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Training Skills with Virtual Environments

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This work focuses on the concept of skills training by means of additional information being modeled within the virtual environment (VE), its control, and its interfaces. The work particularly focuses on how actuated external devices can cooperate in the control of voluntary movements to refine the quality of motor control and hence improve learning of specific abilities. The control of haptic, visual, and vibrotactile feedback in the training environment will be analyzed, and a given set of algorithms for capturing the motion, modeling the reference gestures, and rendering training feedback will be reviewed and discussed. Hence, this work introduces the information needed to model and train the motor and cognitive skills of users. A general architecture to set up a training environment that could learn from examples of experts will be presented, and it will be completed by the presentation of the "digital trainer" that uses such knowledge to drive the training feedback. Different methodologies for information representation and stimuli generation will be presented, and specific applications to haptics, audio, vision, and vibrotactile feedback will be considered. Methods for training sensorimotor coordination and procedural skills, with an analysis of the short-term memory effects, will be discussed on a specific set of test scenarios.

COMPUTERIZED TRAINING ENVIRONMENTS

The use of computers as a mean for learning began in the mid 1960s. At that time, the term *computer assisted instruction* (CAI) was coined (Carbonnell 1970) to identify programs performing tutoring based on a "question-and-answer" approach.

Computers offer a combination of low cost, programming flexibility, repeatability, accuracy in tracing user action, and precision in response that makes them the ideal instruments to create training programs. The technique of using computers for training is usually referred as *computer based training* (CBT).

The use of CBT (Lee and Owens 2004) was pioneered in late 1960s once the film-based techniques demonstrated their limitation in adapting the training material to the quality and the rhythm of students. Several factors limited the advent of CBT techniques as a broad standard adopted in education:

- In early stages of its development, the infrastructural cost, in terms of computing hardware and software development, made this resource limited to a few studies in those universities and research centers that had already gathered the hardware for different purposes.
- The weakness of standards and multimedia performance up until the 1990s, made these resources very limited, and the editing process was mostly text based. Audio and video streaming was not feasible, and only a few added interactions, mostly text-based questions/answer quizzes, were conceived.
- At that time, the digital era had not yet begun. Databases were not available, or they were not interconnected by networks, and all the information had to be brought to the program by manual inputs or scans from editors.

The use of CBT, even supported by the invention of CD-ROMs, failed to become an acceptable alternative to books and other printed material. It was only in the mid 1990s, as a side effect of the Internet boom, that people referred more and more to computers in order to find information that is not equivalently widespread and/or updated using conventional training channels.

According to Gagné (1972), the instructional areas opened by this type of technology and that are available in scientific literature can be organized into five major groups:

- Motor skills in performing physical tasks;
- Cognitive relational abilities;
- Symbolic and declarative knowledge;
- Attitudinal skills, and
- Intellectual and/or procedural skills.

In this scenario, the Internet boom gave new life to CBT, represented by two different types of realization:

- eLearning (i.e., computer- and Internet-based learning) was deeply investigated and promoted by international research plans.

eLearning faced the problem of managing distant simultaneous learning through remote student–teacher interaction, and it created a novel and completely computer-based training methodology, in which the computer replaced the teacher in guiding students to learn.

- The combination of digital libraries, advanced multimedia, and applet technologies users have begun managing learning on digital lessons deployed and personalized by computers. Webinars are now the most widespread source for this type of training.

SHORT HISTORY OF VE-BASED TRAINING

The quality, completeness, and immediacy of interaction is at the basis of VE learning capabilities. As highlighted by Barraclough and Guymer (1998), the original philosophy that motivated the investigation of VE-based training was that the more senses are stimulated, the richer is the information given to the learner and the better are the possibilities for learning. In computer-based simulation, such an approach also served to reduce the gap among the training environment and the real operational environment where the learned information should be employed.

Two elements have greatly contributed to the breakthroughs of VE in training applications: computer graphics progress in generating real-time, three-dimensional, highly immersive and interactive scenarios; and the research on and introduction into the VEs of interactive robots. Such robots, which lately have been called "force displays" (Minsky et al. 1990) or "haptic interfaces" (Klatzky 1989; Brooks 1990), enabled us to enrich those environment with fully sensory feedback, with force and tactile rendering complementing the existing audio and visual channels.

Clark and Horch (1986) already argued the possibilities offered by these kinds of devices and argued that, "Humans have remarkable ability to remember position of their limbs quite accurately and for long periods." This ability to remember motor patterns can be at the basis of motion training with haptic interfaces.

It became rapidly clear that the concept of virtual reality (VR)-based training was not limited, as it was for eLearning and CBT techniques, to mimicking the functionality of traditional training in an immersive and more expensive environment. The true application of motor training concept opened the door to a new class of interaction devices, in which users and machines share a kind of implicit knowledge (Reber 1996) of the task.

Haptic guidance was one of the first training stimuli used in combination with haptic interfaces. Training hand motion by means of haptic interfaces was investigated by several authors. In Figure 14.1, a force-feedback system to guide the hand during writing motion strokes is shown (Avizzano 2005). In these systems, haptic interfaces have a vector-based representation of all

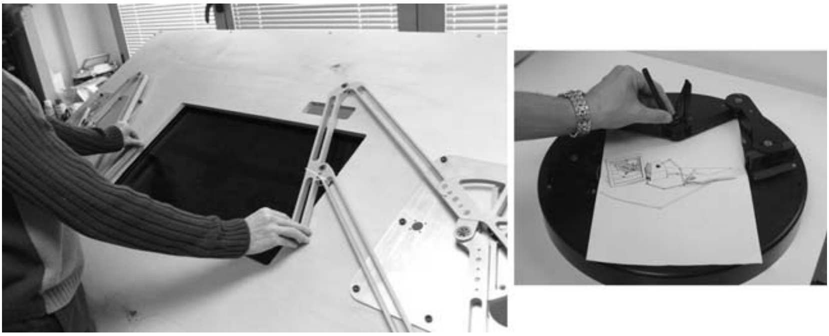

Figure 14.1 Haptic guidance by means of haptic interfaces during writing and drawing.

possible paths of motion and infer the guidance feedback using the distance to the closest path.

Haptic guidance imagines that the robot guides the user to perform motions in space, obtaining correct gestures depending on the training task. Such guidance is achieved by means of cooperation between the user and the robot. Two main types of guidance strategies were proposed and tested. In the *passive guidance approach*, the user grasps a device, which shows the user the proper trajectories and velocities to be followed. In the *active approach*, the robots only act as a "virtual" constraint that aligns the user's motion along the proper trajectory, while the user is left free to decide the velocities and energies to put in the motion.

When comparing the learning effects, both strategies have positive and negative issues that suggest, as we will show, an intermediate adaptive strategy in which the support of the computer is modulated according to the response of the learning subject.

In Figure 14.2, the intermediate strategy represents the potential offered by the combination of three-dimensional graphics with haptic interfaces (Yokokohji 1996). Yokokohji explored this paradigm by replicating an immersive ball–racket interaction in a simulated tennis exercise. He introduced the concept of the "what you see is what you feel" (WYSIWYF) interface, a system capable of generating coherent and co-located visual and haptic information that could be employed to act on virtual objects exactly as if they were real, but with added value in the fact that the physical response was completely computer controlled and therefore open to any alterations that the designer would like to introduce. The potential of this system in training applications was already addressed implicitly by Yokokohji (1996), who stated that if the "system does not provide the proper visual/haptic relationship, the training effort might not accurately reflect the real situation (no skill transfer), or even worse, the training might be counter to the real situation (negative skill transfer)."

Figure 14.2 "What You See Is What You Feel" system, on the left, with a detail of the interactive virtual environment, on the right. Courtesy of the author.

In the subsequent decade, a plethora of VE-enhanced training systems were proposed. In some cases, these systems truly offered some new paradigms of training. In others, they did not provide any real benefits to what could be achieved with traditional training methodologies. At the time, it was natural that the necessity of highly costly instrumentation for VR provided a substantial benefit with respect to direct and indirect costs of training on the job. In defense of the use of haptic interfaces during training, Feygin (2002) argued that the use of this form of training was beneficial, since training occurred in body-centered (or motor) coordinates as opposed to the visuospatial coordinates that can be employed in training by shown examples (video, trainer's examples, or book). According to Feygin, this form of training "removes the need for complex sensorimotor transformation and applies to "three-or-more-dimensional motor skills that are difficult to explain and describe verbally or even visually."

Rosenberg (1993) proposed another way of formulating sensorimotor training in a VE: the concept of *virtual fixtures* (VF). Virtual fixtures were richer than the WYSIWYF concept in the sense that they also addressed the issue of what to feel when interacting with objects. This metaphor helps to identify and translate into physical structures a wide set of effects, including guiding motions, barriers, and mass properties among others. In Figure 14.3, two examples of virtual fixtures, taken from virtual assembly platforms, are shown. On the left, the internal components of a car can be mounted and assembled while the system provides force feedback related to interference and other contact properties to the user. On the right, a similar concept is extended to the maintenance and cabling of an airplane motor. Virtual fixtures in these two examples simulate interference effects during plug-and-play operation in order to verify the design optimality of maintenance operation and to train employees to proper procedural sequences.

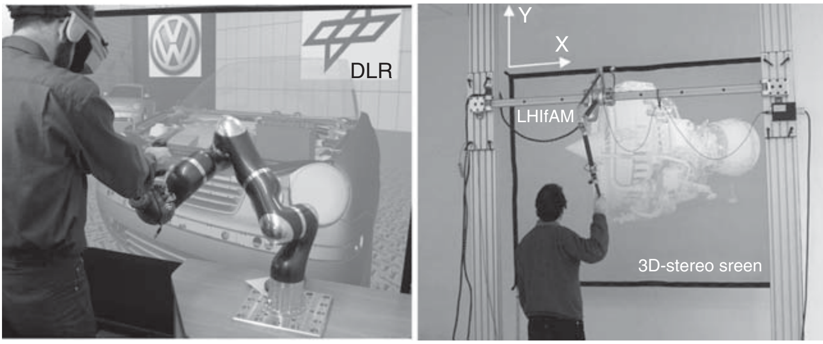

Figure 14.3 Virtual Fixtures, at Institut für Robotik und Mechatronik (*left*) and Centro de Estudios e Investigaciones Técnicas de Gipuzkoa. With permission of the authors.

