A Low Cost Haptic Mouse for Prosthetic Socket Modeling

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Abstract. This paper refers to the design of prosthetic socket adopting a computer-aided approach. The main goal is to make available a modeling tool, named SMA-Socket Modeling Assistant, which permits to replicate/emulate manual operations usually performed by the prosthetist. Typically, s/he also relies on the sense of touch; therefore the underlying idea has been to develop and experiment haptic devices. The paper presents a haptic mouse at low-cost to make it affordable also by small orthopedic labs. It is essentially a traditional mouse device enhanced with a servomotor and a pressure sensor pad integrated with Arduino board and SMA. The application within SMA is described as well as the haptic interaction with physically-based model of the residual limb. Finally preliminary tests are illustrated.

Keywords: prosthesis socket modelling, haptic devices, low cost haptic mouse, Arduino.

1 Introduction

Nowadays, lower limb prosthesis design is a hand-made process and the final results depend on the technician skills. The lower limb prosthesis is composed by standard components (foot, knee, tubes, adaptors) and custom parts (socket and sometimes the liner). The socket is the most important component and has to be realized starting from the shape of the patient's residuum, since it has its own specific and unique geometry. Moreover, the socket is the interface with the human body and the final comfort of the whole prosthesis mostly depends on its quality. The traditional design process starts with the realization of negative and positive plaster casts of the residual limb. The prosthetist pushes and manipulates the residual limb in order to create the right plaster cast and to understand how to modify correctly the geometry and obtain a comfortable socket. Then, the prosthetist manually modifies the positive cast by adding and removing material to reach the optimal shape. This operation is meaningful and necessary to provide the right fitting and lower pressure in sensitive anatomical zones. For example, where there are bony protuberances or tendons the socket does

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not have to press the limb, and at the same time not to be too wide because it could cause other physical problems. Figure 1 shows two examples of residual limb/plaster cast manipulation.

Even if the prosthetist is well skilled, the traditional process follows a trial and error approach and often iterations and socket physical prototypes are required.

In order to optimize the entire process and decrease psychological impact on patients, we have developed an innovative software platform to design and test the prosthesis totally in a virtual environment [1].The platform includes a 3D CAD module, named SMA-Socket Modeling Assistant, which provides a virtual laboratory where the orthopedic technician can replicate all the traditional operations to define the socket shape. The system embeds technicians' knowledge, best practices and rules that drive the traditional process, so the user is guided through the process. Finally, SMA has been integrated with a FE solver to study the interaction between the socket and the residual limb and check pressure distribution over the residuum critical zones.

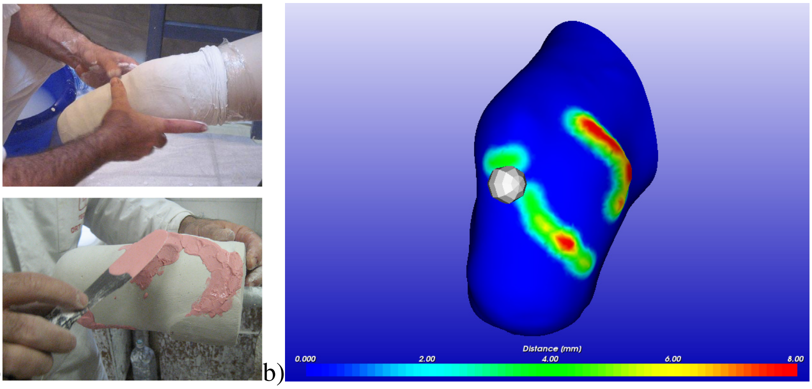
a) b)


Fig. 1. a) Hand-made manipulation; b) SMA Sculpt Tool

The user can modify the socket shape using several tools that help and guide the user to create the right socket shape around the geometry of the residual limb. Some tools work in automatic mode (e.g., circumference reduction), on the base of the design rules embedded in the system. Others are interactive and simulate traditional operations performed by the prosthetist. Among these, the most important is the Sculpt Tool that permits to freely modify the surface geometry. A sphere cursor can be moved over the residuum or socket models and the vertexes inside the sphere are pulled or pushed along their normal axis in order to create the required deformation (Figure 1). It is also possible to change the ray of the sphere in order to set the area of deformation. This operation emulates the operation of adding or removing material from the plaster cast.

