A NEW HAPTIC-BASED TOOL FOR TRAINING IN MEDICINE

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ABSTRACT
This paper describes a new methodology that, making use of a haptic device, can simulate the palpation, a diagnostic manoeuvre aiming to verify the condition of internal organs or anatomical formations.

In the developed application, that has the purpose to pick out an anatomical formation and understand its characteristics, the palpation of a soft tissue has been taken in consideration. Particularly the fingertip, the skin and an anatomical formation have been simulated.

The user, handling the haptic system at disposal can feel the contact with the skin but also perceiving the presence, the shape and the dimension of the subcutaneous formation (invisible to the operator), that has been modelled as a rigid sphere (like a nodule).

The evaluation of the skin deformations, following from the palpation, has been performed through a mass-spring based algorithm, which allows to obtain results in real time.

Keywords: haptic, palpation simulation, virtual reality

1. INTRODUCTION
The sense of the touch is a mechanical stressing of the skin, produced by the physical contact with an object. Such stress depends on the superficial physical properties of the object and how it is touched on. Haptic technology tries to reproduce the sense of the touch in the contact with virtual objects. This advanced methodology allows to increase the reality feeling of a virtual simulation.

Haptic methodology has initially been developed as extension of the virtual reality (VR) simulations. Subsequently, because of not very large spreading of the VR systems, it has been employed in autonomous way with other typologies of applications.

The perception of the contact is reproduced through a suitable peripheral able to produce a force-feedback depending on the properties of the virtual objects.

Obviously it is simpler reproducing the mechanical properties of rigid bodies than simulating the mechanical performances of deformable bodies. In these last cases it needs referring to more sophisticated models of numerical analysis. The most used techniques are based on the finite element method (FEM), the boundary element method (BEM) and the mass spring model (MSM). Each method has some particular advantages and disadvantages, but in general it is possible to state that techniques based on FEM and BEM, even if can give more accurate results, need long times for data processing, whereas with the MSM technique real-time results can obtained.

In the research activity here presented it has been dealt with the problem of the development of a medical training application. An innovative methodology for the palpation, a diagnostic medical technique, has been set up.

Thanks to the developed application the user, by using the available force-feedback device, can moving a pointer, representing the fingertip, and can feel the contact with a surface representing a part of the human skin. Moreover he can also perceive the presence and the shape of a subcutaneous nodule.

Although the first prototype of this application has been implemented in a simplified way, by modelling the human skin like a planar quadrangular surface and a subcutaneous formation as a rigid sphere, the proposed methodology seems to be very powerful and presents many interesting starting points for the development of similar applications.

The mass spring model has been used to evaluate the forces; the objects surfaces have been represented through an implicit geometric formulation. In the setting up of the application, entirely developed in C++ language, OpenHaptics and OpenGL libraries have been used for the haptic and graphic rendering respectively.

2. STATE OF ARTS
Haptic methodology has been applied largely to several fields like the medical training and education (Wang et al. 2007), the reverse engineering (Yang et al. 2005), the mechanical modelling (Liu et al. 2004) (Ma et al. 2004), the artistic sculpture (Gao et al. 2006), the aerospace planning (Harris et al. 2004), etc.

In the surgical sector this technology allows to simulate in very complete way many operations on the human body that, generally, require significant tactile skills.

The more advanced methods of numerical analysis, like the boundary elements method (Wang et al. 2007) and the finite element method, allow to evaluate the forces in very accurate way so, consequently, to perform very realistic simulation, even if the complexity of calculation does not allow real time data processing.

The possibility to perform also real time simulations has led to the development of many training applications allowing doctors and surgeons to gain useful experience in very difficult medical techniques like laparoscopic and endoscopic (fig. 1) operations (Montgomery et al. 2002) (Okamura 2004).

Other very interesting examples of haptic applications in the medical field are the systems simulating the epidural injections (Dang et al. 2001), the educational applications to perceive in realistic way the contact with the anatomical parts of the human body (Heinrichs et al. 2000), the training systems for the positioning of catheters (Basdogan et al. 2001).