The concept of VF introduced a philosophy of feedback generation that is still under investigation, both for application and behavioral training in uncommon or unfriendly environments (space or underwater operation, mission critical environments, etc.), as well as to investigate dynamic fixtures whose behavior is more complexly bound to the state of the scenario. For instance, Abbot and Okamura (2007) introduced a derivation of VF when applied strictly to robot-assisted manipulation (guided virtual fixtures, sensory substitution, cooperation and forbid region). To date, a wide amount of effects are available within this class of feedbacks. In Figure 14.4, a partial grid of the fixture set employed in our laboratory is summarized.

Virtual fixtures found their limitation in their physical bound. Fixtures were expressed as a set of object properties, which reflected the amount of knowledge that was required to properly handle a VE object using motion and guidance information. Simultaneously, Gillespie et al. (1998) and Henmi and Yoshikawa (1998) independently introduced the idea that the knowledge stored in a VE could go beyond the properties of the objects therein represented. Gillespie et al. (1998) expressly introduced the concept of the *virtual teacher*, an additional VE component represented by customized feedback and present only during specific training periods and absent during alternate performance sessions. Henmi, implemented this concept into a virtual calligraphy system (whose concept is represented in Figure 14.5) that replicated the correct drawing path showed to the system by an experienced user (the real teacher). In such a way, training systems became multistate devices, and their knowledge was not inserted a priori by experienced programmers. Such systems had at least two configurations: the learning mode (in which an instructor put his experience into the system) and a teaching mode (that transfers the previously stored experience to new users).

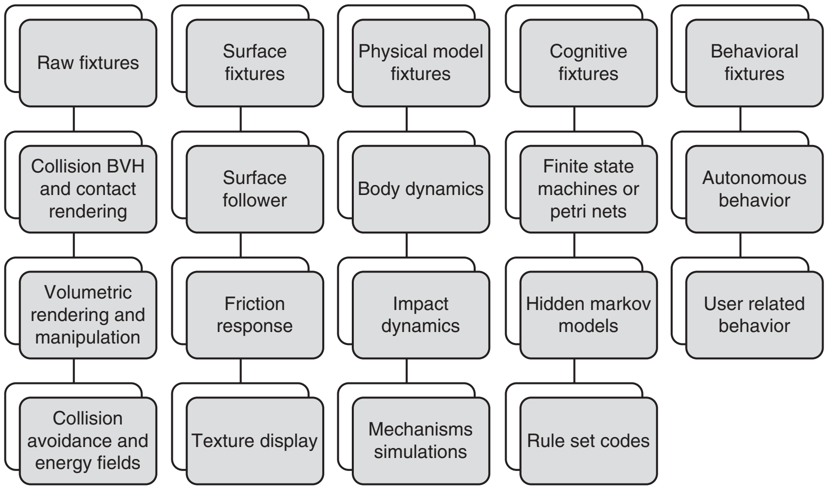

Figure 14.4 Some Virtual Fixtures represented by technological dependence.

At that time, the control issues of Henmi's proposal simply addressed a record-and-playback procedure, without taking into account the complexity factors introduced by the action repeatability. As a matter of fact, the process of handwriting only addressed proprioceptive issues of the perception action loop, with a limited impact on the process dynamics on the environment. With respect to other skills, such as tennis playing for instance, this type of ability only requires the user to control motions with respect to a given and fixed trajectory.

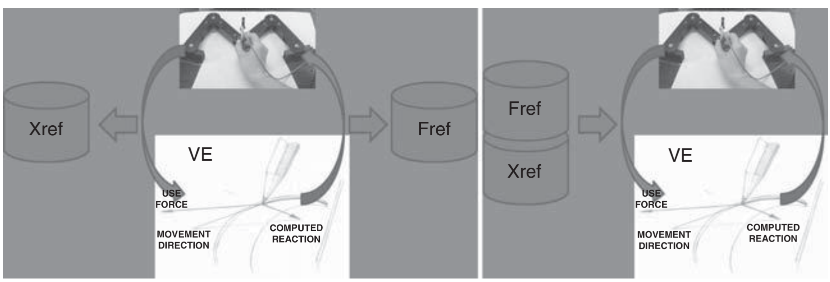

Figure 14.5 The concept of Henmi Virtual Teacher. A record (*left*) and playback (*right*) control procedure. Adapted from Henmi, K., and T. Yoshikawa T. 1998. Virtual lesson and its application to virtual calligraphy system. *Robotics and Automation Proceedings*, with permission of the publisher.

This issue was later reconsidered by several researchers who tried to employ other experts in the loop (Esen 2008) in order to improve teaching behavior or by using artificial intelligence (Sano 1999) to copy and model human control strategies.

An "extreme" application of the virtual teacher concept was achieved when cognitive training was addressed. Here, the elements suggesting to the user the proper steps to perform varied largely from blinking light elements (which represented the proper sequence) to complete agents (instructor avatars), which embedded the knowledge and describe the action to do in a simulated copy of a real plant.

Johnson et al. (2000) proposed a similar environment in which an autonomous teacher interacts with a user-controlled character and at level of speeches and environment control (see Figure 14.6).

In such an environment, it is very easy to imagine and realize systems whose utility greatly overcome their cost. The idea of using digital metrics and scoring procedures to assess the level of efficiency of such environments has been brought to light during the last few years. Ruddle and Lessels (2006) proposed a three-layer metrics to score the utility of a VR training environment. This review work was developed by taking into account learning effects of several studies all focused on a similar topic: *way finding in three-dimensional VEs*. Lessels and Ruddle concluded that at least three different levels of metrics should be taken into account:

- *Task performance during and after learning*. Task performance can be expressed with several benchmarks in the raw data and effectively represents the efficiency of the user in performing the activities in the given virtual environment.
- *Physical behavior*. Starting from the consideration that not all VEs are equivalent, it is necessary to discriminate how the design of the

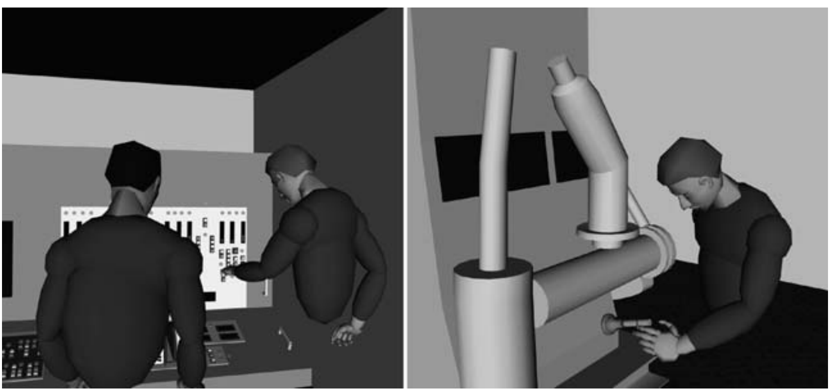

Figure 14.6 Rickel and Johnson (2000) vocational training environment.

VE affects the performance. This indirect benchmark is aimed at identifying and correlating the action performed by the user with those that he will perform in a real environment or in another VE. The physical behavior that describes how the user uses the training system is an indirect metric for at least two factors: the ergonomic aspects of the VE training system and the learning heuristics that the user develops in combination with the VT.

- *Cognitive metrics*. This metric measures the ability of the user to make use of previous knowledge and memories to optimize further action during the learning session with the VE. At least three different kinds of metrics elements could be taken into account: the memory of action patterns, the memory of required behavior, and the ability to abstract and generalize information from content.

In terms of explicit effects derived by robotic guidance, there are at least two major achievements addressed by research: the correspondence between experience and absolute, relatively simple, markers that can be identified in data recording (Moothy et al. 2003); and the ability to design and develop systems that reduce or eliminate the effect of dependence from the feedback (Li et al. 2009).

The research has so far demonstrated that even if certain type of skills can be extremely complex, their complexity can be decomposed into simpler directions, along which elementary metrics can be designed and implemented. Such metrics, once matched in training, realistically contribute to identifying if a similar level of expertise has been achieved or not. In addition, further statistical analysis has demonstrated that the modulation of the VFs during training session ("progressive shared control") helps to achieve a condition in which the same level of expertise is reached without the classical side effect of feedback dependence.

One possible conclusion of almost 20 years of research on VEs for training was presented by Sutherland (2006) in his systematic review of surgical simulators. Sutherland considered a wide database of studies (about 30) documented in the Medline and Embase databases up to April 2005, and selected only those which explicitly randomized control trials as a proof of the efficiency of the simulator. The surprising (at the time) conclusion of Sutherland was that, in contradiction to the common understanding that VE-based training was of benefit for training itself, the training results were not convincingly superior to those of standard training.

This kind of result is becoming more and more common in the scientific literature. However, such results should not compromise our judgment on the quality and usefulness of VE-based training, because additional motivations actually justify both research and use of these systems:

- In terms of applications, one cannot avoid taking the social and economic cost benefits into account. VE-based training allows learners to avoid the use of real subjects and objects, which have a high probability of being harmed by students who have not yet reached an adequate level of expertise. In addition, these tests overcome other material constraints, such as space, time, and external conditions (like weather), and they score the quality of expertise across a uniform and standardized methodology. In terms of medical and aeronautical training, the concept of transfer effectiveness ratio (TER) was introduced (Aggarwal et al. 2007) in order to quantify the effective benefits of simulators employed on operative personnel. In particular, this factor, which accounts for the time spent on the simulator in comparison to the time required to achieve the same level of practice on a real system, has high factors both when addressing airlines pilots (a TER of 0.5, which implies that each hour on the simulator reduces of 30 minutes the flight-training time required on a real airplane) and surgeons (typical TER of 2.38).

