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TUTORIAL

Development of Multimedia Learning Modules for Teaching Human Anatomy: Application to Osteology and Functional Anatomy

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Computer-assisted learning (CAL) is growing quickly within academic programs. Although the anatomical commercial packages that are available for this learning have attractive advantages, they also have drawbacks: they are frequently not in the local language of the students, they do not perfectly answer the needs of the local academic program, and their cost is frequently more than students can afford. This study describes a relatively inexpensive method to create CAL tutorials, whose content can be fully customized to local academic needs in terms of both program and language. The study describes its use in creating multimedia learning modules (MLMs) about Osteology and joint kinematics. The pedagogical content in these modules was collected from objective experiments to give students the opportunity to access new scientific knowledge during their education. It can be replaced, as desired, by almost any content due to the flexibility of the production method. Each MLM consists of two complementary subelements: a multimedia theoretical lecture and a three-dimensional interactive laboratory. Such MLMs are in use at both the University of Brussels (ULB) and the National University of Rwanda (NUR). The development of this work was part of the VAKHUM project, and the pedagogical validation is currently being performed as part of the MULTIMOD project. *Anat Rec (Part B: New Anat) 272B:98–106, 2003.* © 2003 Wiley-Liss, Inc.

KEY WORDS: computer-assisted learning; CAL; education; functional anatomy; multimedia learning modules; MLM; virtual reality; kinematics; osteology

INTRODUCTION

Human anatomy is an important component of the medical student curriculum. For decades, even centuries, books have been the primary medium to propagate knowledge in anatomy, and many excellent textbooks exist. Some of them give both detailed descriptions of the human anatomy and lists of anatomical variations (Testut, 1896). Others concentrate on realistic illustrations (Rouvière and Delmas, 1948; von Lanz and Wachsmuth, 1979; Bannister et al., 1995; Sobotta, 2000). A third category associates clinical cases with practical descriptions of specific topics of interest to clinicians (Moore and Dalley, 1999).

More recently, anatomy has become the subject of commercial software packages, some of which allow students to interact with computer models. Other materials are now also available on the Internet. The development of such systems has increased rapidly in the past few years due to the availability of public data (e.g., the Visible Human Project, www.nlm.nih.gov/research/visible/visible_human.html; Spitzer and Whitlock, 1998) and affordable computer hardware (Trelease, 2002). A list of relevant software and Web sites is given at the end of the study. Previous studies have shown that on-line education is an efficient tool for improving knowledge distribution, using both multimedia technologies to create educational support (Benbunan-Fich, 2002) and the Internet to distribute the knowledge (Smith et al., 1999).

The content of currently available materials is variable, but it is not our aim to assess their intrinsic quality. However, bearing in mind that teaching should usually answer local needs (i.e., the local academic program of

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the institution where the teaching takes place), using commercially available tutorials has practical drawbacks. The content may not exactly match the local curriculum. Language may also be an issue—a medical student will have to address his/her future patients and colleagues in the local language, and should, therefore, develop a professional vocabulary in that language. The software is often too costly for students, which can be in contradiction with local academic policy (some universities are promoting the right of equal opportunity to educational resources, whatever the social background of the students). There is, therefore, a need for CAL systems that are both customizable and economic.

In developing countries, obtaining multiple copies of quality books is often problematic because of their high price compared to the local average income; and the academic libraries often possess only a few copies of inexpensive low-quality textbooks. Many of these countries are making strenuous efforts to acquire computers with access to the Internet so that a substantial volume of information can be retrieved free of charge or at low cost. Unfortunately, the information available on the Internet is often not peer-reviewed nor well adapted to local circumstances. Such countries are almost totally dependent on educational support coming from abroad, which is not the optimal situation for independent development. Another aspect that makes digital anatomical support attractive for developing countries is the typical lack of availability of human specimens for pedagogical purposes due to both local cultural circumstances (e.g., ethics, religion) and logistics condition (e.g., climate constraints, lack of efficient cooling systems).

What about educational content? Anatomy is a field where spatial visualization is of importance. Functional anatomy is a strongly three-dimensional (3D) matter: students must learn particular anatomical structures, their function, and their spatial relationships with the surrounding structures. Some structures may have dynamic functions associated with them. Functions can include displacement of the structures (e.g., joints), deformation of structures (e.g., organs), or both (e.g., ligaments). In each of these, it is important to understand both the physiological and the pathological mechanisms that are related to the anatomical structures.

