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A STUDY OF REAL TIME SIMULATION OF GRASPING IN USER-PRODUCT INTERACTION

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ABSTRACT
Customer evaluation of concepts plays an important role in the design of handheld devices, bottles of douche gel and shampoos, where the phenomenon of grasping needs to be evaluated. In these applications important information on the aspects of ergonomics and user behaviours could be gathered from computer simulation. As in all computer simulation, a trade-off between the fidelity of simulation and the computation time is required on the other hand, in order to achieve real time evaluation of design solutions. This paper reviews the literature of computer simulation methods that are used in simulating the most representative physical phenomena of human product interaction. The paper addresses the following research questions: Which geometric and material representations can be used for simulating particular physical phenomena and how these representations can be used in combined simulation? How the accuracy of simulation is influenced by the computational method and by the geometric representation? What simplifications are applied in order to achieve real time computation?
The paper gives a critical analysis on the influence of various geometric representations (i.e. rigid body, surface mesh, solid mesh, and particle systems) on the performance and accuracy of simulation of different physical phenomena of grasping. In addition it presents open issues in research of grasping simulation for user-product interaction.

Keywords: user-product interaction, real time grasping simulation,

1 INTRODUCTION
In the past decade, computer simulations have been proliferating in industrial design applications since (a) they are cheaper than physical prototyping (b) their fidelity is ever-increasing, (c) the computation time is significantly decreased, and (d) interfaces of software tools are more intuitive and do not require involvement of simulation specialist. This trend projects ahead a future, where design concepts or detailed solutions could be evaluated by potential customers of specific products in real time in VR simulation environments.
Customer evaluation of concepts plays an important role in the design of handheld devices, bottles of douche gel and shampoos, where the phenomenon of grasping needs to be evaluated. In these applications important information on the aspects of ergonomics and user behaviours could be gathered from computer simulation. It is our ultimate goal to develop an environment in which users and designers can freely interact with product concepts. Our VR simulation environment consists of three modules: (a) hand motion based input, which supports generation and manipulation of design concepts based on optical tracking, (b) relational based particle system representation, that is the computational kernel used for modelling of and simulation with design concepts, and (c) a truly 3D open air visualization device, that enables direct interaction with the visualized objects. Related to the first and second module, this paper investigates various approaches for simulating the phenomenon of grasping.
As in all computer simulation, a trade-off between the fidelity of computation and model representation, and the computation time is required, in order to achieve real time evaluation of design solutions. This paper reviews the literature of computer simulation methods that are used in simulating the most representative physical phenomena of human product interaction. The paper addresses the following research questions: Which geometric and material representations can be used for

simulating particular physical phenomena and how these representations can be used in combined simulation? How the accuracy of simulation is influenced by the computational method and by the geometric representation? What simplifications are applied in order to achieve real time computation?
In conclusion, our categorization and analysis of the literature provides a guideline how to treat the trade-off problem of grasping simulation.
Based on the above considerations the rest of the paper is structured into five sections. In Section 2 we introduce our reasoning model that we used to structure the literature on grasping simulation. Section 3 reviews the literature from the aspect of various types of geometric and material representation for capturing information about the human hand and on the grasped objects. Section 4 presents the approaches of simulating physical phenomenon of grasping. This section reviews motion, friction, collision and deformation simulation approaches. Section 5 presents our discussion with a critical analysis of the current approaches and with some suggestions for future research in grasping simulation. Finally the paper ends with some conclusions.

