accuracy, particularly when it comes to simulating accurately the non-linear and anisotropic behavior of cloth materials. Accurate particle-system models can be obtained by carefully formulating strain and stress on the surface of triangle elements according to the positions and forces exerted to its vertices, obtaining a simple implementation which is comparable to first-order finite elements [VDB*07].

Numerous improvements are available for expressing these models in an optimized and simplified way. Saint-Venant-Kirchhoff models allow the simple and explicit expression of the weft, warp and shear material strain out of the triangle element vertex positions, and similarly vertex forces out of the material stress. Such models can be associated to efficient numerical integration methods usually implemented in particle systems [EEH00, VMT05]. Among these, the Backward Euler method offers the best compromises between accuracy, computation time and robustness.

2.3. Three-dimensional Objects: Volumes

The human musculoskeletal system consists of different complex and heterogeneous elements. It provides form, support, stability, protection and locomotion for the human body. Modeling this system remains a big challenge due to its complex geometry, mechanical behavior and interactions. Despite evident interdependencies, the models developed in the various research domains predominantly focus on one specific aspect only.

Anatomical structures are typically extracted from medical data acquisitions (e.g. MRI) through image segmentation, which allows the simultaneous examination of soft and bony tissues. Clinical MRI datasets, however, present large amount of textural information, noise, and low resolution artifacts. Computer graphics techniques can be used to devise more adapted segmentation methods. Originally presented in a computer graphics context by Terzopoulos et al. [TW88], physically based deformable models gave birth to novel approaches in medical imaging analysis [MT96], with successful applications for image segmentation [WS00, GMMT06].

A popular research area requiring physically based modeling of deformable volumetric objects is the interactive clinical visualization of the hip joint examination. Proposed simulations are based on 3D models extracted from MRI and CT datasets – e.g. for surgical planning [SSS*00, SML01] and range of motion estimation [ABT07]. The analysis of the stress and contact distribution in the acetabulum region has been performed through simulations of the hip biomechanics based on spring-mass systems [KKI*03, MSBT05] and finite element methods (FEM) [AVR07, RSGP06]. In the context of volume simulations, a straightforward way to handle deformations is to use the St-Venant-Kirchhoff model, applying Green-Lagrange's non-linear strain measurement, while keeping material linearity [PDA03, BJ05].

3. Keratin Fiber Properties in Hair Simulation

Simulating realistic hair dynamics is an arduous task. Unlike other well-known physical materials, the remarkable mechanical properties of the keratin fibers composing hair strands have not been modeled by accurate equations in the history of physics. As a result, existing state-of-the-art approaches in hair simulation have provided ad-hoc solutions to specific problems, focusing e.g. on the ability to display straight or curly hair, providing a high simulation performance, or enabling interaction. But a universally valid approach capable of capturing all intricacies of hair dynamics in real-time is still missing. This is also due to the computational complexity of hair simulation, which frequently leads researchers to seek for a trade-off between accuracy and performance. Highly realistic, physically based models for hair dynamics are difficult to be exploited in real-time simulation because they are too complex in terms of mechanical behavior, and too expensive in terms of computing resources. Still, physical plausibility can be targeted by taking more into account the mechanics of hair strands and using physical properties. But which are the most relevant mechanical properties of hair fibers which can be used in hair simulation, thus allowing to take advantage of hair specifics to optimize performance? This question is indirectly addressed in hair science and cosmetics, where the mechanical parameters influencing the look and feel of hair are investigated in order to develop new hair care products.

3.1. Physical Properties and Mechanical Behavior

Physical and chemical behavior of human hair has been extensively reported in the literature along with descriptions of the human hair morphology, composition and properties [Rob02]. Common methods to assess fiber alterations analyze color changes, hair shine, protein loss, and changes of elastic properties [Hea00]. However, there are currently no standard procedures for experiments with human hair, and the best methodology to use in these studies, as well as the number of replicates necessary to have statistically significant results, is still undefined [NDJ06].