However, as mentioned before, along the traditional design process, the prosthetist uses his/her hands to manipulate the residuum and/or socket shape (Figure 1a) and often relies on the sense of touch. S/he uses hands to evaluate residual limb tonicity and manipulate/modify accordingly the socket shape. Haptic interaction could help the technician to regulate better the entity of the deformation: the more the user presses on the haptic device, the greater is the depth of the deformation. Adopting a physic-based model makes possible to simulate the behavior of a real limb subjected to the manipulation.

To replicate this operation using sense of touch within SMA (at least partially), we investigated the possibility to adopt haptic device for managing the interaction with the 3D model of the residual limb. Devices available on the market, possible at low cost, have been analyzed, since costs could be a key issue for small orthopedic labs. From the analysis and first tests carried with Novint Falcon device (http://www.novint.com/) [2], we have decided to develop a prototype of a haptic mouse, that can provide the user, at low cost, an haptic interaction with the residuum or socket virtual models.

In this paper we first introduce the scientific background in considered field; then the developed haptic mouse. Finally the application within the SMA module and preliminary results are presented.

2 State of the Art

During last years, computer emulation of the five senses has been investigated by many researchers [3-5] for different applicative fields. For example, [4] describes the use of 3D technologies and stereoscopic vision to support the diagnosis and rehabilitation of low-vision related pathologies. Regarding the sense of touch, interesting applications are related to surgery simulators to emulate real hand-made operations and train practitioners [6-11].Other important aspects involved in the sense of touch simulation are the feeling of temperature, pain, friction and vibration [11]. To this end, many haptic devices have been designed in order to simulate these different tactile perceptions [12-14].

In the prosthetic field, on the market we can find various CAD/CAM systems (e.g., Seattle ShapeMaker, Rodin4d, Bioshape, and Vorum Canfit™). They use reference model templates as starting point to build positive chalks. However, but they do not include any simulation tools, even if we can find in literature several research works that consider finite element analysis to simulate and analyze interaction between the socket and the residual limb[15-17].

In this context, the kind of interaction provided by the existing systems refers to the traditional mouse-keyboard paradigm. Only Rodin (www.rodin4d.com) proposed a CAD system (Rodin4Design software) that utilized the haptic 3D arm Phantom to provide the user force-feedback during virtual carving and sculpting of the 3D models.

Phantom devices are used also in the dental CAD/CAM applications (www.sensabledental.com) and as a general-purpose 3D haptic modeler (http://www.dentsable.com/products-freeform-systems.htm).

For the prosthetic field, haptic gloves, such as the CyberGrasp, from CyberGlove System LLC [18] could be adopted since they permit to replicate the behavior of the hands interacting with a real object. On the other hand, they are complex, expensive and not affordable for small orthopedic labs. Therefore, we decided to consider low-cost haptic devices and, in particular, to develop a haptic mouse specifically conceived and tested for our application.

3 Haptic Mouse Prototype

To build low-cost and easy to use device, we considered, at this stage, sufficient the possibility to interact with one finger, by which the user can feel the softness/hardness of the residuum surface and perceive better the virtual object.

The haptic mouse prototype is basically a traditional mouse device enhanced with a servomotor and a pressure sensor pad (Figure 2).The servomotor is the Hitec HS-225BB high speed model, with 0.14 sec/60 deg. transit time; while, the pressure sensor is the Flexiforce piezoresistive force sensor built by Tekscan. If pressed, its resistance changes from infinite to about 50.000 Ohm. Figure 3 shows the haptic prototype.