A REASONING MODEL

We have classified the grasping simulation approaches in the literature from three aspects: (a) the type of representation that they use for capturing information about the geometric and material properties of the human body and the product, (b) the method of computation of a particular physical phenomenon, and (c) the kind of control and input that represents the way of interaction with the simulation. Related to the first aspect, we have distinguished approaches in which (a) rigid bodies, (b) surface meshes, (c) solid meshes, (d) particle systems were applied. In order to interpret the classification from the second aspect, we took into account the simulation process of grasping, which consists of three phases: approaching the object, making a contact with the object, and releasing the object. The first and the last phase requires (a) motion simulation, (b) collision detection (detection of time and location of collisions), and (c) deformation of the human hand based on posture information. Most of the simulation approaches uses the results of collision detection for switching between the different phases of grasping. In the contact phase in addition to simulation of previous phenomena, (a) collision response simulation (computation of response force and deformation due to the impact), (b) friction simulation, and (c) deformation due to grasping forces should be simulated. From the aspect of control and input data the grasping approaches can be distinguished whether they use internal data (joint torques, neural commands, tendon forces) available about the hand, external data (position of hand parts, external forces exerted by the hand, prescribed motion patterns). External approaches measure or use predefined positions of external landmarks of the hand (e.g. location of the fingertips or particular phalanxes), angle of joints of the hand, predefined motion patterns, and the forces exerted by the fingers. They use this external data on the hand to feed and control the grasping simulation either in an interactive or non interactive way. Internal control and input of grasping simulation uses neural commands, tendon forces, or torques of the joints to control the motion of and the exerted forces by the simulated human hand. The hybrid simulation approaches combines elements of internal and

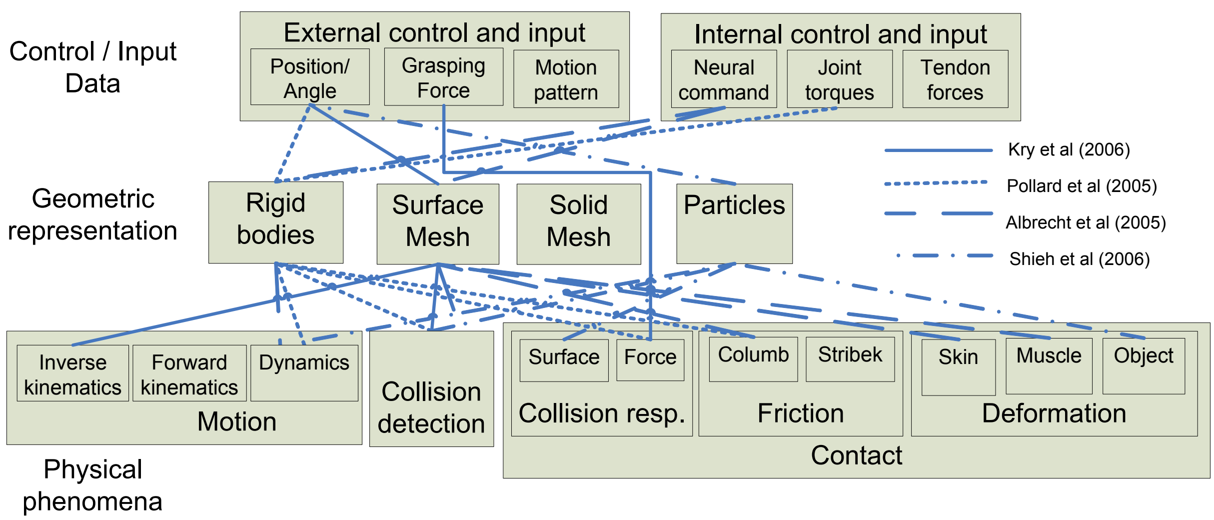

Figure 1 Elements of grasping simulation

external controls.

Figure 1 presents the different elements of grasping simulation including a few examples from the recent literature. An internally controlled simulation is presented by [1], in which the neural commands are used to control the hand. The hand model is built from a combined rigid body (e.g. bones) and surface mesh representation (skin and muscles) and is able to simulate motion by forward kinematics. In addition to the phenomenon of motion their model considers Coulomb friction, and skin and muscle deformation. In the model presented by Shieh and Yang [37] particle systems are applied to capture geometric and material properties of the human hand and the object. Although their model is not able to simulate skin and muscle deformation of the hand due to the low resolution of the particles system they used, object deformation is well represented in their model. In addition to that particle system dynamics, collision detection and contact surface area computation are incorporated into their grasping simulation. Another example is presented by Kry and Dinesh in 2005 [20], in which interactive grasping simulation have been achieved based on measured position of landmarks and grasping forces combined with surface mesh representation. The measured forces are directly fed into the contact simulation and used for calculating the friction between the hand and the grasped object.