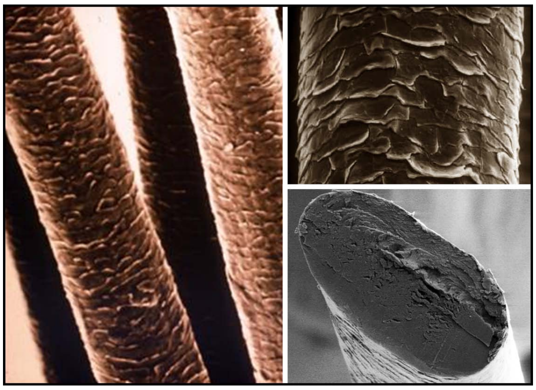

Figure 1: *The surface of hair fibers (left) is composed of tilted scales (top right) which are subject to high friction during motion. Bottom right: Caucasian hair fiber displays a strongly elliptical cross-section.*

The dynamic behavior of strands is mainly dependent on the elastic properties of hair fibers [BFL*01] which define the fiber's tensile, bending and torsion behavior. These properties however have different relevance, and a selection of the primary elastic characteristics allows a targeted exploitation of computing ressources. *Tensile* hair properties can be neglected in the context of VR simulation because hair does not stretch during natural movement [Rob02]. *Torsion* properties can be disregarded in the equations of motion because twist waves travel faster than bending waves in slender objects. Hence, torsion can safely be treated by a static update inbetween simulation frames and excluded from the simulation itself [BWR*08]. Hair *bending* is probably the most important elastic property of strands, and it can also be optimized through a thorough analysis of the hair structure. Because hair fibers display an elliptical cross-section (see Fig. 1, bottom right), there is good evidence that single fibers will naturally bend over their cross section's major axis only [Swi95]. This approximation also holds for Asian hair, whose cross-section is more circular, but still allows to identify cross-sectional major and minor axes. Since the strands' degrees of freedom are influenced by the fiber cross section, the bending over the fiber's minor axis can be neglected or minimized. Reducing the degree of freedom of strands can therefore optimize hair simulation without loss of plausibility. Hence, the main elastic property to consider for hair dynamics can be confined to the bending over the major axis.

Another important physical characteristic of hair fibers is given by their surface, which is not smooth, but composed of tilted scales instead, as Fig. 1 shows. This strong surface roughness causes a high anisotropic friction during hair-hair interactions, which increases the cohesion between strands and leads to wisp formation [LB05]. The consideration of this phenomenon allows to simulate only a reduced amount of "leading" strands influencing the dynamics of wisps, with additional "following" strands interpolated according to their position within the wisps and proximity to other wisps. Using the fibers' frictional coefficient to determine the formation of wisps and subsequently the hairstyle volume, the amount of simulated "leading" hair strands and their area of influence on "followers" leads to a physically plausible and significant performance improvement. While wisp-based optimization and clustering have been already used in early hair simulation approaches [DMTKT93], most attempts did not have a physically based formulation of anisotropic friction leading to a set of corollary effects concerning hair-hair interactions as well as hairstyle motion and volume.

3.2. Hair Handle

While the *quantitative*, objective measurement of elastic parameters can be performed through appropriate chemical, mechanical and optical means, the *qualitative*, subjective evaluation of hair fiber properties is performed by experts who professionally touch and feel hair. In this context, the term *hair handle* (HH) is used to describe to the sensations associated to the manipulation of hair. This multidimensional characteristic allows to define how far specific fiber properties influence hair softness or smoothness and consumer assessments regarding combing ease or manageability. Determining this correlation can be of utter relevance in hair science when developing new hair care products.

Studies conducted for the cosmetic industry divided the most relevant hair fiber properties influencing HH into three main categories [WSJ06]:

- Geometric properties such as fiber cross-sectional shape, ellipticity, diameter and length;
- Elastic properties, especially bending in fiber collectives;
- Surface properties, especially friction coefficients.

This study confirms that among the variety of physical properties of hair fibers, there is a strong analogy between properties which are relevant for hair dynamics and those which apply to hair haptics.

3.3. Suitable Hair Simulation Models

Physically plausible behavior of hair can be computed by a simulation model representing inextensible, unshearable rods with bending and torsion properties, taking primarly into account the strand's major axis bending energy in the dynamics equations, as well as the mass, the cross-sectional geometry and the surface roughness of hair fibers.