Although medical research is rapidly progressing in almost areas, few educational media are suitable to disseminate the knowledge related to functional anatomy in a useful pedagogical manner. Indeed, as mentioned above, textbooks are still widely used as the primary tool to convey anatomical concepts. A book is very suitable for illustrating two-dimensional static topics, but less so for demonstrating 3D dynamic phenomena.

In our experience, medical students frequently encounter problems in understanding certain dynamic aspects of functional anatomy. This discipline is close to both robotics and mechanical engineering: motions are described as occurring about axes and along planes; muscle actions must be interpolated from their spatial excursion, and so on. As most medical students do not have an extensive background in mathematics or engineering, such descriptions do not always convey the action well. However, individuals preparing themselves for a medical career do not actually need to understand the functional mechanics in a detailed mathematical manner to be efficient in their future profession. That is why we hypothesize that both pre- and postgraduate medical students would gain a greater understanding of information related to functional anatomy if this information could be integrated into a proper 3D medium.

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A similar approach has been implemented recently to provide dynamic spatial information about the brain (Lozanoff et al., 2003). Although this implementation is not truly three dimensional, the spatial concept remains the same as ours: to help students to increase their 3D anatomical understanding by giving them spatial clues about the underlying anatomy and its dynamic behavior. As mentioned previously, computer graphics tools already exist. However, to the best of our knowledge, none integrates extensive content on functional anatomy, probably because of the lack of reliable data to create the 3D content.

This study has three goals that aim to solve the problems described above. The first is to describe an economical method for creating MLMs locally; this should avoid the need to hire specialized private companies, so as to limit costs associated to production. The second concerns the need of customized content—the method should allow features of the local teaching program to be integrated and reflect local requirements of CAL support in the local language. For our particular needs, class content should also include a 3D display to allow explanations of 3D anatomical features and mechanisms. The third goal is to produce tutorials that are easily distributed to students through CD-ROMs and computer networks (intranets and/or the Internet). This suggests that the size of the MLM should be suitable for comfortable distribution and visualization on standard personal computers. This study is part of both VAKHUM (www.ulb.ac.be/project/vakhum) and MULTIMOD (www.tecno.ior.it/multimod/) projects funded by the European Commission.

DATA COLLECTION FOR MLM CONTENT

The content of the tutorials described in this study has been developed from recently published results within the VAKHUM project; only a summary is provided here to illustrate an example of MLM content acquisition, but full details can be found in Van Sint Jan et al. (2002a). Production of the MLM service tools is described in a further section.

In vitro data collection included two aspects. The first dealt with image data collection for the 3D reconstruction of realistic bone models. The second dealt with the acquisition of kinematic data to be used to animate the bone models to simulate physiological joint motions. All aspects of the data collection were fully validated. No data editing was performed to ensure anatomically accurate results, at least within the limits of the accuracy of the method. Although data collected from in vitro experiments do not exactly illustrate in vivo morphology and behavior, cadaver preparation is often necessary to obtain useful data for particular multimedia content (Lozanoff et al., 2003). It is the multimedia creator's responsibility to indicate the accuracy of the content. In our case, all data collection methods have been validated and the accuracy of the models is available (Van Sint Jan et al., 2002a). Experimental results were assumed anatomically correct for integration into the educational content.

3D Bone Models

Accurate information on bone morphology was collected to create 3D computer models (Van Sint Jan et al., 2002a). Accuracy was of importance because the bone models were to be used by medical students within osteology modules where small details of bones are taught. A 3D surface scanner could be used, but these devices usually lack sufficient accuracy for the current application. Also a full joint dislocation would be required to allow the joint compartment of each bone to be scanned. This dislocation was not acceptable, because the specimens were to be used for additional functional experiments (see next section). In vitro computerized tomography (CT) facilitated the collection of bone morphology from freshly frozen specimens. Segmentation of the medical imaging data set was performed using commercial software (Amira, www.amiravis.com, Germany), which also allowed the production of 3D bone models. Senior academic staff members at ULB performed visual control of the generated surfaces to guarantee realism of the final 3D bone models.