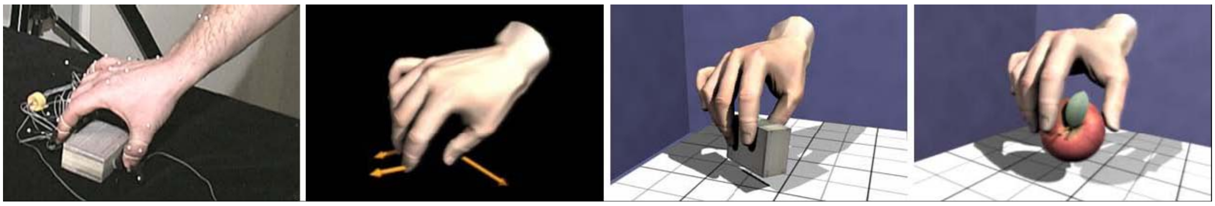

Figure 2 An example for interactive grasping simulation based on landmark position and grasping force measurements [20]

A hybrid controlled approach is presented by Pollard in which both geometric and material properties of the object are represented by rigid bodies and the position of the hand is used to control the grasping simulation [31]. They use rigid body dynamics to compute the motion of the hand and the object, collision detection to separate different phases of grasping e.g. creating-breaking contact, the grasping force is computed with the assumption that the hand closes or opens, and open dynamics engine to take care collision.

GEOMETRIC AND MATERIAL REPRESENTATION

Geometric representations of the human hand and the grasped object have the largest influence on the time for computing collision, contact points, and deformation phenomena in grasping simulation. Early simulations of grasping have applied simple geometric representation (e.g. solid primitives) both for the human hand and for the objects, but deformation has been completely neglected. With this rigid body representations real time simulation have already been achieved in the late 80’s and early 90’s. A grasping of an ellipsoid object by simplified model of the human hand is illustrated in Figure 3. When solid primitives are used in geometric representation, collision and contact point calculation can be solved analytically. Hence the computation time of for these phenomena is not resolution dependent.

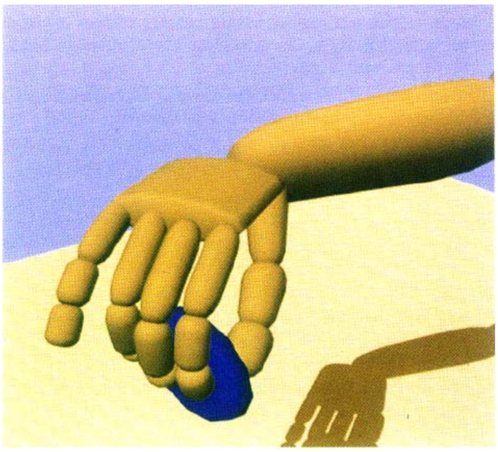

Figure 3 Grasping simulation with rigid body representation [34].

With the development of computers, faster calculation of simulation results has been achieved and larger details of the geometry of the hand and objects have been introduced. Surface mesh representations has been used to capture more accurate geometry of the human hand and products could be represented in more details. However, surface mesh representation required numerical methods, in which the calculation time strongly depends on the resolution of the geometry. To handle this trade-off between the calculation time and the resolution of the geometry adaptive meshes have been developed. These so-called multi-resolution (MR) models typically simplify the shape by neglecting the insignificant or non-influential concrete details of the representation. One subclass of MR models relies on subdivision [43], and the other is based on simplification techniques [8]. In the case of subdivision, the mesh of the large scale geometry is locally refined in order to represent local features. In the case of simplification, a detailed representation of the shape is simplified to show the global shape only. The two techniques alternately support top-down refinement or bottom up generalization. Albrecht et al. developed a surface mesh model of the human hand with underlying anatomical structure [1]. Animation of the hand model is controlled by muscle contraction values. They employed a physically based hybrid muscle model to convert these contraction values into movement of skin and bones. Pseudo muscles directly control the rotation of bones based on anatomical data and mechanical laws, while geometric muscles deform the skin tissue using a mass-spring system. The geometry of the skin and the muscles are represented by surface meshes.