- In terms of research, the major limitations addressed by the systematic reviews seems to be solvable in a short amount of time. Most of the users employed for training so far directly coded and copied human knowledge into the training protocols, without automating the process of optimizing and refining the quality of user motion. Kimura et al. (1999) argued that the "autonomous robots must recognize human motions in real time and interact with them." In mathematical modeling, this was addressed by Rosen et al. (2001) by means of skills signatures: a specific record and modeling of human skills that will enable the machine to understand and cope with different styles.

It is therefore likely that soon a novel generation of VE-based training system will tackle the complexity of human skills and offer, if not a better quantitative feedback, at least training signals that are more contextualized and selective.

MOTION CONTROL ALGORITHMS AND PARADIGMS

At the basis of multisensory training setups, an adequate set of strategies to control user movements in coordination to what is perceived from the VE must be set. This type of control is based on three classic approaches, which have been developed during the last decade of control in haptic research. The forms in which these controls are designed strongly depend on the kind of interaction between the subject and the device. In particular, they are distinguished by:

- *Instrument replicators*. These are usually the most task-effective devices in the sense that they get the user into a training scenario that is as close as possible to the real environment. Some of the controls in such a scenario have been redesigned in order to comply and serve digital controlled loops that embed the stimuli required to train.

- *Encountered-type haptics*. This type of haptic interface can be considered a self-standing robotic system, as can all contact external devices. However, in this case, the robotic system's end-effector is not in contact with the user's hand but is tracking it at a certain distance and moves toward the contact target area only when required by the application. This type of haptic interface shows an intrinsically higher complexity, especially in control terms, with respect to external devices always in contact with the user. In the case of encountered-type systems, two additional essential characteristics should be taken into account: the tracking of the human limb's area where the contact force must be generated, and performance, in terms of the compensation of end-effector dynamics required by encountered-type haptic interfaces.
- *Contact haptic interfaces and exoskeletons*. In these system, the user grasps or is attached to the device, typically at a finite number of points, by which the force and position information necessary for training flows. These systems benefit from the fact that their control strategies can be easily taken from basic robot control, where the user is modeled as an external disturbance. Classic methods of impedance (Zilles and Salisbury 1995), admittance (Adams and Hannaford 1999), or compute torque control (Salisbury et al, 2004) can then be applied.

Most training approaches rely on the ability of the device to replicate any given (synthesis) force at the level of the user's body. The modeling of such devices is commonly addressed using the Lagrange formulation:

$$M(q)q + C(q \cdot q)q + D(q)q + G(q) = \tau_{mot} + J^T(q)F_{human} \qquad \text{(Eq. 1)}$$

Where *M* is the inertia matrix of the manipulator, *C* is the vector of Coriolis and centrifugal terms, *D* is the viscous friction vector, *J* is the Jacobian of the haptic interface, *G* represents gravity effect, *F* is the wrench applied by the operator's hand, and τ is the vector of the joint components applied by motor control. Figure 14.7 shows how these guidance motion schemas can be achieved by block constructions in control schemes. Each term of the equation can be compensated by a feedback control. This results in a map of the desired human force on motor components. In Figure 14.8, the Δ term summarizes the contribution of both viscous friction and Coriolis and centripetal terms.

In quasi-static conditions and when friction and gravity can be neglected, the mapping between the applied force/torque (wrench) and the above equation reduces to a simplified one (Marcheschi 2005), $\tau_{mot} + J^T(q)F_{human} = 0$. In this case, joint components can be derived from the principle of virtual

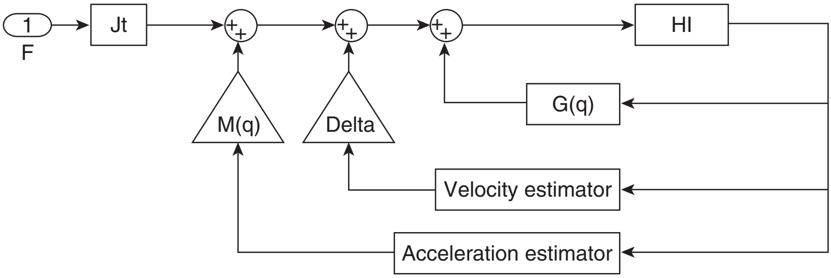

Figure 14.7 Scheme of the closed loop control procedure.

works, provided in particular by the transposition of the manipulator Jacobian: $\tau_{mot} = J^T(q)F_{des}$, where the last term represents the forces the trainer wishes to display to the user.

In more complex dynamic situations, the joint components are required to compensate for the centrifugal, inertial, viscous, and Coriolis effects that affect manipulator dynamics. If we have a good enough model of the haptic device, this compensation could be provided by cancellation. The following is the resulting torque:

$$\tau_{mot} = M^*(q)\overline{q} + C^*(q,\dot{q})\dot{q} + D^*(q)\dot{q} + G^*(q) + J^{*T}(q)F_{des} \qquad \text{(Eq. 2)}$$

where the asterisk refers to model approximations of the mechanical terms. A low-level joint torque control loop is then used. Joint torque sensing allows the user to overcome the problems related to model accuracy, other friction components, and approximations in the kinematic model, and rough or no modeling at all of the device dynamics.

To identify the desired force, a contact model is usually designed. The contact model can both reproduce contact information as well as embed motion constraints and/or guidance effects. In the simplest case—contact information—the contact object is given a limited virtual stiffness that defines the apparent rigidity of the touched object.

The implementation of the virtual stiffness requires the computation of the surface normal (n) at the contact point and of the penetration vector (x, y, z) and the consequent penetration distance d:

$$d = (x\ y\ z)_{hi}\begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix}, \quad f_{des} = \begin{cases} -\vec{n}dK_{stiff} & d > 0 \\ 0 & d \le 0 \end{cases} \qquad \text{(Eq. 3)}$$

The use of an additional digital viscosity can in some cases be added to improve stability issues when low frequency, high stiffness, and closed loops are addressed (Bergamasco 1995).

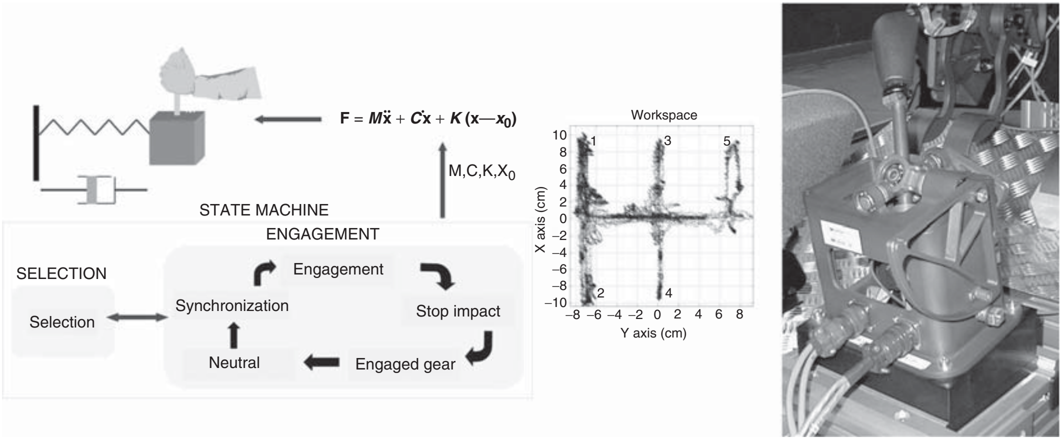

Figure 14.8 The embedded dynamics control model applied to the Gearshift interface. The figure shows the overall control scheme (*left*), simulation data (*center*, *x-y position*), and the employed device (*right*). From Frisoli, A., C.A. Avizzano, and M. Bergamasco. 2001. Simulation of a manual gearshift with a 2 DOF force-feedback joystick. *International Conference of Robotics & Automation*, with permission of the publisher.

When the haptic device assumes the same shape as the instrument that needs to be replicated, the control of the device can be organized as a simulation of the original instrument. If required, additional force components are added to recreate fixture and tutoring stimuli. This is generally done with a parametric closed loop that partially compensates for the interface dynamics in order to approximate the device that needs to be simulated.

Usually, in these devices, most of the mechanics are similar to those of the original device replicated, while the unseen part is different and replaced with motors. The control of these devices may be addressed in a similar way:

$$\tau_{mot} = (M^* - M_r)(q)\overline{q} + C^*(q, \dot{q})\dot{q} + (D^* - D_r)(q)\,\dot{q} + K(q - q_r) + G^*(q) \quad \text{(Eq. 4)}$$

Here, the introduction of the control law enables the user to perceive the interaction with a virtual object whose properties can be modulated by software. Once introduced in the Lagrange model and properly cancelled, the "approximated" terms of this equation lead to:

$$J^T(q)F_{human} = M_r(q)\overline{q} + D_r\,\dot{q} + K(q - q_r) \quad \text{(Eq. 5)}$$

or, in equivalent Cartesian coordinate systems:

$$F_{human} = \tilde{M}_r^*(x)\overline{x} + D_r^*\dot{x} + \tilde{K}_r^*(x - x_r) \quad \text{(Eq. 6)}$$

In other words, this control strategy simulates the feeling of contact between the user´s hand and a rigid object, whose properties (mass $\tilde{M}_r^\bullet(x)$, viscosity $\tilde{D}_r^\bullet$, rigidity and offset forces) are not only an element of the control strategies, but are also dynamically changeable according to the physics of the object being simulated and/or to the training strategies that need to be included in the force feedback. Different interaction behaviors can be represented through this type of control laws. This feature is achieved by programming the control feedback to compensate for component dynamics and make the mechanical response resembling that of the desired model.