Joint and Limb Kinematics

Joint motion analysis was performed according two protocols: electrogoniometry and stereophotogrammetry. Kinematics data at joint level were collected using a custom-made 3D goniometer, which is a six-revolute instrumented spatial linkage including six potentiometers, each of which records 1 degree-of-freedom at 200 Hz. The use of electrogoniometry was limited to the study only of isolated joints, because this device is not best suited to record the relationships between different joints during a particular task (e.g., the relative displacements of the hip, knee, and ankle joints during walking). At joint level, electrogoniometry allows data collection with high accuracy (accuracy is better than 1 degree for orientation and 1 mm for translation, Van Sint Jan et al., 2002a), which provides useful information concerning the intrinsic behavior of almost any joint. Joint kinematics was collected on cadaver preparations already processed during the initial 3D bone modeling.

The second motion data collection system, i.e., stereophotogrammetry, gathered kinematics data for several joints during particular tasks (e.g., walking, stair climbing, chair sitting) simultaneously. Because this method is not invasive, motion data were collected on volunteers. This method allows an analysis of the relationships of several joints in a limb during specific tasks (e.g., both hip and knee behavior during normal walking). However, the precision of this method is lower than that of electrogoniometry (Della Croce and Cappozzo, 2002).

The final process required to animate the 3D bone models using the collected kinematics and motion data is registration. New registration methods have been developed by the authors and described elsewhere (Van Sint Jan et al., 2002a,b). These methods lead to realistic computer graphics displays of human kinematics suitable for integration into MLMs.

Other methods exist to develop 3D motion simulation, but experimental validation of all data is a critical issue if anatomical realism is of importance. For example, accurate 3D models can be segmented from the Visible Human (VH) Project and animated in dedicated software. Unfortunately, no motion data are available from the VH project. Such data, thus, must be obtained from other sources. Final validation of the results is therefore difficult, because of the various data sources. Such problems were avoided in this study, because all data were sampled at one location using validated procedures, and we were able to collect morphologic and kinematics data from the same specimens.

DEVELOPMENT OF MLM SERVICE TOOLS

Final bone models, and registered joint and limb models have been integrated into MLMs to illustrate some aspects of human osteology, arthrology, and joint kinematics. Each MLM has two components: a multimedia interface similar to a lecture and a fully interactive 3D environment similar to a laboratory. The choice of developing two independent interfaces is based on the idea that pedagogy can be characterized by two general categories of knowledge (Benbunan-Fich, 2002): conceptual knowledge is based on fundamental concepts and is similar to traditional classroom lectures, whereas pragmatic knowledge corresponds to the process allowing one to transform concepts into practice. Both knowledge categories are necessary to reach a satisfactory practical assimilation of the lecture material.

Multimedia Lectures: Theoretical Lectures, Conceptual Knowledge

All theoretical aspects of the anatomical MLMs have been included in a multimedia interface. Students can listen to multimedia lectures given by a professor. Such lectures consist of oral explanations describing the 3D models and 3D motion simulations that are displayed on the screen (Figure 1). The students participate passively, i.e., they listen to the presentations, as they would usually do in a classroom. All 3D models described in the lectures are available to students