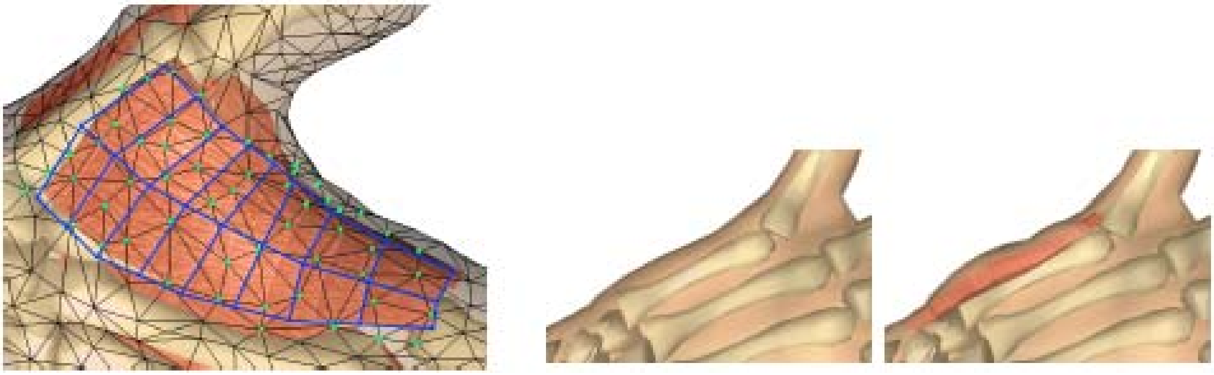

Figure 4 Human hand representation with surface meshes [1]

However, deformation based on surface meshes does not guarantee volume preservation of the geometry or control over volume change during simulation. This problem can be handled by solid geometric representations, such as finite element meshes or volumetric particle representations combined with mass-spring models. In Gourret’s method, FE calculations were employed in an updated Lagrangian formulation in small strains [12]. They used a classical engineering stress measure (Cauchy stress) and a linear constitutive law for flesh tissue. Their formulation is simple, but it gives good visual results, without requiring long calculations. FE meshes have also been used to simulate realistic muscle deformation [23]. The implementation of a stand-alone computational model in combination with the finite element analysis allows for the inclusion of novel features in the active muscle constitutive equations that eliminate potential instabilities on the descending limb of the force-length relationship in skeletal muscle. Computer animation approaches focuses on realistic modelling and visualization of the skeletal muscle architecture and of the transmission of the resultant deformation, of a group of muscles, to the human or animal skin to produce body deformation. In order to achieve realistic simulation of skin deformation FE meshes can be combined with implicit [40] and subdivision surfaces modelling technique [44]. However, real time calculation of realistic deformation has not been achieved, therefore results of the simulation has to be post processed to create a realistic animation.

The interactions between the particles can represent not only the shape, but also physical properties of the modelled object. Relationships between neighbouring particles can be specified and can be used to describe some kind of behaviour of a particle system. A particle system model is usually implemented as a time dependent model, which is able to change its embodiment, location, and shape as a function of time. In addition to its position and shape, a particle can also be defined in terms of its mass, velocity, acceleration, physical properties, visual attributes (color, transparency) and, in some cases, lifetime. Combined with mass-spring models particle systems can be used as representation of shape with physical principles. This modelling method has been successfully applied to concurrent handling

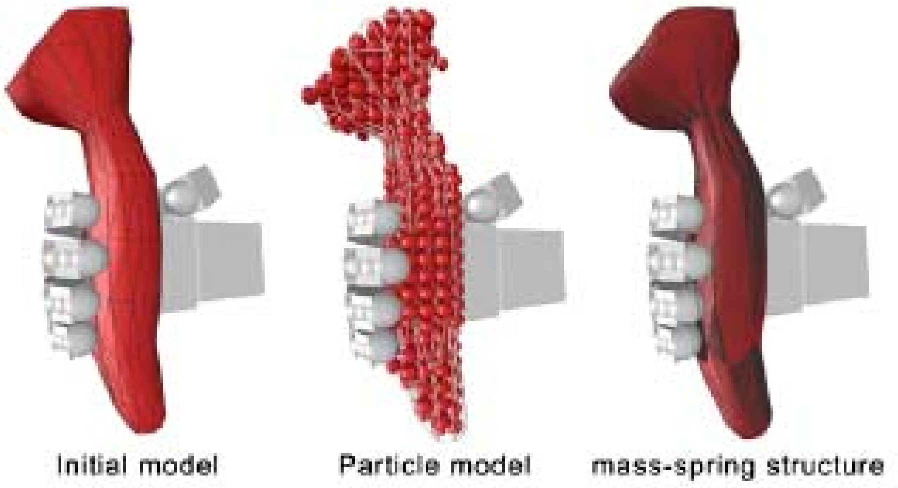

Figure 5 Grasping simulation with particle systems Shieh [37]