The adoption of this control strategy, which only partially cancels the mass and viscous properties of the haptic interface, allows a better exploitation of the device's natural dynamics and higher thresholds in terms of effective force and dynamic ranges. An application of this control strategy was applied by Frisoli et al. (2001) in the control of a gearshift-like haptic device to be employed in a car simulator.

Figure 14.8 highlights the model of nonlinear dynamics that was implemented to simulate the effects of interacting with a real multistate object. It integrated an embedded dynamics impedance-controller with a finite state machine that changes the parameters of the model in real-time according to the state of the gear (selection, engaged, synchronizing).

Only recently have the evolution of application programming interfaces (APIs) for the simulation (PhysX 2008) and improvements in computer performance allowed the VE to simulate the entire physics of the environment to a sufficient level of detail and time granularity to allow a complete and smooth interaction using haptic devices. The combined control of what is simulated in the VE (without the notion of interactive force feedback) and of the mechanical device response is achieved by a common procedure called *virtual coupling*.

In virtual coupling, one or more parts of the user's body are in contact with an equal number of attachments to the haptic device. Those contact attachments are reflected by an equivalent set of "virtual contacts" between the manipulated objects and the interface proxies.

The virtual coupling concept is shown in Figure 14.9. The user is grasping a handle, which is virtually bound to the digital object through an elastic and damping joint that provides the feedback forces simulated in the VE to the user's hand and vice versa. Each coupling is generated on the fly, whenever the user enters into contact with a virtual object. This paradigm is particularly useful when the training VE is to teach the user the proper sensorimotor properties of an object in the environment.

Particular care should be taken with coupling properties, since poles are added for each contact and, if damping is not properly managed, an unstable condition may result. As for all digitized control systems, the use of virtual coupling adds instability to the system when the overall simulated stiffness is too high in comparison to the simulation frequency. This is true both for single contact point properties, as well as when multiple couplings interact with the same object. In such a case, the overall stiffness is the weighted series of single coupling stiffness.

LOOPS FOR TRAINING ENVIRONMENTS

To date, there have been several environments dedicated to training using VEs. Such systems can be classified into two basic categories: training environments supported by VEs, and VEs for training. Most of the systems

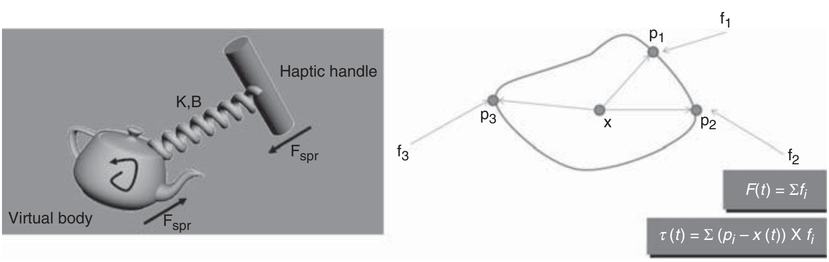

Figure 14.9 Virtual Coupling rendering approach. On the left is depicted the schema of Virtual Coupling with the Handle and the Virtual Object for the interaction. On the right is presented the schema of multiple contact points affecting a single object.

developed so far only fall into the first category since they simply use the VE as a support tool to recreate realistic conditions in which to practice skills. For the second category, we consider the presence of three basic issues that need to be addressed and implemented as an integral part of the training program:

- Bilateral interactions between the user, the real, and the digital environment, which includes a training structure to model user progress.
- A knowledge database of expert behaviors, their styles of motion, their cognitive background, and quality metrics for evaluating the achieved results.
- A training set of feedback stimuli, strictly related to user behaviors and dedicated to deliver the most effective imprint to the trainee (transfer and persistence of learning).

The proper combination of these three elements allows the design of specific training environments that may circumvent the three stages of learning as defined by Fitts and Posner (1967): cognition learning, integration learning, and automation learning.

There are several methodologies by which to approach the definition and modeling of skills. Warren (2006) inspected common approaches and identified two dominant main categories. First, the model (state space–based) approach relates to the execution of some skills primarily as a complete dynamic system, where physical bodies and muscles interact based on motor patterns commanded by the brain. Second, the embodiment and behavioral approaches decompose interactions along natural behaviors that can be shown by the actors in the environment, such as reaching, grasping, standing, etc. According to Warren (2006), both categories present positive and negative features when considering the need to explain specific elements of the interaction, such as the perception–action relationships, the emergent behaviors, optimization procedures, and the automatic learning of inverse task dynamics. Warren (2006) also highlighted the way in which different authors have explained interaction elements by referring to the properties of one or the other theoretical approach. Finally, Warren (2006) proposed a hybrid model in which both approaches were reflected.

Warren (2006) allowed three separate dynamical descriptions to identify the environment and the user's response. In addition, relationships of perception and action are modeled separately.

In Warren's approach, described in Figure 14.10, the behavior of an agent is modeled in terms of exchanges of information between the agent itself and the environment, each described as a dynamical system. The dynamics of perception and action (PA), according to Warren, can be decomposed into two basic differential equations (the ψ sensorimotor function and the χ cognitive dynamics), one environment dynamics (ϕ), and two nonlinear selection filters that map the different dynamical spaces.

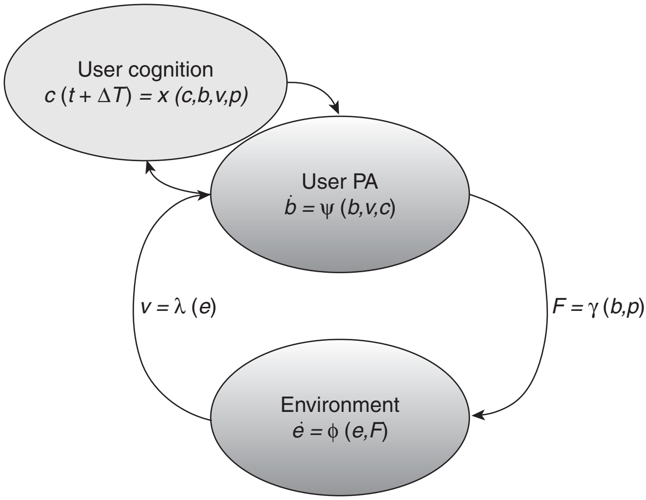

Figure 14.10 An approach to represent Perception and Action loop. Adapted Warren, W. 2006. The dynamics of perception and action. *Psychological Review* 113: 358–389, with permission of the publisher.

The environment has an internal state "e" and a descriptive function ϕ that are mapped onto the agent through an observation function λ. Similarly, the internal state of the user 'b' evolves with the ψ function and is mapped in the environment with a set of forces via the γ function. Here, two vectors of parameters guide the cognitive response (c) in performing the skill and constrain the physical limitation (p) in terms of fitness and physical abilities.

Although Warren did not describe how to introduce elements related to training, he decomposed interaction along basic, independent, and clearly defined components. We chose such a model, since it allows us to make a coherent identification of all those components required to enable digital guided training and support multiuser interaction as well.

Even if Warren did not provide any insight for modeling the internal functions: ψ, λ, χ, γ, we will show that the basic structure of his model offers the opportunity to enhance the interaction model toward a digitally mediated interaction, which handles separately the elements of style and training as discussed earlier.

The methodology described here proposes extensions to Warren's model, which applies the use of the enactive knowledge as described by Gibson (1969). This training method addresses a training process in which information connects the skill-related data to sensorimotor perception by means of immersive VEs, to allow access and acquisition of this knowledge.

Before illustrating the concept, it is useful to recall the experience of applying machine learning algorithms to robot control, as demonstrated by other research groups. Capture of style is more than capture of expert data. The preliminary experiments on point lights by Johansson (1973) more than 30 years ago demonstrated that information on gestures and walking can be encoded in a reduced set of variables. In the past decade, substantial efforts have been put into classifying and identifying human motion from observation. Troje (2008) and Gritai et al. (2004) focused on styles of walking and reduced representation for the human poses and motion. One common approach to model and classify styles is to associate them according to so-called *motion signatures* (Vasilescu 2002). Signatures identify invariant properties of the motion which can be extracted from the acquired signals through different types of data processing. Pattern simplification techniques (Davis and Gao 2003), such as principal component analysis (PCA), combined with pattern recognition, are commonly employed to determine the action style. Calinon (2006) proposed an integrated architecture that helped a robot to behave in a human-like manner in training by demonstration. The proposed system extracts relevant motion features from the observation of humans by using a probabilistic description encoded in a proper support space (determined with PCA). This behavior is created from a mixture of density function (Gaussian and Bernoulli), which defines spatiotemporal correlations across different modalities, and cognitive relationships in the observed action.

Similar concepts can be applied to robot- and VE-based training, once a proper digital model of the human skills is defined. Such a model has been designed by keeping the following factors into account:

- *The underlying components of the user–environment interaction*: For example, the amount of information to model a proper skill interaction, both in terms of observable items and controllable actions. These components are supposed to be a reduced information set of those measurable in the environment.
- *The behavioral elements that identify and classify styles*: For example, definition of the invariant and the variable elements in the constraints describing a successfully learned skill.

It is particularly relevant here that, in an approach using multimodal interfaces, we can completely or partially replace the real environment with a VE whose behavior and dynamics are defined by code and completely known to the designer. This is an essential step to digitally access measurements that are not easily caught in real environments.

The originality of our approach (Avizzano 2009) lies in the fact that the recognition is not completely performed by automated tools. Instead, it relies on a content decomposition, which has been designed in agreement with motion scientists and human factor designers (Bardy 2008). This approach has been structured by introducing the concept of subskills.