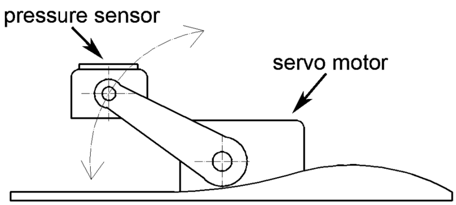


Fig. 2. Haptic mouse operating principle

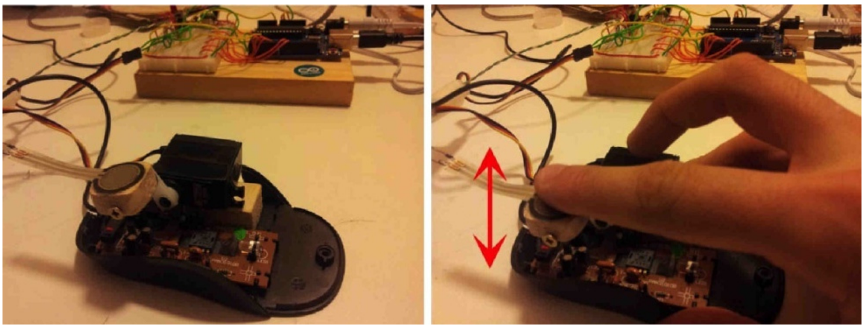


Fig. 3. Haptic mouse prototype

The pressure sensor pad works as input device, measuring the force the user applies with her/his finger. The servomotor works as output actuator setting its position according the physic-based model computations.

To get data from the pressure sensor pad and to drive the servomotor, we exploited the Arduino board linked to the computer running the Socket Modeling Assistant (Figure 4). The communication between Arduino board and the computer is through USB port, with serial protocol.

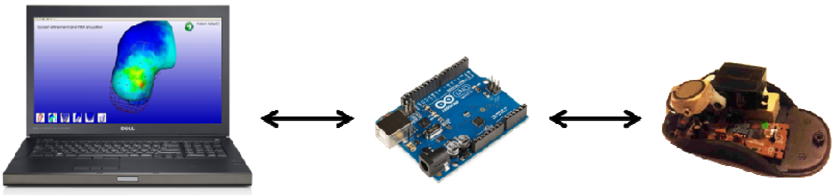


Fig. 4. Computer - Arduino - Haptic mouse workflow

The user can move the sphere cursor of the Sculpt Tool by moving the mouse, as s/he would do with a traditional mouse. Putting one finger on the pressure pad, the user can push the pressure sensor and the pressure value is read by Arduino and transmitted to SMA. The embedded physic-based model computes the deformation created by the applied force and calculates the new servo motor position, which is moved by Arduino board. The more the user pushes the pressure pad, the deeper is the deformation of the surface and the servo motor position is lowered.

The input data from the pressure sensor pad are smoothed by keeping a FIFO (first in first out) buffer with the last collected samples and averaging them.

3.1 Physics-Based Model of the Residuum

In order to compute the deformation of the surface according to the user input, we developed a physic-based model, embedded within SMA. The model described in [19]and developed for surgical simulation applications has been taken into consideration.

The mathematical model is composed by a mesh of tetrahedral elements and obeys the following equation:

$$f = Mu'' + Du' + Ku$$

where:

- M is the mass matrix.
- D is the damping matrix.
- K is the global stiffness matrix.
- f is the vector of the external forces applied to the model and obtained by reading the pressure sensor pad.
- u is the vector of nodes displacements due to the deformation.

The equation is solved with an explicit approach [19]. In order to give the user a consistent simulation of the sense of touch, the haptic loop has to be rendered at least with a frequency of 1000 Hz and the equation has to be resolved in real time. Therefore SMA uses GPU computation that permits to obtain about 10x faster computation speed.

For simplicity, we considered lumped masses at nodes; so, M and D are diagonal matrices and this can simplify computations. To reduce computational time, a pre-processing phase performs condensation of the K matrix: we eliminate rows and columns corresponding to the fixed nodes (e.g., those belonging to the bone). For materials characterisation (bones and soft tissues) we considered data found in literature [15-16].

After the pre-processing and matrix condensation phase, the part of the equation having high computational times is only the Ku multiplication. This kind of computational problem is well addressed by GPU computation. As K is a sparse matrix, we perform the Ku multiplication with the CUSPARSE library (a sub-library of CUDA) that has fast and optimized matrix-vector multiplication features.

4 Preliminary Testing

We experimented the haptic mouse to create the shape of the socket starting from the residual limb model and to emulate the operation of adding and removing material from the plaster cast.The 3D model of the residual limb of a transtibial (amputation below knee) patient has been acquired by MRI (Magnetic Resonance Imaging) and automatically reconstructed using a hoc module embedded within SMA [1]. The 3D model, represented by NURBS surfaces, includes bones soft tissue geometry.