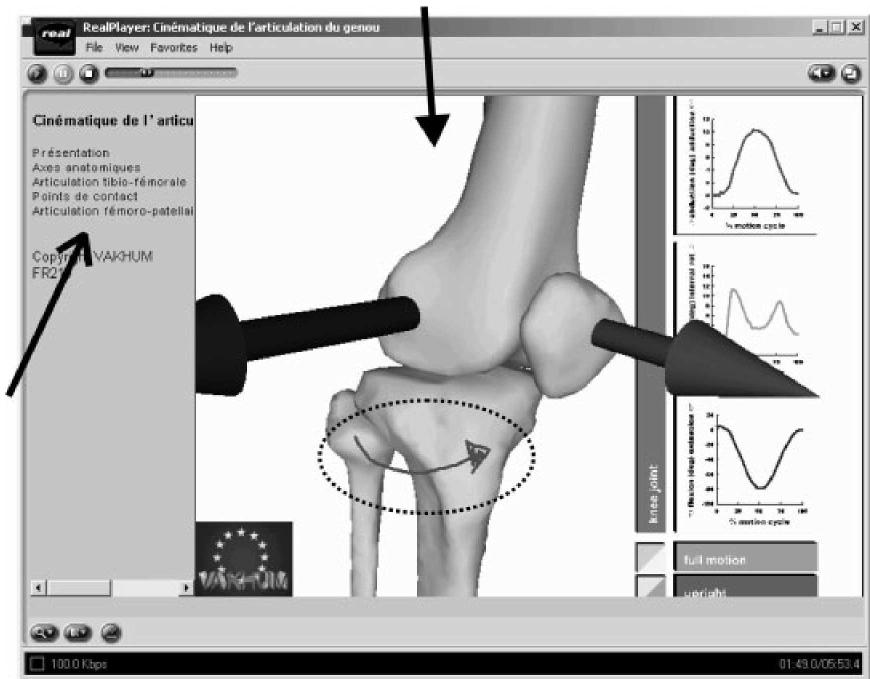

Figure 1. Three-dimensional (3D) narrated navigation (theoretical lecture). The content can be listened to using standard AVI readers. The interface shows a table of content (open arrow) allowing the selection of particular parts of the lecture. The main window (black arrow) shows an animation displaying the same 3D models as are available in the practical modules (see Figure 2). The animation also contains annotations and visual clues from the lecturer: for example, for this particular lesson on knee kinematics, he indicated the direction of the internal rotation associated with knee flexion using an arrow (dotted ellipse) drawn by hand using a numerical graphics tablet. The illustrated MLM can be found at http://homepages.ulb.ac.be/~anatemb/mlm.htm.

for rehearsal when they are taking the laboratory, as explained in the next section.

According to the Merriam Webster dictionary, a tutorial is both a class conducted by a tutor for a small number of students, and a paper, book, film, or computer program that provides practical information about a specific subject. The tutorial production provides practical information concerning aspects of anatomy and follows a linear instruction path without diversion to alternative pathways while examining a 3D model. That is why we prefer to use the term "3D narrated navigation" instead of "multimedia lectures."

The option of starting the MLM with a noninteractive lecture was taken to avoid the following problems with students without prior theoretical knowledge. Anatomy classes usually contain many descriptions, and students, thus, are faced with a large number of new names and concepts. At this stage, the student should concentrate on developing a theoretical understanding of the material—this theoretical content prepares the students for the later practical assimilation. We, therefore, decided to record a virtual navigation performed by a professor using the same type of interface and 3D bone models available later for the students during the interactive laboratory. This strategy allows students to retrieve more easily the anatomical features described in the lecture.

All actions performed by the professor were stored on disk using special software (Camtasia, www.camtasia.com) that records the various states of the screen display during the virtual navigation. This screen recorder also offers the ability to enhance the recording with pointers and drawings of various colors (Figure 1). Audio support can be added either during screen recording or afterward. In our case, we produced the audio explanations later because we found that is was difficult to navigate in the 3D environment, if we were adding pointers and giving oral explanations simultaneously.

A first step consisted of recording the 3D navigation and adding pointers to enhance the location of some anatomical features. The intermediate result was stored in a compressed AVI format, using a special TSCC video codec freely available for playback (www.realnetworks.com). The second step added audio support. The final file was also stored in AVI format. The TSCC codec is attractive, because it can produce relatively small AVI files even with a high number of frames per second (fps) and large screen resolution (e.g., 640×480 pixels). AVI files are easily portable and can be edited, trimmed, and combined thanks to the availability of many dedicated low-cost applications.

The result of these steps is a copy of the navigation performed by the professor, without any loss of screen and sound quality. A typical size for a standard AVI tutorial running at 800 kbps is around 100 MB (duration, 17 minutes; screen resolution, 640×480 pixels; 15 fps; full-color screen depth and standard sound quality, 22.05 kHz, 16 bit, Mono). This kind of tutorial can then easily be distributed to students on CD-ROMs or DVD-ROMs.

This size, however, is too large for comfortable Internet downloading. Such access is only possible after supplementary processing of the above AVI files. Without losing too much quality, we downgraded the original TSCC-AVI files to a 100 kbps stream using the RealVideo codec (www.realnetworks.com). The frame frequency was reduced to 5 fps, and the sharpness of the converted images was enhanced. The final reduced result was a so-called SMIL file associated with the tutorial stored in another file (i.e., a RealVideo file, with extension *.rm) and the table of contents of the current tutorial (i.e., a RealText file, with extension *.rt). These three files can be placed on an Internet server to be visualized by users in streaming mode without downloading. The user needs, in this case, a constant 100 kbps bandwidth and can follow the tutorial only while connected to the Internet. Because of this constraint, we also preferred to allow the user to download a zip file containing the three elements, and run the tutorial even when his/her computer is not connected to the Internet.