Subskills can be defined as cognitive or sensorimotor components of a task that possess specific features and metrics to be investigated with analytical tools, verified with mathematical algorithms, and stimulated with proper feedback. The subskill approach is the opposite of VFs and/or virtual teachers in the sense that it does not focus specifically on a single operation taken outside the overall task interaction. In our approach, summarized in Figure 14.11, 14 different categories of subskills have been introduced in order to measure different properties in the motor (eight categories) and cognitive (six categories) spaces. Sampling of the above-mentioned relevant points is gathered indirectly by means of *performance indicators*.

Subskills are mapped to control and training loops using a hierarchical decomposition that allows the higher semantic levels to be coordinated with the lower data content. In particular, in addition to the selected raw data and the machine learning tools described previously, the following relevant levels of information have been introduced:

Features

Features are compound logical and quantitative information that maps basic components of the motion to more relevant dimensions that characterize the style. The introduction of features in the computing process allows us to have a better targeted process, making clearer distinction between style components and focusing better on styles that are considered of primary importance by trainers. Contrary to what it seems, these

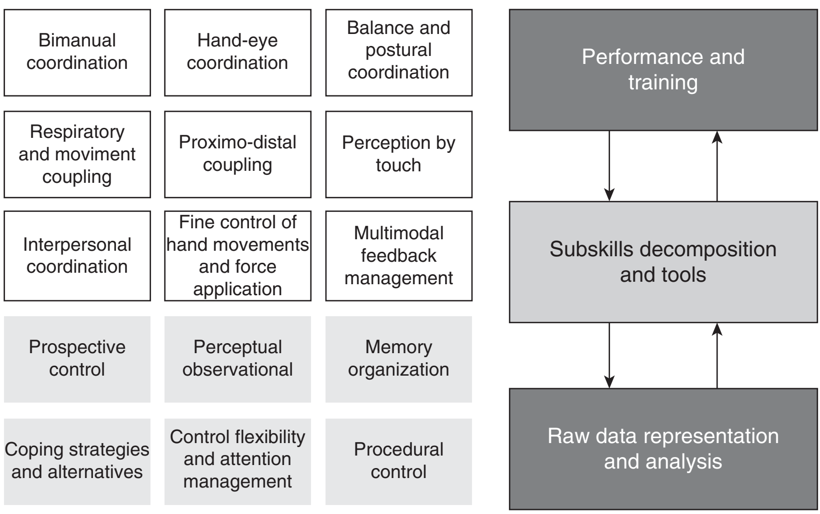

Figure 14.11 Subskill classifications (*left*) and their role in the training/learning VE (*right*).

features do not simplify the representation of the task. In fact, they increase the dimension of the representation vector and introduce more elements to be analyzed. On the other hand, features greatly simplify and improve the analysis of the performance. Each feature is designed to have a particular relationship with the performance indicators that highlight the quality of the execution of a particular phase of the skill.

Digital Subskills

Features are expected to catch a list of relevant points that could be observed in user physical and cognitive spaces (b,c) and in their characteristic evolutionary functions (ψ, χ). Hence, using features, we expect to have a methodology to qualitatively sample the hidden dynamics in those points, which the trainers consider to be of high relevance for the performing of action. The introduction of digital subskills allows immediate correlation of trainers and motion science indicators with the analytical model employed for the representation. This is performed by decomposing the user skills into the relevant subskills that are required for the specific task, then defining performance tools that measure the distance among performers. This approach allows us to redefine the digital signature of an expert style as the set of performance indicators that an expert produces when repeating a task with a given style.

Digital Training

Warren's approach has been extended to support a new model that allows training embedded in the interaction: the *digital trainer* (Fig. 14.12). The most relevant properties of the digital trainer is that it allows the user to "learn by doing," by gathering relevant task information from the direct interaction with the environment.

In the digital trainer model, the training logic and the subject interaction play a symmetric role in the hybrid virtual–real environment, within which both of them interact. The digital trainer aids the user with a set of style encodings that have been acquired from experts. With respect to traditional training, digital training can benefit from the additional power the trainer has in controlling the virtual animation of the environment.

The digital trainer has additional capabilities with respect to those at the disposal of a real trainer acting in the same situation. In particular, the observation of the subject is not limited to the external observation of actions but is enhanced with real-time biometric measurements (electroencephalograph [EEG], electromyelograph [EMG], electrocardiograph [ECG], oxygen consumption, eye tracking, etc.). These measures provide a more accurate discrimination of conditions that determine a user's responses and actions. In addition, the feedback from the trainer to the environment can bypass the need for physical interaction and directly affect the behavior

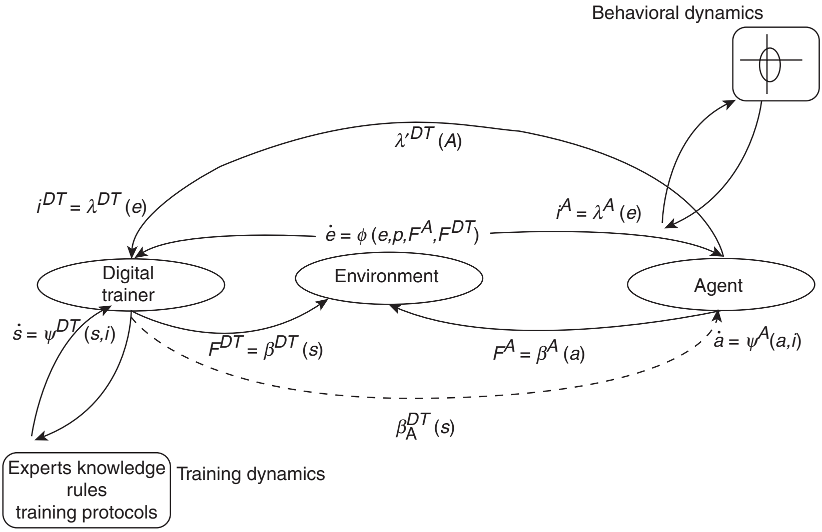

Figure 14.12 The Digital Trainer model. The Digital Trainer model extends Warren's approach (*right side*) to include the dynamics of the interactive VE and the train controller (*left side*). From Avizzano et al. 2009.

of the environment. Finally, the digital trainer feedback can completely bypass the environment and communicate directly to the user by means of real-time rendering for the purpose of driving actions or correcting errors (e.g., by means of vibrotactile stimuli, haptics, or sound).

IMPLEMENTATION

The implementation of a control framework to support digital training requires a complex integration between the architecture of the VE and the architecture of the learning control. The initial step is to model and maintain user- and expert-related knowledge with a stable source of information. In our work, this has been achieved by interconnecting the information related to user skills into a portable database. Such a repository system is based on SQlite (Owens 2006). The choice of SQlite as a reference database was explicitly done in order to embed the data capture and to maintain the data collection in a unique structure. SQlite has some unique features in terms of performance, portability, supported languages, and manipulation tools that currently make it the most suitable platform.

Additionally, in order to maintain a clear organization of the information archived into the database, a systematic tool to describe, organize, store, and recall the information has been developed. The information stored at this level exactly mirrors the hierarchy of information described earlier, which spans raw data up to digital subskills. Raw variables are the starting point of the services offered by the database. They store the data gathered from the experimental sessions, but do not highlight the semantic knowledge that is encoded in them.

An overall structure of the repository system architecture is represented in Figure 14.13. The VE has been decomposed into its different functions (i.e., interconnection, capturing, and rendering of information). In such a way, it is possible for the digital trainer to connect to and interact with real-time control processes of the environment's interaction with knowledge stored into databases.

Therefore, the repository systems also offer an additional level of information storage in order to embed a more complex organization of information in the data values and their semantic content. This is achieved by tools that process data inside of the repository and create higher levels of abstraction, which can be employed by the digital trainer in further training. Three kinds of operation are possible: outer processing, inner processing, and fruition. In *outer processing mode*, an external program will provide handles to the data in order to create higher levels of representation. *Inner processing mode* is similar but exploits functions encoded into the database to execute mathematical algorithms stored inside embedded python code. Finally, *fruition* operations retrieve information for analyzing and comparing the progress of training with respect to the signatures left by experts during their sessions.

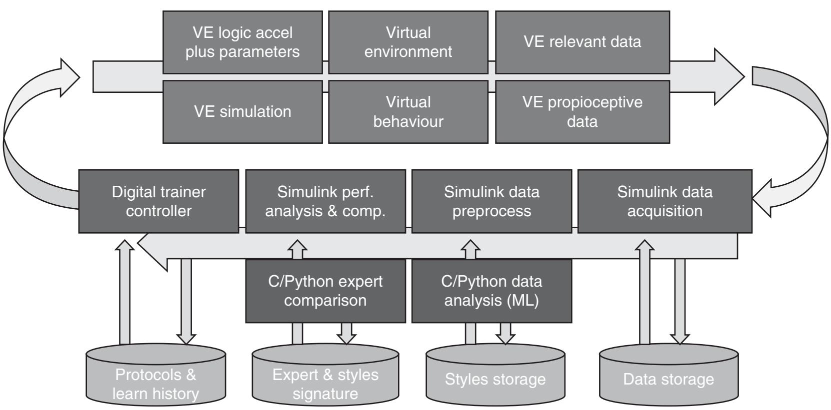

Figure 14.13 Integrated structures adopted for the digital trainer implementation. From Avizzano, C.A., E. Ruffaldi E., and V. Lippi. 2009. *Skills Digital Representation and Storage*, SKILLS09 International Conference on Multimodal Interfaces for Skills Transfer, Bilbao, Spain, with permission.