of deformations, collision, motion, and fracture of shape [9][18]. A mass-spring model describes bodies as sets of point-masses, assigns material properties to the point-masses, and represents the relations in the form of a configuration of springs. It is still an unsolved problem how to connect in these systems the kinematics and deformation simulation with contact mechanics to handle dynamic contacts between objects. Other issues also wait for ultimate solution, e.g., detection of multiple collisions [4], and direct calculation of contact forces [2]. A successful usage of particle systems for simulating grasping behaviour has been implemented by Shieh et al. [37]. Figure 5 illustrates their unified mass-spring representation applied to the human hand and to the grasped object. However, there are some shortcomings to their current simulation system. First, the current simulation model only has limited response surfaces according to the movement of the virtual hand. Although the deformable model in their system is simulating based on physical rules, additional material properties has to be introduced into the deformable model, especially when the behaviour of the human hand is considered. Details of the geometry of the human hand is not represented, nor its non-linear physical behaviour.

PHYSICAL PHENOMENA OF GRASPING

Kinematics of grasping and kinematics of the human hand

When kinematics of grasping is to be simulated direct or inverse approaches can be applied. Inverse kinematics of grasping is the problem of obtaining the joint displacement of fingers from data available on the position/orientation of the object. Depending on whether data is available on the contact points of the finger and the object two cases can be distinguished. In the first case finger’s joint displacement/angles and the contact points are determined based on data available for the position and orientation of the object. In the second case only finger’s joint displacement and angles need to be calculated based on the contact points, and the position and orientation of the object. On the other hand, with direct kinematics the position of the hand can be calculated from the amounts of rotation and bending of each finger’s joint. Direct kinematics of grasping is the problem of obtaining the position/orientation of the object from multifinger joint displacements. Direct kinematics of grasping has two cases: one is the case when all the contact points on fingers are known from tactile sensors attached on fingers, and the other is the case when contact points are unknown. Although there some analytical solutions proposed by [28], but they do not guarantee realistic motion of the human hand. Typical application of this approach can be found in robotics and animations.

A different approach that is used in animation and simulation applies forward or inverse kinematics of the human hand only and it computes contact of the hand and the object based on physical principles. When inverse kinematics of the human hand is simulated or animated, positions and angles of joints are to be determined based on measured position of the finger tips and from a set of constraints. However, in most cases this problem is inherently underdetermined. For example, for given positions of the hands, there are many possible hand poses that satisfy the constraints [14]. To reduce the number of possible solutions physiological constraints of the hand can be used [34]. Based on Landsmeer's [21] empirical studies of the physiology of the human hand Rijpkema incorporated into his human hand model the relationship between the joint angles of the fingers and the activation of the tendons. In order to improve the realism of inverse kinematics based hand motion, compliant joints have been used in computer animation for capturing emotion or style [29], as part of controllers for synthesizing motion [33][36], and for reacting to impacts [41]. However, the compliance (or stiffness) parameters of these solutions are either selected by hand, or approximated through complex optimizations that must simultaneously deal with estimated contact forces. Kry et al. proposed a solution that can provide compliance estimates from captured data [20]. They modelled the finger as a kinematic chain of three hinge (revolute) joints with joint angles collected in a vector. The compliance was represented as a collection of torsional springs that, when displaced from a reference configuration, produced joint torques by the relation.

In forward kinematics the angles of the joints are supplied to the simulation, and the resulting motion is computed and animated. The forward kinematics problem is easily solved by using the product of the transformation matrices of the joints [11]. Forward kinematics is useful for bending fingers at the joints; however, it is inadequate for simulating the human ability to place the tip of finger at a certain location. Forward kinematics is typically used in human hand animations or modelling the anthropometry of the human hand.