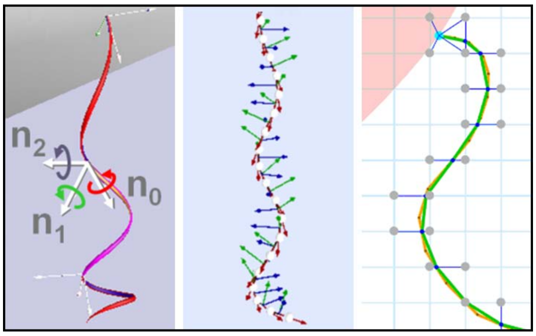

Figure 2: *Hair strands can be simulated as simplified super helices (left, [BMMT08]), hair-optimized discrete elastic rods (center, [KBMT09]), or particle systems subject to springs on a FFD lattice (right, [VMT06a]).*

These hair specifics can be adopted to optimize different simulation approaches (see Fig. 2). Models based on the Cosserat theory of elastic rods and particle systems figure among the most suitable. The first category offers an appropriate framework to efficiently model the discussed bending and torsion effects based on hair specifics, e.g. as simplified super-helices [BMMT08] or hair-optimized elastica [KBMT09]. A drawback of this approach is that it is indeed very hair-specific, and integration within different simulation environments is sometimes difficult. The second category offers a more versatile modeling of hair strands, which can be represented as a set of particles connected with stiff springs and hinges. Hair bending rigidity is ensured by angular springs at each joint. Using an altitude spring model within a tetrahedral mesh can improve the drawbacks concerning the torsional rigidity and nonstretching behavior of previous implementations, and also allows to model the individual hair-hair interactions with physical parameters such as friction or static attraction. This precision however also implies large computation times for complex hairstyles. Hence, another alternative is to use a truly real-time method animating the hair shape using a free-form-deformation lattice which is deformed as a particle systems and coupled to the hair shape through viscoelastic forces [VMT06a].

Reproducing plausible hair physics in VR can foster the development of hair care products by evaluating virtual combing ease (e.g. measuring force feedback during haptics-based interaction with hair strands, see Fig. 3).

4. Textile Properties in Cloth Simulation

Similarly to hair, the major challenge in cloth simulation is to find the best compromise between the high requirement for physical plausibility (quantitative accuracy with

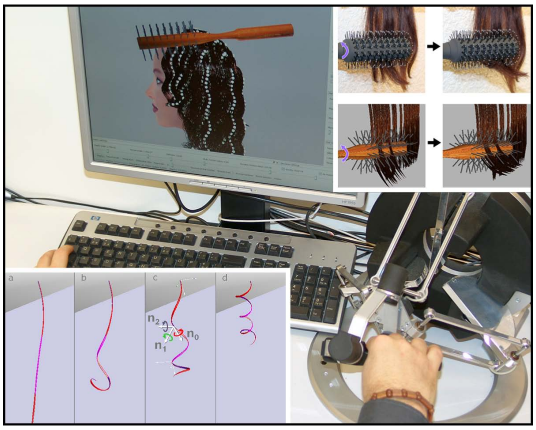

Figure 3: *Physical parameters can be used to model the hair type and the combing feedback during haptic interaction. Top right: torque evaluation on real and virtual hair samples. Bottom left: the influence of bending and torsion stiffness on individual hair strands.*

anisotropic non-linear strain-stress behavior) and the drastic performance requirements of real-time applications.

4.1. Physical Properties and Mechanical Behavior

The behavior of cloth can be expressed by mapping the possible cloth deformations on the textile material composing the two-dimensional cloth surfaces. Deformations arise in three main directions, given by the two orthogonal directions of the thread (weft and warp) and the shear. They are simulated according to the fabric's mechanical properties, among which the *elastic* behavior can be considered more relevant for cloth dynamics than the *viscosity* and *plasticity* aspects – which however can be useful to reproduce dissipative effects, e.g. when interaction is required. Elastic effects can be divided into *metric elasticity* (deformations along the surface plane), and *bending elasticity* (deformations orthogonally to the surface plane). For linear metric elasticity, the main laws relating the strain to the stress involve:

- the *elastic modulus*, summarizing the material's reaction along the deformation direction, i.e. longitudinal strain (also known as the *Young modulus*).
- the *Poisson coefficient*, characterizing the material's reaction orthogonal to the deformation direction.
- the *shear modulus*, pertaining to oblique reactions, i.e. shearing strain (also known as the rigidity modulus).

4.2. Fabric Hand

Physical properties of textiles strongly influence the make and the quality of textiles. Hence, this domain is of particular importance in the textile industry, where garments must be manufactured respecting practical production criteria while at the same time matching the consumers' expectations in terms of visual appeal and comfort. The comfort sensation of a fabric has a multi-dimensional character which is impossible to describe through a single physical property, but is commonly defined as *fabric hand* (FH). FH provides many information concerning the mechanical properties of textiles, as it refers to the sum of the sensations experienced when a fabric is touched or manipulated with the fingers [Hat93] (see Fig. 4). Often the fundamental aspect that determines the success or failure of a textile product, FH is a complex parameter which is related to the fabric flexibility, compressibility, elasticity, resilience, density, surface contour (roughness, smoothness), surface friction and thermal character. Similarly to hair handle (see Sec. 3.2), FH is therefore an important descriptor of physical parameters which can be exploited in the context of interactive VR simulation.