To evaluate how the haptic mouse replicates the curves and slopes of the residuum virtual surface, we first tested it only with the servomotor and without the pressure sensor. By moving the mouse on the table plane, the servomotor sets its height position according to the height of the surface of the virtual model. In case of fast movements, we noted a small delay to update the servomotor position due its speed limits. However, in case of normal movements in a limited area, the servomotor follows the virtual surface with good approximation. Afterwards, we tested the complete system including the pressure sensor pad. We found some fake peaks in the detection of applied forces; however the filtering software routine limited the problem.

Prosthetist considered interesting these first tests, even if the haptic device permits to emulate only the interaction of one finger. Figure 5 shows some example of the shape modeling using the haptic mouse. Anyway, the haptic force feedback can help the technician to manipulate the geometric model as s/he usually acts using hand.

As mentioned before, in previous research activities, the commercial low cost device, namely the Novint Falcon, has been tested. From a preliminary comparison of results reached so far, we noted that the haptic mouse seems to be more intuitive and easy to use. For example, sometimes, the first testers were not able to correctly understand the position of the cursor respect to the virtual model of the residual limb.

We have planned to test the prototype with real cases in collaboration the orthopedic lab involved in the project, in order to test if this kind of devices could be included in the real workflow. We have also planned to evaluate other input sensors and output actuators with better performances.

5 Conclusions

In this paper, the authors presented the first prototype of a haptic mouse integrated with a prosthetic modeling tool, i.e., SMA, to interact with the 3D model of the residual limb or of the socket. This should make more natural the interaction especially for those users, such as orthopedic technicians, without specific skills on computer-aided tools. The main features are one-finger haptic interaction and ease of use. The haptic mouse works like a traditional mouse, permitting to control a virtual cursor with the movement of the hand on a plane; moreover, it's possible to interact with a virtual object and feel its surface with the added haptic feature. Preliminary results have been considered promising; however, we need to evaluate hardware (servo motor and pressure pad) with better performance while maintaining the working principle.

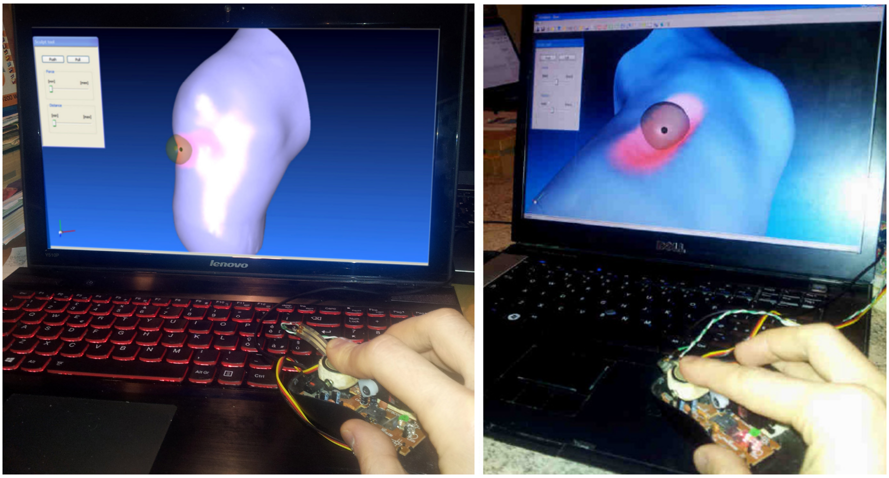


Fig. 5. Use of the haptic device to interact with the 3D model of the residuum or of the socket

The haptic device can be improved and used in other application fields. For example, we can add more couples of servomotor and pressure sensor to provide haptic force-feedback with multiple fingers. This should permit to perceive better curves and slopes of the surface. Another potential field of application the authors are going to investigate is the use of the haptic mouse for visual impaired people to help them to feel a virtual surface. Finally, it would be interesting to test this kind of device with general purpose or artistic modeling software, such as Pixologic Zbrush (pixologic.com).

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