Figure 1: Haptic based device for endoscopic simulations

There are also advanced applications that make use of particular instrumentations like the force-feedback gloves (Bouzit et al. 2002), and the virtual reality environments to simulate surgical operations (Tendick et al. 2000) or to train doctors for the diagnosis of particular pathologies like the prostate cancer (Burdea et al. 1999).

With regard to the use of the haptic technology as an aid in the training for palpatory diagnosis, some research activities (Delingette 1998) (Langrana 1997) have already been developed, but nowadays not any proposed solution has been yet largely used in a very efficient way, for this reason it is opportune to continue in the research of very powerful and multi-purpose solutions, given that the palpation training represents a very important stage in the doctors' education and could be made more efficient through the use of this methodology.

3. PALPATORY TECHNIQUE

Palpation is a diagnostic manoeuvre performed with one or two hands, but also with the fingers (fig. 2), that is adopted to verify the state of internal organs or anatomical formations and their mutual positioning.

The most important information that can be got with palpatory diagnosis are related to the shape, the volume, the dimensions and the consistence of the internal organs, the characteristics of their surface (smooth, wrinkled, etc.), the temperature, the tenderness, the spontaneous and provoked mobility.

It is so evident the most important factor in the diagnosis through this simple technique, is a good training phase; a skilled doctor can, for instance, understand the difference between a stiffening and a volume increasing, or which dimension of a nodule represents a critical state.

Figure 2 - Example of palpating

The kind and quality of the information gained through this technique, therefore, depend on the skilfulness of the doctor, that can perceive the presence of anomalies by touching the interesting zone and feeling the changes of the mechanical behaviour as a consequence of the induced stressing.

It is clear that, in particular conditions, the touching sense represents a very important diagnostic method able to give basic information about many physical problems.

The mechanical response obtained as a consequence of the palpation is quite complex, in fact it is the reaction to a distributed load on a small area with not linear mechanical characteristics. Moreover this behaviour changes depending on the zone in examination: palpating a soft tissue differs from the analysis of an area in which a bony structure is present; this last, in fact, has very different mechanical characteristics in comparison with other organic tissues.

To simplify the application here introduced it has been studied the palpation on soft tissues with the purpose to identify an anatomical formation, perceiving its shape and stiffness.

4. TOOLS AND METHODS FOR THE HAPTIC APPLICATION DEVELOPMENT

In a practical way palpation is performed touching the skin surface with the fingertips. For this reason, in the developed application, a finger-based haptic device should be used.

In this job, nevertheless, a hand-based system, the Phantom Omni (fig. 3) device of SensAble, available at the VR laboratory of the "Dipartimento di Meccanica" of Palermo has been used.

Figure 3 – Phantom Omni haptic device

However some modifications are being produced in this system so to allow its use through one or two fingers, following the scheme of other finger-based haptic systems like that shown in figure 4.

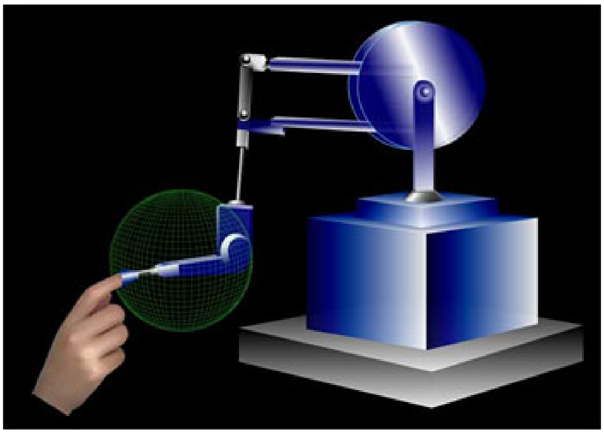

Figure 4 – A finger based haptic device

For what concerns the software characteristics, it has been decided to use an advanced programming language like the C++, in order to allow any improvement and modification of the application in a very fast and easy way.

Two kind of open source libraries have been used: OpenHaptics and OpenGL. The first is related to the haptic rendering while the second to the graphic one.

The graphic rendering is used to setup the scene visualization and manage its changes in real time.

The haptic rendering, instead, is used to define the objects' properties and evaluate the forces following the mutual collisions among objects. The haptic rendering is the most distinctive aspect of a force-feedback application.