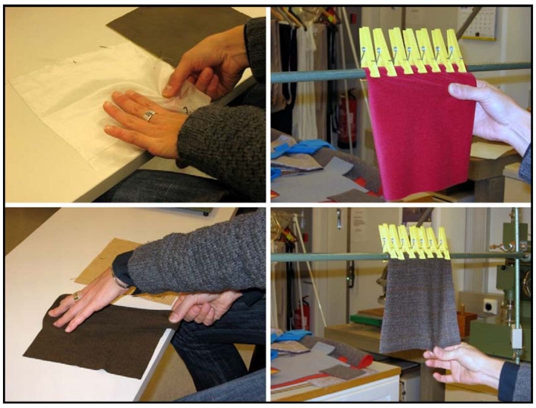

Figure 4: *Evaluating fabric hand [LVMTM07].*

Besides the subjective assessments of FH, the physical parameters of textiles can be objectively measured through standard fabric characterization experiments such as the "Kawabata Evaluation System for fabrics" (KES-f), the "Fabric Assurance by Simple Testing" (FAST) or the "Fabric Automatic Measurement and Optimisation Universal System" (FAMOUS). These existing characterization methods, however, do not specifically address the requirements of the simulation of textiles in virtual environments. Therefore, parameters obtained from measurements cannot be applied to a dynamic simulation in a universal way, but rather reflect the specific capturing capability of the particular measurement method [LMT08]. Moreover, the information obtained from standard measurements might be not enough. For example, a correct representation of the dynamic mechanical behavior of textiles requires additional information about the viscoelastic damping behavior of the simulated fabric. To this aim, further measurement standards are being developed, such as the step-tensile method, which examines the textile elongation properties under the effect of several consecutive extension-relaxation cycles [VDB*07].

4.3. Suitable Cloth Simulation Models

The textile surface can be described with regular square particle grids. The elongation stiffness can be modeled by springs along the edges of the grid, the shear stiffness by diagonal springs, and the bending stiffness by leap frog springs along the edges, as depicted in Fig. 5. Such a model, however, is still fairly inaccurate because of the unavoidable cross-dependencies between the various deformation modes relative to the corresponding springs. It is also inappropriate for non-linear elastic models and large deformations. More accurate variations of the model consider angular springs rather than straight springs for representing shear and bending stiffness, but the simplicity of the original spring-mass scheme is then lost. These issues can be addressed by combining the simplicity and speed of particle systems with the accuracy of a model that evaluates strain and stress on the true deformed surface of cloth [VDB*07]. Such an approach describes the mechanical behavior of cloth as strain-stress curves measured along the weft, warp and shear deformation modes (see Fig. 6) and is capable to express the relevant metric elasticity parameters.

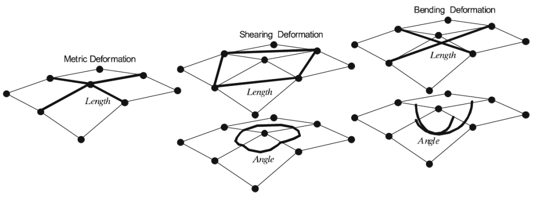

Figure 5: *Using length or angle springs for simulating cloth with a square particle system grid [VDB*07].*

Bending stiffness should also be considered. However, bending forces are quite low in actual cloth materials, and they can be neglected when using large elements in order to save computation time. Still, when stiff bending forces are to be considered, fast linear bending simulation schemes [VMT06b] may offer a very good computation compromise.

The use of accurate simulation parameters can help assessing the fitting of garments according to the mechanical properties of the cloth materials (see Fig. 7).

5. Soft Tissue Properties in Cartilage Simulation

Motivated by the increasing clinical interest in the causes and consequences of injury and pathology of human joints, several studies have characterized the intrinsic material properties of the tissues and cartilages surrounding joints in order to obtain a more thorough understanding of their mechanical behavior. Studies evaluated the material properties of the knee menisci [TA95] and glenoid labrum [Car98], as well as the mechanical behavior of the bovine acetabular labrum [FBI01]. The latter measurements are especially interesting for the VR simulation of the acetabular and femoral cartilage.