In the case of forward dynamics the position and angle joints are computed based on torques and forces applied to the joints. For instance, a kinematic model for flexion and extension of the fingers has been developed by [22]. Their model is based on the assumption that the moment arms of the tendons at the joints are constant. Considering external forces affecting the joints, they compute the finger strength for the given joint configuration. Albrecht et al. developed a system around a reference hand model, which are animated using muscle contraction values. They introduced a hybrid muscle model that comprises pseudo muscles and geometric muscles. While pseudo muscles control the rotation of bones based on anatomical data and mechanical laws, the deformation of geometric muscles causes realistic bulging of the skin tissue. As a result, the created animations automatically exhibit anatomically and physically correct behaviour. However, their model does not include bone movements based on tendon movements, and collision detection among the parts of the hand.

Contact modelling

Contact events of grasping (i.e. new contact occurs or existing contact breaks off) can be easily detected from geometric information such as computing intersection of the hand and the grasped objects and determining the location of the contact and the normal vectors at each contacting point. From the calculated data the response of collision can be determined to correctly model the object motion. In order to achieve real time simulation, the intersection algorithm is required to be fast because it is called with the frame rate of simulation. In grasping simulation the hand and the grasped object make contact at multiple points, and the rigid body model implies that these contacts are very sensitive to small changes in object state. Although rigid body models are simplification of the model representation and thus speeds up the simulation of collision detection and kinematics of grasping simulation, they are surprisingly computer intensive for contact simulation. This is due to the assumption of rigidity, which makes the contact problem highly singular, requiring discontinuous jumps in contact forces for small changes in position. In reality, all objects are deformable to a certain extent, and contact produces stresses that lead to deformations which may be small but significant.

Two types of contact modelling approaches have been developed in the literature: impulse-based methods that treat even continuous contact as a type of impact and use a coefficient of restitution to determine the post-impact velocity of the object [17][27][15], and optimization-based animation methods [24]. The former approach is easier to formulate, but could require a large number of steps to resolve the resulting impact sequences. It uses small time steps when many contact points are in the scene, for instance, for a simple scenes the number of steps per frame time can easily rise to the millions. In general, efficiency suffers in these techniques due to small integration time steps and computations that are done between frames. Huge amounts of computations are used to simulate motion that the human eye does not even see. In addition to that impulse based methods results in wobbling problems when resting contact with complex models is simulated. To resolve this problem, virtual springs and dampers at the contact points have been introduced [13]. Another alternative proposed the usage of impulse based methods with mass-spring models, since the coefficient of restitution seem to be more physically meaningful for particles [25]. Optimization-based animation [24] has similar advantages. It consists of four algorithms: 1) partial sequential collision resolution, 2) final resolution of collisions through the solution of a single convex QP (positive semidefinite quadratic program), 3) resolution of static contacts through the solution of a single convex QP, 4) freezing of "stationary" bodies. Freezing speeds up this simulation by more than 25 times stacking with standard Newtonian physics using an optimization based method to adjust the predicted positions of the bodies to avoid overlap. One drawback is that the procedure tends to align bodies non-physically.

Pauly et al. have introduced quasi-rigid representation, which can combine the benefits of rigid body models for dynamic simulation and the benefits of deformable models for resolving contacts and producing visible deformations [30]. In quasi-rigid representation of objects, the surfaces can undergo modest deformations in the vicinity of a contact, while the overall object still preserves its basic shape. There are a lot of objects that could be modeled in this way, including biological manipulators such as our hands and feet and everyday objects that appear rigid visually. In fact quasi rigid representation of objects could enable a more realistic simulation of the physiological processes of grasping, if small volume changes simulated in a controlled way.

One of most often used friction model in simulation is the Coulomb friction combined with viscous friction. This model takes into account the relative velocity of two bodies in contact, the Coulomb friction level, and the coefficient of dynamic friction. The Coulomb friction model is implemented in the form of a friction cone. A friction cone is simply defined by the friction angle: $\tan \theta = M/N = \mu$, where θ = the half angle of the cone apex, M = maximum friction force, N = normal/reaction force, μ = coefficient of friction. The intersection of this cone with a surface of an object (a polygon) will define a friction circle since the surface is normal to the principal axis of the cone. The Coulomb friction cone is defined as the set of possible forces that can be supported by the frictional surface. A polyhedral approximation of the cone can simplify the calculation without large influence on the accuracy. At low velocities the friction force is decreasing continuously with increasing velocities. This phenomenon is called the Stribeck friction [39]. The friction force as a function of velocity for constant velocity motion is called the Stribeck curve, and can be used together with the Coulomb model. To compute a Coulomb friction combined with static and viscous friction in a simulation is rather difficult as the relative velocity of the contacting objects needs to be zero. For this reason, the Karnopp model [19] defines a zero velocity interval. It can deal with the problems with zero velocity detection and it can avoid switching between different state equations for sticking and sliding. The