4.1. Haptic rendering

Through the haptic rendering the geometric and tactile properties of the objects are defined, the mapping and the management of the real and virtual spaces are performed, and the output forces are evaluated.

The mapping of the spaces establishes a relationship between the working volume, in the real world and in the simulated one, of the haptic device.

With the haptic rendering the shapes of the objects and the related parameters can be defined. These parameters are used to define the tactile properties of the virtual objects, identify which sides of the surfaces must be used to apply the haptic effect, set the stiffness, the kind of damping, etc.

However the prime importance aspect in the haptic rendering is the calculation of the force-feedback. This evaluation is very simple if only rigid bodies are analyzed, while when working with deformable bodies, the basic model of the haptic rendering cannot be used. It is so necessary referring to methods able to calculate the reaction forces following the bodies' deformations. Among these calculation techniques, the most used are based on the:

- Finite Element Method (FEM),
- Boundary Element Method (BEM),
- Mass Spring Model (MSM).

The first two methods give very reliable results but they need very long calculation times that, in general, do not allow their use in real-time application.

The MSM, instead, although provides approximate results, need processing times that, particularly for simple models, are very short and that allows its large use for applications that need real time force-feedback evaluation, like the application here introduced.

4.2. Mass Spring Model

The Mass-Spring Model (MSM) schematizes the surface of a deformable object as a net of masses and springs, as shown in figure 5.

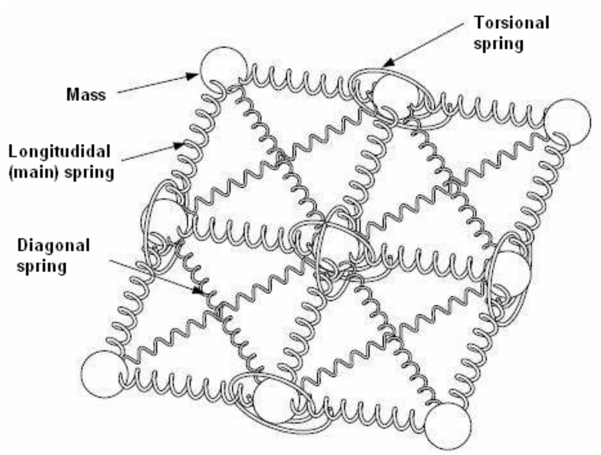

Figure 5 – The MSM scheme

The system parameters like position, speed and acceleration of the masses, are regulated according to the newtonian laws.

Three kinds of springs can be defined (fig. 5): the longitudinal main springs, that keep the distance between adjacent masses, the diagonal springs, that provides the transversal resistance, and the torsional springs that are employed for maintaining the right angle value between the longitudinal springs.

The basic MSM scheme can be also enriched with other objects to simulate dumping forces or other effects.

Both external and internal forces can be applied on every single mass. External forces are those applied by colliding objects whereas internal forces are those exchanged among the masses through the net of joining springs.

The total force F_i applied to the generic mass i is equal to:

$F_i = f_D + f_L + f_T + F_e$;

where:

- f_D is the dumping force;
- f_L represents the force due to the longitudinal and transversal springs;
- f_T is the force due to the torsional springs;
- F_e is the external force.

For the evaluation of the force-feedback it is necessary to calculate the external force.

Almost all the introduced parameters are dependent on the time so, as a consequence, the MSM scheme can be described through a system of differential equations. By giving the initial conditions (like position, speed and acceleration) at the starting of the application, it is possible to solve the system of equations. This can be made through different methods, the most used are the "Eulero" and the "Runge-Kutta" integration techniques.

These methods combine good quality approximate results, little time processing and calculation easiness; all that goes with the setting up of real time applications.

It is very important to note that the mass spring method can be used both for linear and not linear materials, with elastic or plastic behaviour; it only needs giving as input the right parameters' values .

4.2.1. Evaluation of the external forces

In the application here introduced the only deformable structure that makes use of the MSM is the skin. The surface is meshed into quadrangular polygons of which all the vertexes have a connected mass (fig. 6).