The data processing of information makes use of several types of algorithms. Principal component analysis, dynamic time warping (DTW), K-means, and other similar techniques are used to filter and classify expert motions, while trained hidden Markov models (HMM), probabilistic neural networks, and similar tools are employed to deliver computational results in real time. The information related to training and to expert references is derived by preprocessing the samples from experts into a properly encoded form for interactive use.

The bridge among the processing frameworks, the VE, and the expert knowledge is provided using a commercial tool for control simulation and hardware in the loop control, Matlab/Simulink®. Such a tool implements most of the basic building blocks to perform continuous signal handling, basic neural networks, and the like, while more complex computation can easily be introduced into the environment by means of C-based S-functions plugged into the system.

This has been achieved by developing a full set of Simulink toolboxes that handle the archiving and retrieval functions by using Simulink components, which can manipulate data in real time and embed the results in interactive VE trainers. Specific scripting modules and online filters allow the user to implement any sort of training data, performance indicators, and expert models.

The Matlab/Simulink environment also provides a bridge toward information stored in the database. Such a choice brings the following benefits: First, it completely decouples information processing from the interaction data managed within the VE algorithms, and second, it allows processing information in a unique, coherent, and graphical approach that can be clearly understood and reusable by exploiting the graphical expression of the Simulink schematics.

In addition, the bridge between Simulink and the database organization allows decoupling of the continuous time control, which can be handled in Simulink alone, from discrete event systems, which requires the management of information in the database. Specific blocks provided in the library precisely control when to trigger computing and storing action in the database, while interacting in real time with the control facilities. In such a way, it is possible to simultaneously retrieve behavioral data information from the database content, and to store periodic, semantic, or qualitative information related to the data processing, such as styles and high-order abstraction.

Connections to the VE have been created for several frameworks:

> XVR (Ruffaldi 2006), OpenSG, and VRML with Avalon Instant Reality (Behr and Froehlich 1998). In all such cases, however, VE integration requires that the VE exports the basic interaction elements described in Figure 14.13, in order for the digital trainer to control the learning approach. Using such a framework, it is thus possible to implement performance indicators, style identifiers, training protocols, and

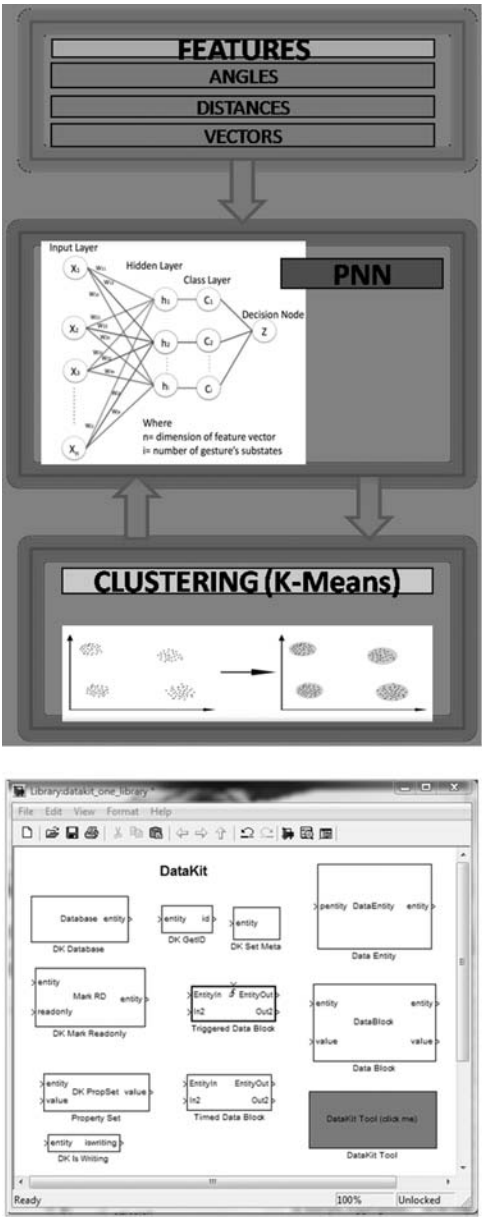

Figure 14.14 Example of data processing (*left*; from Portillo-Rodriguez et al. [2008]) and graphical user interface in Simulink (*right*; from Avizzano [2009]). From Portillo-Rodriguez, O., C. Sandoval-Gonzalez; A. Avizzano, E. Ruffaldi, D. Vercelli, and M. Bergamasco. 2008. *Development of a 3D real time gesture recognition methodology for virtual environment control*. In the 17th IEEE International Symposium on Robot and Human Interactive Communication RO-MAN, 279–84; and Avizzano, C.A., E. Ruffaldi, and V. Lippi. 2009. *Skills Digital Representation and Storage*, SKILLS09 International Conference on Multimodal Interfaces for Skills Transfer, Bilbao, Spain, with permission of the publishers.

learning accelerators according to the theories of sensorimotor learning by Schoner and Kelso (1988).

EXPERIMENTAL CASE STUDIES

Several types of demonstrators that exploit such a paradigm have been developed recently. In particular, this methodology has presently been applied to two specific domains: rowing and juggling. The *SPRINT rowing system* (Ruffaldi et al. 2009) is a platform for indoor rowing training that is aimed at improving the specific subskills of rowing. The system has as its basis a simulation component that recreates the motion of the user and provides a haptic feedback mirroring interaction with the water (see Fig. 14.15). Over the simulation basis, a set of exercises based on multimodal feedback for training specific subskills is built: technique procedure, energy management, and coordination. Relevant expert data has been collected by tracking the angles of the oars, the trolley position, the exerted forces, and the head position. Data segmentation and clustering made it possible to identify the path that is most efficient for both boat motion and user physiology. The path has been segmented by taking the major elements of a rowing stroke into account (see Fig. 14.16 for an example), and successively modeling these in a pseudo-parametric form, in order to adapt to the different sizes of the users.

Figure 14.15 Photography of the rowing training system SPRINT.

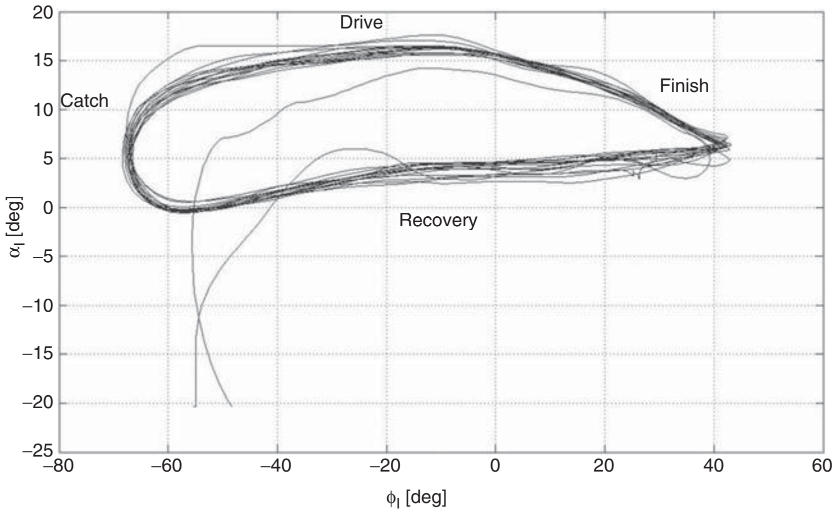

Figure 14.16 Sample trajectory of a rowing cycle shown in the space of the fundamental oars angles (tilt vs. swing).

This model is then used for training purposes. Two types of feedback, one based on the visual presentation of the trajectory (both in real-time and after the task) and the other in the form of vibrotactile feedback, show the user his or her motion errors.

In the *juggling trainer*, a VE has been designed to improve the technique of the juggler in performing specific tricks. The training elements considered as relevant for training were spatial coordination properties, as well as timing synchronization. The trainer provides two types of platform: a purely visual guidance that uses Polhemus sensors and VR-based animation to represent hands, balls, motion, and training stimuli, and a haptic training platform based on encountered-type haptic interfaces (Tripicchio et al. 2009; shown in Fig. 14.17. Here, a couple of symmetric haptic devices serve to present the relevant stimuli to left and right hands as they catch balls. The training system simulates ball trajectories and coordinates the robotic devices to improve the control of sensorimotor coordination.

CONCLUSION

Novel multimodal interactive systems enable researchers to develop integrated systems that handle sophisticated interaction protocols within the interaction loops. In the case of training systems, this is achieved by integrating the existing knowledge on required motions and experts' samples

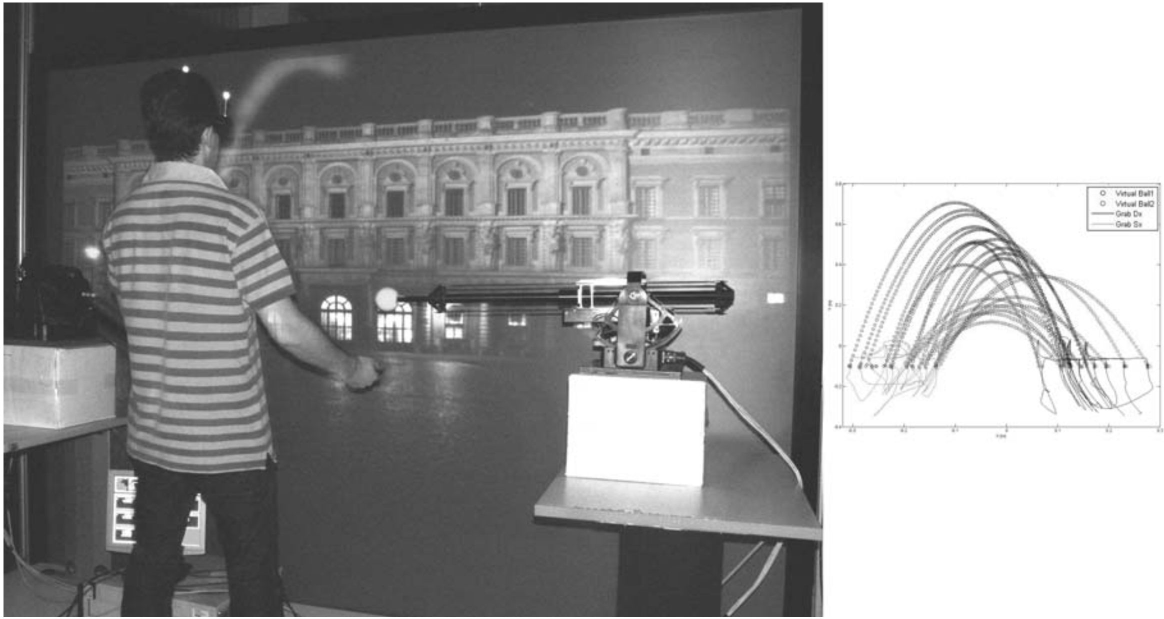

Figure 14.17 Juggling virtual trainer. An integrated visuo-haptic platform, on the left, interacts to show the user correct motion sequences. Raw data plot of hands and balls tracking are reported on the right. From Bardy, B.G., C.A. Avizzano C.A., et al. 2008. Introduction to the Skills project and its theoretical framework. *IDMME-Virtual Concept*, Berlin: Springer-Verlag.