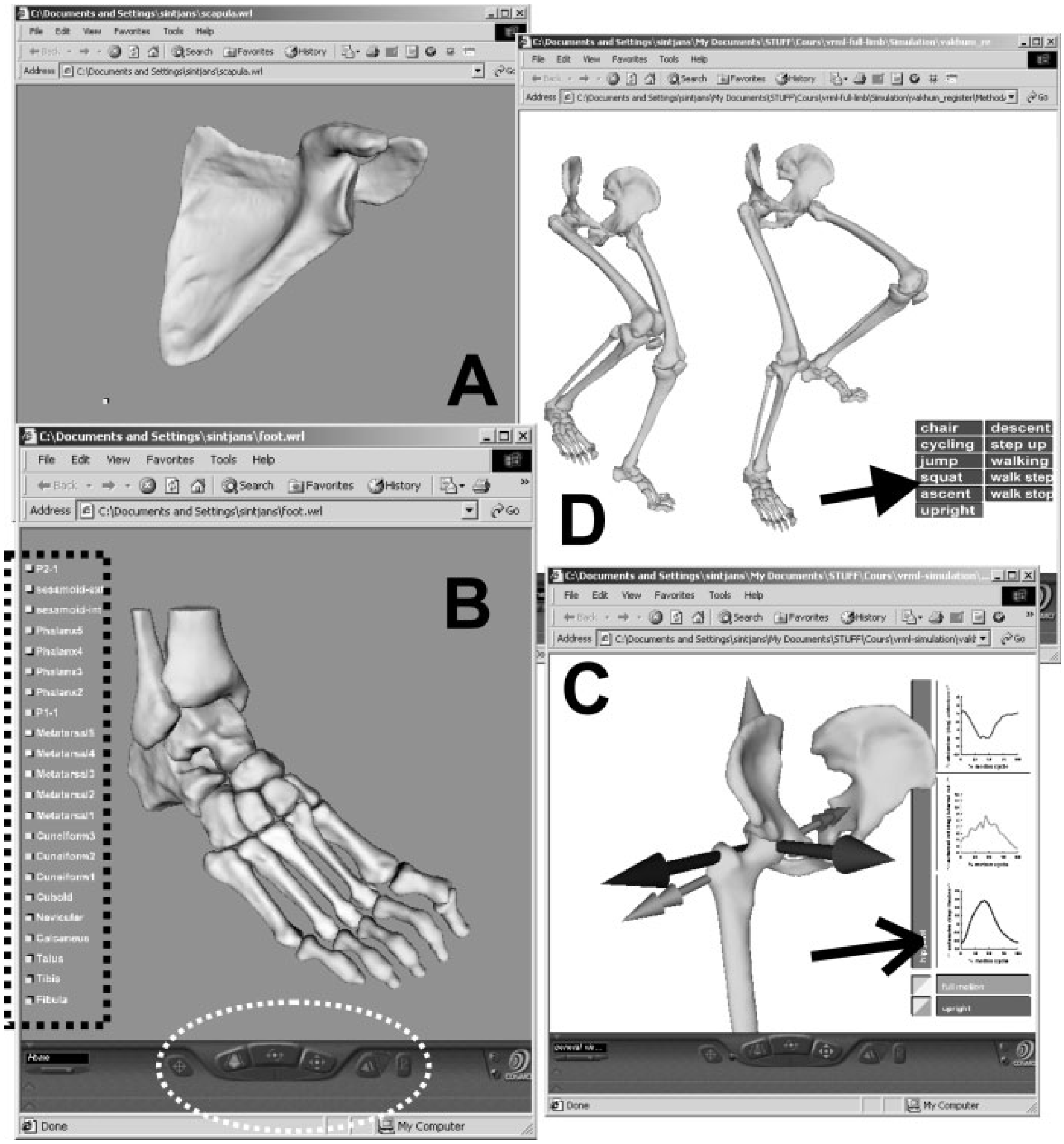

Figure 2. Three-dimensional (3D) interactive environment (laboratory). Examples of 3D anatomical models integrated into an interactive computer graphics environment. **A:** Left scapula. **B:** Right foot. **C:** Hip joint kinematics. **D:** Lower limbs kinematics during cycling. The navigation interface (dotted ellipse) allows standard spatial transformations of the 3D models available in the scene: rotation, translation, and scaling. With this interface, users can observe the anatomical structures from any point of view. When several bones are displayed simultaneously (B) a list of structure names (dotted box) is also given. Clicking on a particular anatomical structure 3D model or name label discards this structure from the scene; a further click returns it once more to the scene. This feature is convenient when studying a particular structure together with its relationships with adjacent bones. The 3D interface about joint kinematics (C) includes extra buttons (open arrow) to start real-time joint simulation. A few graphs show the motion curves defined according to conventional anatomical axes (Van Sint Jan et al., 2003). These are used for the understanding of normal joint motions. Simulation about limb motion (D) offers the choice of visualizing the behavior of several joints during specific tasks (cycling, walking, chair sitting, etc.). Task simulation is used for the understanding of normal limb motions during everyday life. Clicking on a particular task button (arrow) starts the simulation. Interfaces similar to those illustrated can be found at http://homepages.ulb.ac.be/~anatemb/mlm.htm.