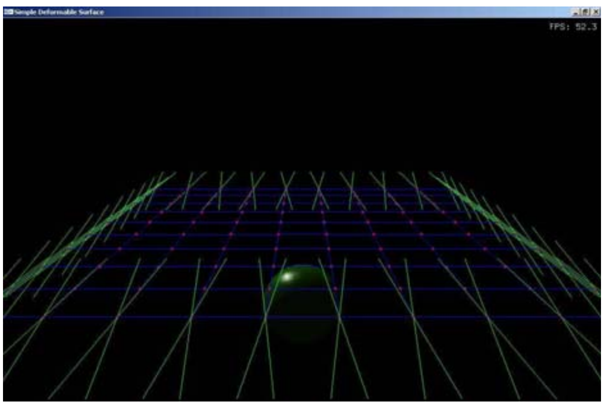

Figure 6 – The adopted MSM model of the skin

Longitudinal springs are placed along the sides of the polygons; moreover, in order to dissipate energy so that allowing the return at the initial position without oscillations around the position of equilibrium, a dumping effect depending on the speed of the masses has been implemented.

The dynamics that regulates the mass spring model can be described through a system of differential equations like this:

$$\left(\dot{x}_i\right) = \left(v_i\right) \quad (1)$$

$$\left(\dot{v}_i\right) = \left(f_i / m_i\right) \quad (2)$$

where x_i e v_i are the position and velocity vectors, while fi is the total force on the mass m_i.

The force fi can also be written by an explicit formulation:

$$f_i = -k_d v_i + K_m \sum_j \frac{l_{ij}}{\left|l_{ij}\right|}\left(\left|l_{ij}\right| - r_{ij}\right) + f_i^e \quad (3)$$

where k_d is the dumping factor, K_m is the spring stiffness, l_{ij} represents the displacements vector, r_{ij} is the length of the spring and f_i^e the external force.

Equations 1 and 2 can be written in a more compact way:

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} v \\ a \end{bmatrix} = \begin{bmatrix} v \\ f/m \end{bmatrix} \quad (4).$$

Equation (4) represents a system of first order differential equations depending on the time t. By replacing the explicit formulation of the external force f_i^e (eq.3) in the previous system (eq.4) and giving the initial conditions, it is possible to solve the system and find the value of f_i^e.

This can be made with the Eulero method. By considering a little time variation Δt around the initial time t_0, it is possible to obtain a rounded solution by writing the equations (4) in the following way:

$$\begin{bmatrix} x(t_0+\Delta t) \\ v(t_0+\Delta t) \end{bmatrix} = \begin{bmatrix} x(t_0)+\dot{x}(t_0)\Delta t \\ v(t_0)+\dot{v}(t_0)\Delta t \end{bmatrix} = \begin{bmatrix} x(t_0) \\ v(t_0) \end{bmatrix} + \begin{bmatrix} v(t_0)\Delta t \\ f(t_0)\Delta t/m \end{bmatrix} \quad (5)$$

When the application is running and the surface is deformed, as a consequence of a collision, the lengths of the springs (l_{ij}) and the velocities of the masses change. By introducing the up-to-date springs lengths l_{ij} in the equation 3 and substituting it in the equation 5, the external force f_i^e can be evaluated.

4.3. Surface reconstruction

When the system of differential equations (4) is solved, the position, the speed and the acceleration of the masses are calculated. Thanks to these information is possible to redraw the up-to-date surfaces of the virtual objects deformed as a result of a collision.

To make that many methodologies are available, among all, one of the most famous is based on an algorithm proposed by Dachille et al. (1999). Such technique suggests to use the knots of the mass spring model as control points of the B-spline geometries. Moreover, by using this method, it is possible to give different weights to the knots that have larger or lower displacements so obtaining a surface that represents in a very precise way the shape of the MSM mesh. This technique turns out to be efficient, intuitive and fast to implement.

The density of the mesh can be related to the resolution of the surface and, by planning different kind of meshes, differences and precisions of the calculation can be verified. It is also possible to work on multi resolution surfaces (Gao et al. 2006) to evaluate local effects.