with a proper feedback that stimulates user perception without disturbing the main components of the perception action loop. Here, we presented an integrated architecture to merge present VE systems with known learning and interaction models. In particular, the proposed architecture highlights the presence and the core role of a digital trainer, a software tutor that senses user actions and controls the configuration parameters of a VE to facilitate and accelerate learning.

The methodology to design the digital trainer has been discussed by correlating the technical constraints to the human factors considered relevant. The resulting process has shown the necessity of introducing a new concept into the control design: the digital skill, a mathematical entity that links the data required for the technical implementation and the information handled by trainers, experts, and researchers on human factors. The current work has also shown how the information required for the digital skill can be extracted from experts' examples by the adoption of existing machine learning and control tools. The implementation of these concepts on two platforms developed in the context of the EU-SKILLS integrated project have also been shown.

REFERENCES

Abbott, J., and A. Okamura. 2007. Pseudo-admittance bilateral telemanipulation with guidance virtual fixtures. *International Journal of Robotics Research* 26: 865–71.

Adams, R., and B. Hannaford. 1999. Stable haptic interaction with virtual environments. *IEEE Transactions on Robotics and Automation* 15:465–74.

Aggarwal, R., J. Ward, I. Balasundaram, P. Sains, T. Athanasiou, and A. Darzi. 2007. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. *Annals of Surgery* 246:771–76.

Avizzano, C.A., E. Ruffaldi, and V. Lippi. 2009. *Skills Digital Representation and Storage*, In Proceedings of SKILLS09 International Conference on Multimodal Interfaces for Skills Transfer, Bilbao, Spain. ISBN:978-84-613-5456-5.

Avizzano, C.A., M. Raspolli, S. Marcheschi, and M. Bergamasco. 2005. Haptic desktop for office automation and assisted design. In Proceedings of *IEEE International Conference on Robotics and Automation* 4086–91, Barcelona.

Barraclough, A., I. Guymer. Virtual Reality 1998. -A Role In Environmental Engineering Education?. Wien: Water Science & Technology, Vol. 38(11): 303–310.

Bardy, B.G., C.A. Avizzano. et al. 2008. Introduction to the Skills Project and its theoretical framework. *IDMME-Virtual Concept*, Berlin: Springer.

Behr, J., and A. Froehlich. 1998. AVALON, an open VRML VR/AR system for dynamic application. *Computer Graphics Topics* 10:28–30.

Bergamasco, M. 1995. Force replication to the human operator: The development of arm and hand exoskeletons as haptic interfaces. In *Robotics Research,* eds., G. Giralt and H. Hirzinger. Berlin: Springer.

Brooks, F.P., M. Ouh-Young, J.J. Batter, and P.J. Kilpatrick. 1990. Project GROPE - haptic displays for scientific visualization. *Computer Graphics* 24:177–85.

Calinon, S., F. Guenter, and A. Billard. 2006. On learning, representing and generalizing a task in a humanoid robot. *IEEE Transactions on Systems, Man and Cybernetics* 37:286–98.

Carbonell, J. 1970. AI in CAI: An artificial-intelligence approach to computer-assisted instruction. *IEEE Transactions on Man-machine Systems* 11:190–202.

Clark, F.J., K.W. Horch. 1986. Kinesthesia. In *Handbook of human perception and performance*, Vol. I, eds., B.F. Boff, L.L. Kaufman and J.P. Thomas. New York: John Wiley & Sons.

Davis, J., and H. Gao. 2003. Recognizing human action efforts: An adaptive three-mode PCA framework. *Computer Vision Proceedings* 1463–69.

Esen, H., K. Yano, and M. Buss. 2008. Force skill training with hybrid trainer model. In Proceedings of *IEEE International Workshop on Robot and Human Interactive Communication Proceedings* 9–14. ISBN: 978-1-4244-2212-8.

Feygin, D., M. Keehner, and R. Tendick. 2002. Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill. Haptic Interfaces for Virtual Environment and Teleoperator Systems Proceedings 40–47, ISBN: 0-7695-1489-8.

Fitts, P., and M. Posner. 1967. *Human performance.* Brooks/Cole Publishing Co.

Frisoli, A., C.A. Avizzano, E. Ruffaldi, A. Filippeschi, and M. Bergamasco. 2008. Preliminary design of rowing simulator for in-door skill training. In Proceedings of *Ambient Media and Systems.*, ICST Brussels.

Frisoli, A., C.A. Avizzano, and M. Bergamasco. 2001. Simulation of a manual gear-shift with a 2 DOF force-feedback joystick. In Proceedings of *International Conference of Robotics and Automation*. 2:1364–1369. Seoul, Korea.

Gagné, R. 1972. *Interchange, in domains of learning* 87–105. Berlin: Springer.

Gibson, E. 1969. *Principles of perceptual learning and development*. New York: Prentice Hall.

Gillespie, R., S. O'Modhrain, P. Tang, D. Zaretzky, and C. Pham. 1998. The virtual teacher. In Proceedings of *ASME International Mechanical Engineering Conference and Exposition, Dynamic Systems and Control* 171–178.

Gritai, A., Y. Sheikh, and M. Shah. 2004. On the use of anthropometry in the invariant analysis of human actions. *International Conference on Pattern Recognition Proceedings* 2:923–26. ISBN: 0-7695-2128-2.

Henmi, K., and T. Yoshikawa. 1998. Virtual lesson and its application to virtual calligraphy system. In Proceedings of *IEEE International Conference on Robotics and Automation*, Leuven, Belgium. 2:1275–1280

Johansson, G. 1973. -Visual perception of biological motion and a model for its analysis. *Perception & Psycholophysics*, *14*, 201–211. Lawrence Erlbaum

Johnson, W., J. Rickel, and J. Lester. 2000. Animated pedagogical agents: Face-to-face interaction in interactive learning environments. *International Journal of Artificial Intelligence in Education* 11:47–78.

Kimura, H., T. Horiuchi, and K. Ikeuchi. 1999. Task-model based human robot cooperation using vision. In Proceedings of *IEEE International Conference on Intelligent Robots and Systems Proceedings* 2:701–706. ISBN: 0-7803-5184-3

Klatzky, R., S. Lederman, and C. Reed. 1989. Haptic integration of object properties: Texture, hardness, and planar contour. *Journal of Experimental Psychology: Human Perception and Performance* 15:45–57.

Lee, W., and D. Owens. 2004. *Multimedia-based instructional design: Computer-based training, web-based training, distance broadcast training, performance-based solutions.* New York: John Wiley and Sons.

Li, Y., J. Huegel, V. Patoglu, and M. O'Malley. 2009. Progressive shared control for training in virtual environments. *World Haptics Proceedings*, IEEE Computer Society: 332–37, Salt Lake City. ISBN: 978-1-4244-3858-7.

Marcheschi, S., A. Frisoli, C.A. Avizzano, and M. Bergamasco. 2005. A method for modeling and control complex tendon transmissions in haptic interfaces. In Proceedings of *IEEE International Conference on Robotics and Automation Proceedings* 1773–78, Barcelona. ISBN: 0-7803-8914-X.

Minsky, M., M. Ouh-Young, O. Steele, F.P. Brooks, and M. Behensky. 1990. Feeling and seeing: Issues in force display. *Computer Graphics* 24:235–43.

Moorthy, K., Y. Munz, S. Sarker, and A. Darzi. 2003. Objective assessment of technical skills in surgery. *British Medical Journal* 327:1032–37.

Owens, M. 2006. *The definitive guide to SQLite.* Berkeley, CA: Apress. doi: 10.1007/978-1-4302-0172-4.

PhysX. 2008. AGEIA.

Reber, A. 1996. *Implicit learning and tacit knowledge: An essay on the cognitive unconscious.* New York: Oxford University Press.

Rosen, J., B. Hannaford, C. Richards, and M. Sinanan. 2001. Markov modeling of minimally invasive surgery based on tool/tissue interaction and force/torque signatures for evaluating surgical skills. *IEEE transactions on Biomedical Engineering* 48:579–91.

Rosenberg, L.B. 1993. Virtual fixtures: Perceptual tools for telerobotic manipulation. In Proceedings of *Virtual Reality Annual Symposium* 76–82, ISBN: 0-7803-1363-1.

Ruddle, R., and S. Lessels. 2006. Three levels of metric for evaluating wayfinding. *Presence: Teleoperators and Virtual Environments* 15:637–54.

Ruffaldi, E. 2006. Haptic web: Haptic rendering and interaction with XVR. In *Proceedings of XVR Workshop*. Pisa: VRmedia.