3D Interactive Environment: Laboratory, Pragmatic Knowledge

As stated previously, it is generally acknowledged that conceptual knowledge must be reinforced with pragmatic experience. For that reason, the theoretical content of the above multimedia lectures can be actively explored thanks to fully interactive 3D laboratories running on standard home computers (Figure 2). Such an environment allows observation of the anatomical structures from any point of view, according to the student's own needs and understanding. Furthermore, the interface can include buttons that initiates real-time joint motion simulation obtained from the experimentally generated data. In our applications, all computer graphics applications were stored in VRML (Virtual Reality

Markup Language) format. The advantage of this format is its portability and the availability of free-of-charge viewers (see www.web3d.org/vrml/browpi.htm). The user interface also allows the following advantages: it is easy to use for individuals (e.g., medical students) with limited computer graphics knowledge, it runs on low-end and inexpensive platforms without requiring any particular graphics accelerator hardware, and the navigation interface does not require a multimedia developer, because it is a standard option in most viewers.

Figure 3. Osteology lecture at the Faculty of Medicine, National University of Rwanda (Butare, Rwanda). After a theoretical lecture based on classic computer presentations (using Power Point presentations), the lecturer demonstrates the current topic content (e.g., about the wrist, as illustrated here) by displaying accurate three-dimensional anatomical models, and emulates student participation by asking questions. The same models are also made available to students in the local computer classroom

MLM CONTENT AND NETWORK ACCESS

At present, complete MLMs, including both multimedia lectures and 3D interface, are available only for the lower limb. The other body parts (spine, upper limb, head) are available only through uncommented 3D laboratories. Completion of the MLM database is in progress.

Figure 1 shows the multimedia component of the MLM regarding knee joint kinematics (available as a demonstrator from the ULB Web site, http://homepages.ulb.ac.be/~anatemb/mlm.htm). Note that this particular MLM requires knowledge about osteology of the femoral bone, patella, and tibial bone, and arthrology of the knee joint as a prerequisite (all MLMs necessary to obtain that particular pre-knowledge are available from the same Web site).

MLMs should be used as follows. All MLMs about bone osteology related to the knee joint should be used first. Students are advised to use both MLM components for full assimilation. Of course, a student is free to skip one or both components if he/she feels comfortable with the MLM content, and wishes to move forward. The next logical step after the study of isolated bones is the description of their relationships with adjacent bones—joints.

Descriptions of joint morphology and joint kinematics are available from separate MLMs. So far, the MLMs that we have developed do not contain pathological information, although it is usually explained in the classroom. The next step in our MLM development is to integrate clinical simulation related to joint disorder (e.g., rupture of the cruciate ligaments). The main problem for such development is the unavailability of validated numerical data concerning that topic that are suitable for simulation.

MLMs are available to students on a restricted-access ULB Web site called the Virtual University. This is a service organized by the local Technological Center for Teaching (Centre des Technologies pour l'Enseignement, www.ulb.ac.be/ulb/cte/) to allow the entire ULB academic staff to distribute pedagogical information to their students: e.g., images, Power Point presentations, questionnaires, or in our case, MLMs. Access is simple, but restricted by password control based on the ULB student ID. The site consists of lists of Internet links to the available materials. Although Internet access to the Virtual University is promoted, CD-ROMs are also used when no other distribution alternative exists, for example for students without network access or narrow network bandwidth. MLM distribution in Rwanda mainly occurs through the local NUR intranet, and students are consulting the available classes using local multimedia facilities (Figure 3). To our knowledge, no students in Rwanda are downloading MLMs from their home computer.

DISCUSSION

Economic and Social Aspects

The protocol described here to produce MLMs is relatively inexpensive from a technical point-of-view. Indeed, once the developer has 3D models available, several inexpensive software applications exist to relate oral explanations provided by a teacher to the 3D animations. The protocol should also be useful for departments or faculties wishing to develop customized tutorials that answer their local needs, without depending of external sources. For example, the Osteology MLMs we developed cover most of the material taught in the classroom at ULB. In principle, if students are using the MLMs, they do not need to purchase supplementary sources of illustrations.