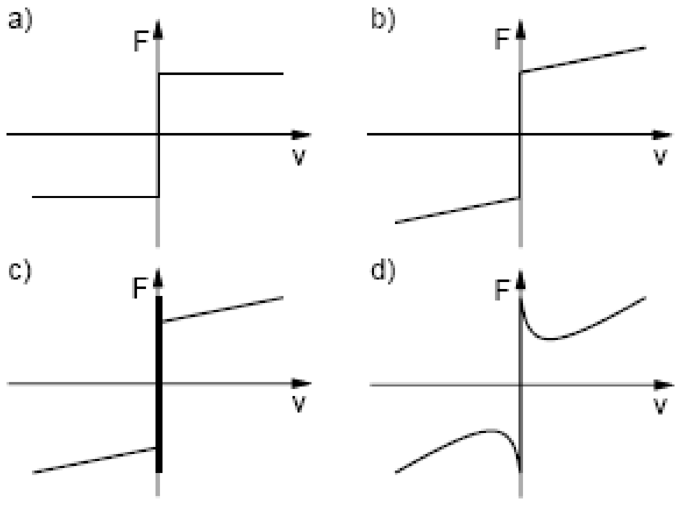

Figure 6: Examples of static friction models. The friction force is given by a static function except possibly for zero velocity. Figure a) shows Coulomb friction and Figure b) Coulomb plus viscous friction. Stiction plus Coulomb and viscous friction is shown in Figure c) and Figure d) shows how the friction force may decrease continuously from the static friction level.

main disadvantage when using a model such as, for simulations or control purposes, is the problem of detecting when the velocity is zero.

The resulting friction force is influenced by many parameters of the contact model which dynamically changes during contact simulation (e.g. the velocity between the contact surfaces, deformation of surfaces, presence of lubricants between the surfaces). In order to take them into account dynamic friction models have been introduced which should be taken into account in order to get a more accurate feedback from the simulation. The Dahl friction model [10], and its extension the LuGre model [6], are incorporating tangential compliance. Perhaps the most comprehensive friction model is the LuGre friction model which in turn is a development of the Dahl model and includes an internal state to allow for microslip. Chen et al. [7] render friction and adhesion in a manner similar to the "bristle" model of friction [16] in which virtual bristles are attached to sliding surfaces. The bristles alternately bond to each other and break away at a rate that depends on the bond strength and compliance.

DISCUSSION

In this paper we analysed the influence of various geometric representations (i.e. rigid body, surface mesh, solid mesh, and particle systems) on the performance and the accuracy of different physical phenomena of grasping. As in all simulations there is a trade-off between the accuracy of the simulation and the time of computation that it requires. In table 1 we summarized findings of our literature study. We investigated the trade-off between the accuracy and performance of simulating various physical phenomena and it is affected by the geometric and material representations. To determine the motion of the hand and the object forward kinematics (FK), inverse kinematics (IK), forward dynamics (FD) and inverse dynamics (ID) have been applied in grasping simulation. In inverse and forward kinematics, the forces of grasping need to be externally measured, which might results in inaccuracies regarding the position and orientation of contact forces. The method of dynamics enables to incorporate internal forces and torques in the hand model and thus it better handles the collision response of grasping. When inverse versus forward approaches are compared, the control of grasping can be more accurate with inverse approaches as the position of the hand and the object directly specified but at the same time it is more computation intensive. In forward approaches, the angle or the torques of the joints is specified which makes the control a bit clumsy as the user of the system is not able to directly determine the position of the object compared to the hand.