5. APPLICATION CHARACTERISTICS

Considering the characteristics of the palpation manoeuvre, like for example the possibility to use one or more fingers, or that the contact is only on the external surface of the body, that the movements of the internal organs are constrained, it has been possible to impose some simplifications during the planning of the developed application. One of these is related to the objects to simulate that, in this case, are only three: the fingertip, the skin and the anatomical formation, that have been implemented through three suitable C++ classes.

It is important to notice that all the objects, with the exception of the proxy (that needs only the graphic rendering), must be defined twice: the first one for the haptic rendering (the object is tangible but not visible) and the second one for the graphic rendering (the object is visible but not tangible).

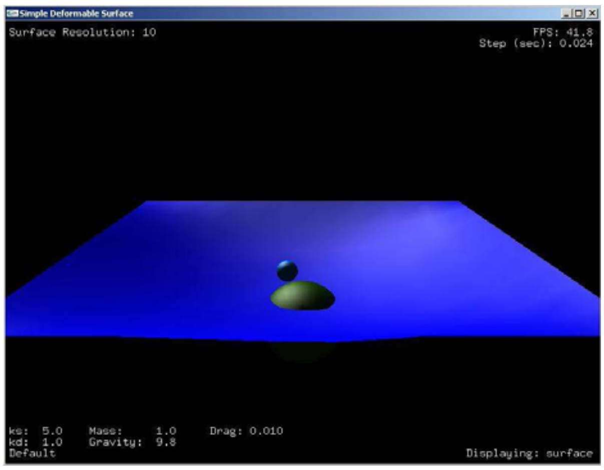

Figure 7 – Objects represented in the application

5.1. Finger

The virtual finger used to touch and to interact with the skin has been approximate with a small sphere, the blue one in fig. 7, having suitable dimensions (as regards other objects dimensions).

This object, also called “proxy”, is analogous the mouse pointer of any window-based software application, and is used to interact with other virtual objects.

This kind of scheme has been adopted since only the fingertip is in contact with the skin.

Kinematics and dynamics characteristics of the object "fingertip", like the working volume, the maximum measurable speed, etc.., are related to the characteristics of the haptic peripheral.

Since the interaction among different deformable objects (Ruan et to the. 2004) is generally more complex to manage in regard to the force-feedback calculation, it is convenient, if possible, to use rigid bodies characteristics for the virtual objects.

In this case, even if the fingertip can have elastic deformations, these usually are very little and so negligible. For this reason the proxy (fingertip) has been considered as a rigid body.

Other main properties of the proxy are the following:

- it must be able to push the surface of the skin but not to drag it;
- the push must be applied only on a side (the external one) of the skin, so the proxy cannot go beyond it;
- the interactions with the anatomical formation must be indirect, in fact the tactile perception must happen through the skin.

5.2. Anatomical formation

The second object is the anatomical formation, representing a nodule, that has been represented as a bigger sphere in comparison with the proxy (fig.7).

In this case the graphic rendering is not so important like the haptic rendering, that is instead essential.

The contact with other objects can take place only through its external surface. This object, like the fingertip, has also been modelled as non-deformable body. In fact, since the contact between the finger and the skin happens on a reduced surface and with a very low external load, the tissue between the skin and the anatomical formation, distributing the external load on a wide surface, stresses the nodule in a very light way, causing very small elastic deformations. For this reason it is reasonable to hypothesize its behaviour similar a rigid body.

5.3. Skin

The last object to simulate is the skin. It has been modelled as a planar and deformable surface. An “integrated” MSM system has been used for its haptic and graphic representation. The system can be defined “integrated” because the same points’ coordinates have been used to define the MSM mesh and the vertexes of the polygons defining the surface. Certainly in this way, the graphic rendering accurately follows the haptic rendering.

As regards the haptic rendering, the mechanical characteristics of the tissue have been defined by setting the parameters of the MSM system.

Other characteristics that do not depend on the MSM system, like the rules that regulate the interaction and the collision with other objects, have been defined through the implementation of dedicated classes in C++ language.

5.3.1. Tissue mechanical characteristics

A large part of the soft tissues is generally constituted of collagen, elastin and polysaccharides.