The protocol is also interesting for developing countries, where the economic environment is not favorable for the purchase of expensive systems. We have previously mentioned that students in such countries greatly rely on non–peer-reviewed Internet sources, which can give them a biased message. Because some developing countries are investing in modern educational systems, multimedia support is becoming increasingly appropriate to answer their needs.

When a student borrows a book from the library, it remains unavailable to fellow students for the duration of the loan. In contrast, a computer room allows several students to access the same information simultaneously. Digital support also allows numerous copies of the same pedagogical tool at no extra cost except, of course, if it is of a commercial nature and subject to licensing.

MLM Content

A small part of the course material is omitted from the MLMs on purpose so that students still attend both traditional lectures and laboratories rather than using only MLMs. We strongly believe that only proper classrooms can stimulate students' curiosity and discussion both between students and with their academic staff. From our experience, we do not believe that reducing a lecture to a multimedia presentation with no real interaction between students and the academic staff is the most effective instructional method.

The volume of preclinical anatomical knowledge that students must assimilate is considerable and requires proper guidelines and explanations from well-trained academic staff. Of course, other educational strategies may be required at different locations. For example, problem-based learning tutorials used to train medical students pursuing clinical rotations (Jacobs et al., 2003; Caudell et al., 2003) are highly interactive. Anatomical preknowledge required by such systems are taught to students in lower grades so the training systems can concentrate on the practical aspects of clinical problems without the constraints of a sizeable theoretical content.

MLM Interface and Distribution

Logically, students should first view the theoretical 3D narrated navigation modules. A menu allows access to a particular topic without the requirement of listening to the first part of the lecture. Once the student feels comfortable, the virtual 3D environment is used for practical rehearsal. The user interface available in the VRML browser permits students to navigate almost freely within the data set. Students can choose the point-of-view that is the most suitable to study the current anatomical structure. Zooming is also available to gain a closer view of a particular anatomical feature.

The motion simulation triggers realistic simulations without requiring any technical knowledge about computer graphics techniques or programming. Because instruction is not provided within the interface, students are required to be more independent and to retrieve the information taught within the theoretical multimedia presentation. This independence increases the students' active participation. Both MLM components can be opened simultaneously on the user's screen: students can listen to the theoretical lecture running in one screen window, then pause it to concentrate on the related 3D laboratory opened in another window.

The protocol described here to produce MLMs is relatively inexpensive from a technical point-of-view.

Of course, one could argue that it would be better to integrate all MLM components into one software interface. Such integration could be provided by hiring specialized software developers, but this would be in contradiction of the first goal of this study, which was to propose an independent and economical MLM development. Indeed, most departments of Anatomy do not have the resources to start full software development—they just need inexpensive development of MLMs to illustrate their classes. This particular economic constraint was previously mentioned by Lozanoff et al. (2003).

No major computer memory problem has been reported so far when using MLMs. They can be visualized on most personal computers without any special rendering hardware. The total storage size of the distributed 3D models included in the MLM laboratory was purposely kept at approximately 4 MB, which is acceptable for most modern PCs and Internet access.

The creators of the 3D bone models tried to find a suitable balance between realistic surface resolution and data storage, with the result that the 3D model of an individual bone will have a higher surface resolution than the model of the same bone when included in a rendered scene with several other bones. For example, the scapula model illustrated in Figure 2A has a high resolution, which allows the smallest surface features to be demonstrated for an osteology module. Bone models used within complex 3D scenes (Figure 2C and 2D) have lower resolution, because several bone models must be included within the 4 MB memory limit. Adjacent bones are visualized only during motion simulation, where surface resolution is less important, so this reduction in resolution does not present any major problems. Examples are available for downloading from homepages.ulb.ac.be/~anatemb/mlm.htm.

The size of the MLM theoretical lectures (typically between 1 MB and 11 MB) remains a problem for narrow-bandwidth Internet access, although this is not a major issue for students located in Belgium. Indeed, most domestic Internet connections in Belgium have a guaranteed download speed of between 750 kbps and 4 Mbps, depending upon the providers (note that the 750 kbps lower limit will be raised to 3 Mbps in the first quarter of the year 2003). Bandwidth in Rwanda is 1,300 kbps and should allow relatively comfortable downloading. Unfortunately, the slow network backbone between Africa and both USA and Europe is still a limiting factor for voluminous data transfer. Internet penetration (0.034%) is also low in Rwanda (Uneca, 2002) compared to other part of the world (for example, USA = 58.5%). This is probably the reason why no local NUR students seem to download MLMs from home.