Ruffaldi, E., A. Filippeschi, A. Frisoli, O. Sandoval, C.A. Avizzano, and M. Bergamasco. 2009. Vibrotactile perception assessment for a rowing training system. *World Haptics Proceedings,* IEEE Computer Society: 350–355, ISBN: 978-1-4244-3858-7.

Salisbury, K., F. Conti, and F. Barbagli. 2004. Haptic rendering: Introductory concepts. *IEEE Computer Graphics and Applications 24(2):* 24–32.

Sano, A., H. Fujimoto, and K. Matsushita. 1999. Machine mediated training based on coaching. *IEEE System, Man, and Cybernetics Proceedings* 2:1070–75.

Schoner, G., and J. Kelso. 1988. Dynamic pattern generation in behavioral and neural systems. *Science* 239:1513.

Sutherland, L., P. Middleton, A. Anthony, J. Hamdorf, P. Cregan, D. Scott, and G. Maddern. 2006. Surgical simulation: A systematic review. *Annals of Surgery* 243:291–99.

Tripicchio, P., E. Ruffaldi, C.A. Avizzano, and M. Bergamasco. 2008. Virtual laboratory: A virtual distributed platform to share and perform experiments. *Haptic Interfaces for Virtual Environment and Teleoperator Systems* 311–18, ISBN: 978-1-4244-2005-6.

Tripicchio, P., E. Ruffaldi, C.A. Avizzano, and M. Bergamasco. 2009. Control strategies and perception effects in co-located and large workspace dynamical encountered haptics. *World Haptics Proc.* IEEE Computer Society 63–68.

Troje, N. 2008. *Retrieving information from human movement patterns.* New York: Oxford University Press.

Vasilescu, M. 2002. Human motion signatures: Analysis, synthesis, recognition. In Proceedings of *International Conference on Pattern Recognition* 3:456–60, ISBN: 0-7695-1695-X.

Warren, W. 2006. The dynamics of perception and action. *Psychological Review* 113:358–89.

Yokokohji, Y., R. Hollis, T. Kanade, K. Henmi, and T. Yoshikawa. 1996. Toward machine mediated training of motor skills. Skill transfer from human to human via virtual environment. In Proceedings of *IEEE International Workshop on Robot and Human Communication Proceedings* 5:32–37, ISBN: 0-7803-3253-9.

Zilles, C., and J. Salisbury. 1995. A Constraint-based God-object method for haptic display. In Proceedings of *International Conference on Intelligent Robots and Systems Proceedings* 3(3):3146–52, ISBN:0-8186-7108-4.

Pierantozzi, M., M.G. Palmieri, M.G. Marciani, G. Bernardi, P. Giacomini, and P. Stanzione. 2001. Effect of apomorphine on cortical inhibition in Parkinson's disease patients: A transcranial magnetic stimulation study. *Experimental Brain Research* 141: 52–62.

Poewe, W., R. Granata, and F. Geser. 2004. Pharmacologic treatment of Parkinson's disease. In *Movement disorders: Neurologic principles and practice*, vol. 2, eds. R.L. Watts and W.C. Koller, 247–71. New York: McGraw-Hill.

Politis, M., P. Piccini, N. Pavese, S.B. Koh, and D.J. Brooks. 2008. Evidence of dopamine dysfunction in the hypothalamus of patients with Parkinson's disease: An in vivo (11. C-raclopride PET study. *Experimental Neurology*. Epub ahead of print.

Ponsen, M.M., A. Daffertshofer, E. van den Heuvel, E. Wolters, P.J. Beek, and H.W. Berendse. 2006. Bimanual coordination dysfunction in early, untreated Parkinson's disease. *Parkinsonism & Related Disorders* 12: 246–52.

Ponsen, M.M., A. Daffertshofer, E. Wolters, P.J. Beek, and H.W. Berendse. 2008. Impairment of complex upper limb motor function in de novo Parkinson's disease. *Parkinsonism & Related Disorders* 14: 199–204.

Prodoehl, J., D.M. Corcos, and D.E. Vaillancourt. 2009. Basal ganglia mechanisms underlying precision grip force control. *Neuroscience & Biobehavioral Reviews* 33: 900–908.

Rinne, J.O., J.T. Kuikka, K.A. Bergstrom, J. Hiltunen, and H. Kilpelainen. 1997. Striatal Dopamine transporter in Parkinson's disease: A study with a new radioligand, [(123. I]B-CIT-FP. *Parkinsonism & Related Disorders* 3: 77–81.

Rinne, O.J., E. Nurmi, H.M. Ruottinen, J. Bergman, O. Eskola, and O. Solin. 2001. [(18. F]FDOPA and [(18. F]CFT are both sensitive PET markers to detect presynaptic dopaminergic hypofunction in early Parkinson's disease. *Synapse* 40: 193–200.

Robichaud, J.A., K.D. Pfann, S. Leurgans, D.E. Vaillancourt, C.L. Comella, and D.M. Corcos. 2009. Variability of EMG patterns: A potential neurophysiological marker of Parkinson's disease? *Clinical Neurophysiology* 120: 390–97.

Ross, G.W., R.D. Abbott, H. Petrovitch, C.M. Tanner, D.G. Davis, J. Nelson, et al. 2006. Association of olfactory dysfunction with incidental Lewy bodies. *Movement Disorders* 21: 2062–67.

Ross, G.W., H. Petrovitch, R.D. Abbott, C.M. Tanner, J. Popper, K. Masaki, et al. 2008. Association of olfactory dysfunction with risk for future Parkinson's disease. *Annals of Neurology* 63: 167–73.

Sabatini, U., K. Boulanouar, N. Fabre, F. Martin, C. Carel, C. Colonnese, et al. 2000. Cortical motor reorganization in akinetic patients with Parkinson's disease: A functional MRI study. *Brain* 123 (Pt 2): 394–403.

Spraker, M.B., J. Prodoehl, D.M. Corcos, C.L. Comella, and D.E. Vaillancourt. 2010. Basal ganglia hypoactivity during grip force in drug naive Parkinson's disease. *Human Brain Mapping* Epub Ahead of Print.

Spraker, M.B., H. Yu, D.M. Corcos, and D.E. Vaillancourt. 2007. Role of individual basal ganglia nuclei in force amplitude generation. *Journal of Neurophysiology* 98: 821–34.

Tessa, C., M. Giannelli, R. Della Nave, C. Lucetti, C. Berti, A. Ginestroni, et al. 2008. A whole-brain analysis in de novo Parkinson disease. *AJNR American Journal of Neuroradiology* 29: 674–80.

Tissingh, G., H.W. Berendse, P. Bergmans, R. DeWaard, B. Drukarch, J.C. Stoof, and E.C. Wolters. 2001. Loss of olfaction in de novo and treated Parkinson's disease: Possible implications for early diagnosis. *Movement Disorders* 16: 41–46.

Tissingh, G., P. Bergmans, J. Booij, A. Winogrodzka, E.A. van Royen, J.C. Stoof, and E.C. Wolters. 1998a. Drug-naive patients with Parkinson's disease in Hoehn and Yahr stages I and II show a bilateral decrease in striatal dopamine transporters as revealed by [123I]beta-CIT SPECT. *Journal of Neurology* 245: 14–20.

Tissingh, G., J. Booij, P. Bergmans, A. Winogrodzka, A.G. Janssen, E. A. van Royen, J.C. Stoof, and E.C. Wolters. 1998b. Iodine-123-N-omega-fluoropropyl-2beta-carbomethoxy-3beta-(4-iod ophenyl) tropane SPECT in healthy controls and early-stage, drug-naive Parkinson's disease. *Journal of Nuclear Medicine* 39: 1143–48.

Tolosa, E., C. Gaig, J. Santamaria, and Y. Compta. 2009. Diagnosis and the premotor phase of Parkinson disease. *Neurology* 72: S12–20.

Ungerstedt, U. 1968. 6-Hydroxy-dopamine induced degeneration of central monoamine neurons. *European Journal of Pharmacology* 5: 107–10.

Ungerstedt, U., and G.W. Arbuthnott. 1970. Quantitative recording of rotational behavior in rats after 6-hydroxy-dopamine lesions of the nigrostriatal dopamine system. *Brain Research* 24: 485–93.

Vaillancourt, D.E., and K.M. Newell. 2000. The dynamics of resting and postural tremor in Parkinson's disease. *Clinical Neurophysiology* 111: 2046–56.

Vaillancourt, D.E., J. Prodoehl, L. Verhagen Metman, R.A. Bakay, and D.M. Corcos. 2004. Effects of deep brain stimulation and medication on bradykinesia and muscle activation in Parkinson's disease. *Brain* 127: 491–504.

Vaillancourt, D.E., M.B. Spraker, J. Prodoehl, I. Abraham, D.M. Corcos, X.J. Zhou, et al. 2009. High-resolution diffusion tensor imaging in the substantia nigra of de novo Parkinson disease. *Neurology* 72: 1378–84.

Vaillancourt, D.E., H. Yu, M.A. Mayka, and D.M. Corcos. 2007. Role of the basal ganglia and frontal cortex in selecting and producing internally guided force pulses. *Neuroimage* 36: 793–803.

van Eimeren, T., and H.R. Siebner. 2006. An update on functional neuroimaging of parkinsonism and dystonia. *Current Opinions in Neurology* 19: 412–19.

Weintraub, D., C.L. Comella, and S. Horn. 2008. Parkinson's disease—Part 1: Pathophysiology, symptoms, burden, diagnosis, and assessment. *American Journal of Managed Care* 14: S40–48.

Yu, H., D. Sternad, D.M. Corcos, and D.E. Vaillancourt. 2007. Role of hyperactive cerebellum and motor cortex in Parkinson's disease. *Neuroimage* 35: 222–33.