In the case of identifying collision among objects the influence of various geometric and material representations does not differ significantly. For all representations, the problem of collision detection is typically reduced to detecting the intersection among objects in the simulation space. Rigid body objects are either represented as primitives or more typically as non-deformable triangulated meshes. In the former case the representation of objects is oversimplified and thus collision detection can be easily solved. In the latter case, structuring of mesh elements, for instance by binary space partitioning, can speed up the collision calculation to the order of NlogN but the computation time remains to be resolution dependent. In the case of deformable models space partitioning should be updated when large deformation takes place during grasping. Hence the collision detection is more time consuming for deformable representation than for rigid bodies. For all representations, collisions are typically processed chronologically backing the rigid bodies up to the time of impact [17]. When small number of collisions are possible in the simulation scene, timewrap algorithm can be used, which backs up objects that are involved in collisions and non-colliding objects are further simulated in time [26].

To determine the contact surface among rigid bodies a given tolerance of penetration is applied in the grasping simulation. However, this way the contact surface of rigid bodies is computed based on geometric information and time steps of the simulation rather than based on physical principles. This problem can be easily handled by allowing deformation between bodies in contact. Hence using surface meshes, solid meshes and particle systems can more accurately and efficiently model the contact surface area in grasping.

Static friction modeling can offer very high quality visual feedback on friction modeling, as they are able to simulate Coulomb friction, viscous friction, and stick and slip effect. However, huge amounts of computations are used to simulate motion that the human eye does not even see. In addition to that rigid bodies introduce wobbling problems when resting contact with complex models is simulated. In the case of kinetic friction, particles can introduce a wobbling effect, since they are only approximations of the nominal shape of the human hand and the grasped object. Wobbling effect is especially present in grasping simulation when relatively large spherical particles are used in the representations. When lubricants are involved in the simulation dynamic friction models can perform better in order to simulate the changes of circumstances between the contact surfaces.

Deformation of the hand and the object can be realized based on surface mesh, solid mesh and particle system representations. Although the first one can imitate physically based deformation, it is mostly suitable to mimic skin deformation of the hand. Solid meshes and particles are able to simulate the deformation of muscles and they are also able to capture heterogeneous material properties of the hand. Accurate simulation of physiological processes of the human hand requires high resolution representations and non-linear deformation. A major impediment to building accurate hand model and soft tissue models is the lack of quantitative biomechanical information. It is therefore necessary to develop more efficient algorithms for deformation of non linear visco-elastic tissue models, collision detection between deformable bodies, computation of contact forces between deformable bodies.

Table 1: Evaluation of the trade-off between accuracy and performance of geometric and material representations in grasping simulation

		Accuracy-performance trade-off			
Geometry + material		Rigid	SUM	SOM	Particle
Motion	FK	👍👍	👍	👍	👍
	IK	👍👍👍	👍👍	👍👍	👍👍
	FD	👍👍👍	👍👍	👍👍	👍👍
	ID	👍👍👍👍	👍👍👍	👍👍👍	👍👍👍
Collision detection		👍👍👍👍	👍👍👍	👍👍👍	👍👍👍
Contact surface calc.		👍	👍👍👍	👍👍👍	👍
Fric-tion	Static	👍	👍👍👍👍	👍👍👍	👍👍
	Kinetic	👍👍👍	👍👍	👍👍	👍
Deformation		👎	👍	👍👍	👍👍

CONCLUSIONS

In this paper we presented a literature study on interactive grasping simulation. We reviewed and analysed various approaches in order to investigate how different geometric and material representations and the modelling and simulation of various physical phenomena influence the trade off between performance and accuracy of grasping simulation. In our analysis we could not find the absolute best geometric and material representation for simulating grasping, but certain representations can definitively provide better results for a particular physical phenomenon. The results of our analysis are summarized in Table 1. It seems that deformation is the most difficult phenomenon of grasping to simulate due to its highly non-linear nature and small volume change of the hand during deformation. A surprising result is that rigid body representation requires extra computation in a situation when the object is resting in the palm.

Although many solutions have already been reported in the literature there are some open issues to be researched in the future. For instance determination of the grasping force in a quasi static situation is still not solved. Current solutions either measure the grasping force or try to estimate it from previous movements. Another research topic for the future is simulating adhesive contact between hand and the object.

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