Collagen is a protein with a fibrous structure and has the purpose to limit the deformations and prevent the mechanical breaking of the tissue. The fibres have a helical shape then, if submitted to an axial load, initially show a very low “shape” stiffness, once the fibres become straight, instead, the mechanical properties considerably increase, because of the very high strength of the intra and intermolecular bonds.

Elastin is also a structural protein with high elasticity values but generally lower than the collagen.

Polysaccharides are polymers made of sugars and have viscous characteristics.

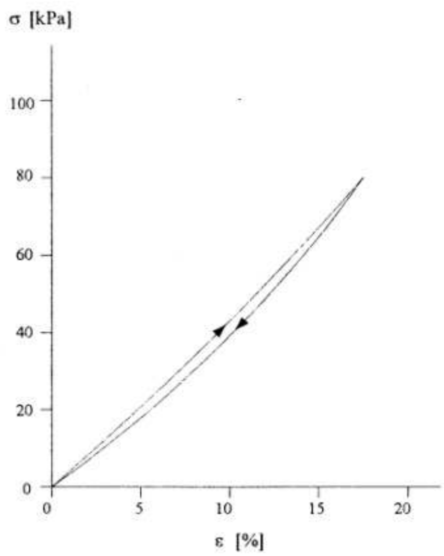

Figure 8 – Mechanical characteristics of a tissue

The skin tissue so has an elastic not linear behaviour. Moreover the loading and unloading curves slightly differ, describing a little hysteresis loop as shown in figure 8.

In the presented application, considering the typology, the values of the applied loads (at the most some dozens of grams) and the thickness of skin (about 1-2 mm), the tissue has been modelled like a perfectly elastic material , without making a big error.

5.4. Algorithm for collision detection

The available algorithms in the OpenHaptics library allow to evaluate only the collisions between the proxy and other objects, but do not allow to detect any collision between other user–defined objects. For such reason the OpenHaptics algorithm has been used to evaluate the collision between the proxy and the skin, whereas another technique has been used for the collision detection between the sphere, representing the nodule, and the surface, representing the skin. This has been necessary because there can be no interpenetration between the skin and the anatomical formation.

It has been used an algorithm based on the implicit formulation of the surfaces that, in this particular case, has been implemented in a simplified way because one of the two objects (the sphere representing the nodule) is fixed.

Moreover another simplification has been performed in analysing the collision between the proxy and the nodule rather than evaluating the one between the skin and the nodule. That has been possible because, even if the real collision is between the skin and the nodule, in effect the skin is moved by the proxy and it always has its same positions. For this reason, to simplify the procedure, in the following all the calculations, even if related to the proxy, are equally valid for the skin.

The implicit formulation of a sphere is the following:

$$(x-x_0)^2+(y-y_0)^2+(z-z_0)^2-r_n{}^2=0 \qquad (6)$$

where x_0, y_0, z_0 are the coordinates of the centre and r_n is the radius of the sphere.

In particular for the sphere representing the nodule, the used values are the following:

$$\begin{cases} x_0 = 0 \\ y_0 = 2 \\ z_0 = 0 \\ r_n = 1 \end{cases},$$

so the equation 6 can also be written in this form:

$$f(x,y,z)=x^2+y^2+z^2+4y+3 \qquad (7).$$

By changing the equation 7 into an inequality it is possible to select the internal points ($f(x,y,z)<0$) and the external ones or those on the sphere surface ($f(x,y,z)\geq 0$).

Because the coordinates of the proxy are always known, it turns out very simple to evaluate if there is any collision. If so the proxy is inside the sphere and it is necessary to drag it on the surface.

By supposing the proxy is just a little inside the sphere, it is possible to calculate the point on the surface where the proxy must be moved, by dragging it along the direction joining the proxy position and the centre of the sphere. It needs then to calculate the straight line passing through the proxy (which has coordinates P_x, P_y, P_z) and the centre of the sphere; the parametric formulation of this line is the following:

$$\begin{cases} x = P_x * t \\ y = -2 + \left(P_y + 2\right) * t \\ z = P_z * t \end{cases} \quad (8).$$

By replacing the equation 8 in the equation 6 it is possible to calculate the value of the parameter t that verifies the system of equations 8 and 6:

$$t_1 = \sqrt{\frac{1}{\left[P_x^2 + (P+2)^2 + P_z^2\right]}} \quad (9).$$

Using this value (t_1) in the equation 6, the coordinates of the intersection point S between the straight line and the sphere are known.