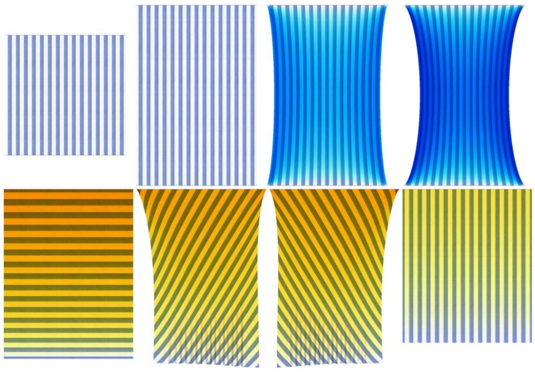

Figure 6: *Top: A square piece of cloth attached at two opposite edges (far left), extended at 150% of its initial length. The material is linear isotropic, with a Poisson coefficient of 0 (left), 0.25 (center), 0.50 (right). Color visualizes the transverse compression strain. Bottom: A square piece of cloth attached at the top edge, texture lines depicting weft orientation. Shear stiffness is significantly lower than weft and warp stiffness, which produces orientation-dependent deformations depending on how the fabric square is cut relatively to fiber orientation. Color visualizes average tensile strain.*

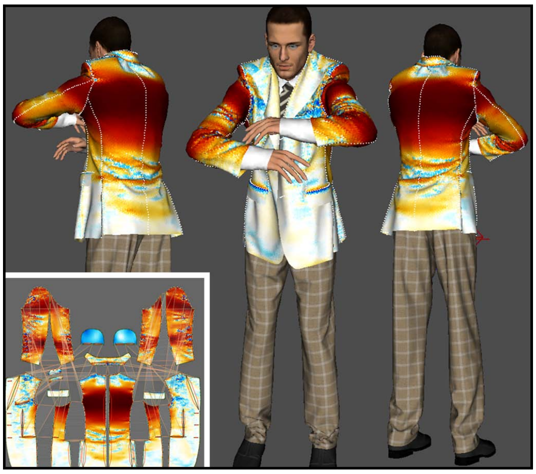

Figure 7: *Virtual prototyping applications require an accurate representation of cloth material behavior for evaluating precisely the stretch forces (color scale) on the garment in particular postures of the character.*

5.1. Physical Properties and Mechanical Behavior

Mechanical properties of human or animal soft tissues – typically measured in a controlled environment – can include tissue water content, aggregate compressive modulus, tissue permeability, material parameters describing the non-linear toe region of the tensile stress-strain curve, strain limits of the near-linear region of the stress-strain curve, tensile Young's modulus (from the near-linear region), tensile yield strain, maximum tensile strain and maximum stress at tissue failure. Results for the measurements on the bovine acetabular labrum reported high stiffness values (10-15x) for the labrum in tension with respect to the adjoining articular cartilage, and a stiffer posterior region (45%) with respect to the superior region. The labrum's low permeability may contribute to sealing of the hip joint. The high circumferential tensile stiffness of the labrum, together with its ring structure, reinforce the acetabular rim and may contribute to joint stability.

5.2. Suitable Soft Tissue Simulation Models

Suitable simulation models in the context of medical appliactions associate computational performance with the context of large deformations (for handling soft tissues) and high versatility (for handling collisions). A good solution is based on a first-order Finite-Element implementation of St-Venant-Kirchhoff materials. Full linearization of the model is not visible because of the large deformations context. Therefore, depending on the simulation context, it can be used in two modes:

1. The unrotated mode, which computes strains and stresses along predefined material axes. This approach offers the simplest and fastest computation, and allows efficient formulation of anisotropic material properties.
2. The rotated mode, which computes strains and stresses along the eigendirections of the strain tensor (corotational scheme). This approach, rather adapted to the simulation of isotropic materials, allows a more robust handling of compression (avoiding material collapse).

The elasticity strain-stress relationships are formulated using non-linear expressions, typically modeled as polynomial splines. For anisotropic materials, six curves may be used (for the three tensile and the three shear deformation modes), complemented by additional curves using linear combinations of these six modes. This formulation offers a fairly simple, yet general modeling of non-linear material behaviors, offering the possibility of modeling complex effects (such as volume preservation) non-linearly. Viscosity is modeled in the same manner, through the use of the strain rate. Plasticity results from hysteresis in the strain-stress behavior of the material. Like viscosity, the main noticeable effect of plasticity is also the material motion damping caused by energy dissipation. Such a model can be extended for modeling plasticity through an adequate processing of the strain-stress behavior based on Prony series approximations.