Pedagogical Validation Plan

Assimilation of the lecture content should be increased compared to sit-

TABLE 1. Planned MLM validation

	Theory	Laboratory	External input
Group 1	Professor Oral In classroom Duration: 2h Tools: *Power-Point presentations* *Active drawings* Little staff-student interaction	Teaching assistant Oral In classroom Duration: 2h Tools: *Proper manipulation (dry bones, dissection)* *Active drawings* Staff-student interaction	None
Group 2	MLM lecture Oral At home Duration: unlimited No staff-student interaction	MLM laboratory No oral explanations At home Duration: unlimited No staff-student interaction	None
Group 3	= Theory Group 2	None	Textbooks
Group 4	None	= Laboratory Group 2	Textbooks

MLM validation will include two parts. The first part will compare two different educational pathways. A classical educational pathway (Group 1) will rely on a theoretical class given by a senior professor and a real practical laboratory. The second pathway (Group 2) will only use MLMs as described in this paper. The second part of the validation will attempt to determine the information retained by students for each MLM component: Group 3 and Group 4 will only receive the MLM theoretical component and MLM laboratory respectively. Results of Group 3 and Group 4 will be compared with Group 2. This should allow us to determine if both MLM components are complementary.

uations where students have no opportunity to interact with the content (Benbunan-Fich, 2002). The first tests of the system by medical students were positive. At NUR, where few opportunities for proper laboratories are available, students especially appreciate the proposed system and they are regularly using it to study human osteology and arthrology. The 3D computer graphics environment seems particularly helpful for their understanding of the spatial relationships between the structures taught during theoretical lectures.

Although extensive validation of the system has not yet been performed, it must be emphasized that academic results related to osteology obtained by both NUR students (using the system frequently) and ULB students (using the system less frequently because of the availability of real extensive laboratories) are similar. Proper validation of the system's effectiveness is in progress (EDUCA module within the MULTIMOD project, www.tecno.ior.it/multimod/).

Several students groups (Table 1) will be evaluated after taking an anatomical module about a particular topic, e.g., the knee joint. The selection of the students for each group will be randomized.

The first group (group 1) will access the relevant knowledge according to the conventional pathway followed at ULB. They will first receive theoretical descriptions and oral explanations from a senior staff member using well-illustrated and custom-made Power Point presentations in a classroom. During such lectures, frequent use of on-the-fly drawings is included. Only limited interaction between the lecturer and the students is possible because of the large number of students (e.g., typically more than 250 and 150 students in first and second grades, respectively). Students will then attend a laboratory where they can manipulate the anatomical structures. Laboratories are under the supervision of several staff members (both senior and junior) who are also available to clarify all students' questions, including those related to theoretical lectures.

Group 2 will use only an MLM similar to those illustrated in this study. Standard questionnaires given to students from both groups 1 and 2 will assess both conceptual and pragmatic knowledge of the students to determine the strengths and weaknesses of the educational pathway followed by each group.

Supplementary groups will be created to compare the multimedia and 3D interactive components of the proposed MLM. Groups 3 and 4 will receive only the multimedia lecture and 3D environment, respectively. Both groups will be allowed to use external sources of information, such as textbooks, as they deem necessary. Questionnaires about MLM usability will also be distributed to assess the expectations of the users, i.e., the students, and allow us to perform improvements if necessary. Whether the proposed system is, or is not, a real alternative to more traditional educational pathways will be known only once the above validation is performed.

It must be emphasized that it is unlikely that MLMs will fully replace traditional educational tools (Lozanoff et al., 2003) even if they appear to be superior. The main reason would be the lack of communication between the academic staff and the students if MLMs were used exclusively. This could be solved by on-line distance learning (Jacobs et al., 2003), but then hardware costs would dramatically increase, contradicting the aim of economy. Currently, the MLMs produced are used locally as a supplementary source of illustration for students alongside traditional classrooms and textbooks. However, they could probably be used alone if the lack of interaction between the pedagogical staff and the students is not considered as a problem. Furthermore, the MLM development presented also seems a useful alternative for locations where the organization of proper lectures and laboratories remains a problem.

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