This procedure would be correct if the proxy is a point. Because it has a spherical geometry, the previous calculation must be lightly modified taking into account the radius r_p of the sphere representing the proxy.

Repeating the previous described procedure, it is possible to find the right value of t :

$$t_2 = \frac{r_p}{\sqrt{P_x^2 + (P+2)^2 + P_z^2}} + t_1 \quad (10)$$

By using this values of t in the equation 6, the point on which moving the centre of the proxy after the collision with the anatomical formation can be evaluated.

6. USERS' TEST AND FUTURE WORKS

The application has been tested by some users, some of these are doctors other, instead, engineers. All of them have shown a good familiarity with the haptic device and the system, and have been able, in a simple and fast way, to identify the subcutaneous nodule, of which they have understood the shape, the dimensions and the consistency.

Some of them have complained about the absence of other internal organs and about the shape of the surface used to simulate the skin. This last, in fact, has been simulated with a not much intuitive and realistic planar quadrangular surface.

For these reasons most of the future works will be addressed to the modelling of a larger portion of skin and the use of curved surface to simulate in a more realistic way the external shape of the human body.

Moreover other internal organs and some parts of the bony structure will be added in the application.

It will be also necessary to modify opportunely the MSM method to apply it to volumes and so being able to simulate also the mechanical properties of the internal organs, modelled as deformable bodies.

It will be also necessary to modify the collision detection algorithm because it can be used only for geometric shapes that can be represented through explicit and continuous functions, and that represents a particular working condition.

To simulate in a more realistic way the mechanical properties of the skin, it will be studied the use of more complex multilayer and multimaterial physical models (Yang et al. 2004).

Finally, it could be interesting to study the integration of the application in a virtual reality environment in order to give the users the possibility of a more realistic graphical perception of the objects.

7. CONCLUSIONS

The innovative aspects and the advantages introduced by the haptic technology are, without any doubt, remarkable and will certainly increase more and more with the improvements of the working techniques and devices.

In this context, the research activity here presented, represents a promising innovative methodology for the medical palpation training.

Thanks the presented system an user can "touch" a virtual representation of the human skin a perceiving it as real. It is possible, in fact, thanks the use of the developed force-feedback system (fig. 9) to feel the contact with a surface, representing the skin and, through a palpation manoeuvre, understand if there is some problem, like the presence of a nodule, a particular anatomical formation.

Although the system has been implemented in a simplified way (fig. 9), all the users that have tested it, think the proposed technique can represent a very powerful tool for the training of not skilled doctors.

The problem of the force-feedback calculation has been solved making use of the MSM and a simple but very efficient algorithm has been implemented for the collision detection among the rendered objects.

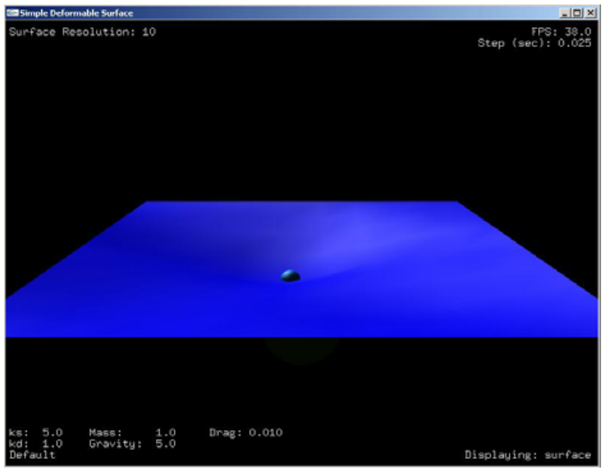

Figure 9 – a screenshot of the developed application

In general it can be stated that the obtained results are very promising. In the development of similar future applications, the proposed methodology can represent a valid reference to analyze more complex conditions and to model other objects with different dynamics and structures.

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