An efficient simulation scheme allows taking advantage of mass-lumping in order to get a particle system implementation capable of explicitly supporting external constraints, such as those resulting from collisions. A wide choice of numerical integrators can be used for relaxation or time-integration. As in the cloth simulation scenario, the Backward Euler method is the most versatile and robust integrator, which offers quite a good performance in both of these contexts. When dynamic accuracy is more important (motion accuracy), Implicit Midpoint of 2nd-order Backward Differential Formula may also be used, at the price of robustness. High-accuracy dynamic simulations can also be obtained using explicit methods (Runge-Kutta) at the price of computation time. Compared to theoretical computations and commercial finite-element packages (Code-Aster [VWD07] and FEBio [MRW09]), the model demonstrates a good accuracy (see Figure 8).

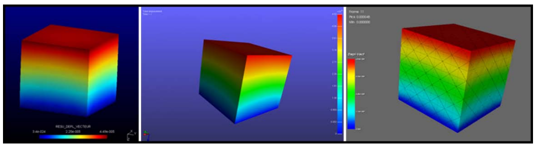

Figure 8: *Accuracy comparison between reference models: Code-Aster (left), FEBio (middle), and the proposed particle-system based soft tissue model (right).*

Figure 9 shows a simulation example of evolving acetabular cartilage deformation during motion, performed in order to evaluate a key clinical motor task in orthopaedics. This validation study analyzes the hip joint articulation congruity by applying a motion of 90° hip flexion plus a 40° internal rotation on a patient laying down.

The 3D models of the bones are approximated as rigid bodies, and cartilage meshes are tetrahedralized with $\sim$20 K tetrahedra per model, with material properties taken from relevant clinical studies [RSGP06] (e.g. elastic modulus (Young's modulus E) and Poisson's ratio (ν) set to 12 MPa and 0.42, respectively). Biomechanical materials are assumed to be linear elastic and isotropic.

The simulation shows a distribution of stress and strain on the deformed surface during motion which is prone to the relevant joint angle. Deformations are mostly located in the posterosuperior region of the acetabular cartilage, which is confirmed by the clinical observations. Indeed, this is consistent with movements like flexion or abduction. During a flexion the femoral head will slide with respect to the acetabular cavity and increase stress in this region of the cartilage. This also explains why higher strain is observed in movements with high flexion and internal rotation. This clinical motion is specifically used to create significant stress in the hip joint: by assessing the patient's pain tolerance, potential hip joint lesions can be detected.

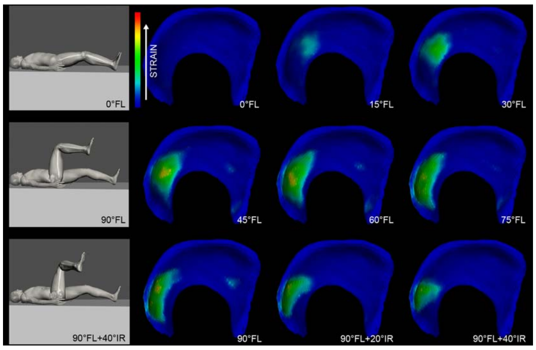

Figure 9: *3D cartilage simulation for the analysis of the hip joint articulation congruity.*

6. Conclusions and Future Work

The simulation elements discussed in this paper represent essential components in the research towards the real-time animation of physically based virtual humans with deformable hair, clothes and body. A simulation framework capable of reproducing physically sound deformations of complex, styled, dressed human bodies has applications in a vast range of different fields, including medical research, industrial prototyping, quality and comfort assessments, fashion design, virtual training, teaching, entertainment, and many more.

Particle systems have always been of interest in the field of interactive mechanical simulation, as they offer a simple, intuitive and flexible way to model mechanical systems. Simple-yet-accurate particle systems can be used to model the elastic properties of hair, textiles and soft tissues through appropriate springs. Such systems have the potential to provide a fast simulation approach which is still accurate enough to compute plausible deformations. Furthermore, they can be combined with a large range of numerical integration schemes, according to the relevant features of the simulation context (e.g. dynamic accuracy, convergence speed, fast and approximate simulation, robustness, et al.).

Further work in this area is focused on exploiting parallelization mechanisms on multi-core and multi-gpu architectures, implementing an optimized simulation library using one unique solver and allowing to plug-in elements of varying complexity. The main motivation driving this research is the development of a simulation framework displaying unprecedented realism and speed in the physically based animation of interacting virtual humans.

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