Physical Simulators

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Take-Home Messages

- Box trainers and anatomic bench models by their inherent physical nature offer the great advantage of providing complete sensory feedback (i.e. visual and proprioceptive senses).
- Dexterity tests, box trainers and anatomic bench models are suitable for training arthroscopic skills provided that training tasks are adapted to the capabilities of the chosen simulator.
- Objective performance monitoring based on motion and force metrics is possible when using box trainers or anatomic bench models.

6.1 Definitions

All box trainers and anatomic bench models are physical by nature; that is why we propose to use the term ‘physical simulators’ as opposed to virtual reality simulators. Characterisation of these physical models can be intuitively performed using the level of realism (low fidelity vs. high fidelity) as criterion. The following definitions are made:

Box trainer is a physical training model that does not necessarily resembles a human joint. Thus, box trainers can literally exist of a *box*. For this reason, a box trainer is considered a low-fidelity simulator.

Anatomic bench model is a physical training model that does resemble a human joint. Other words used to describe these types of models are dummy, mannequin or phantom. Such models consist primarily of plastic elements that are shaped according to the anatomy of the intended joint. Although we realise that not all of these models have high resemblance with actual human joints when performing arthroscopy, we classify these models as high fidelity compared to the box trainers.

Additionally, the presence of sensors that register performance can be used as a second criterion to differentiate between types of models. Both box trainers and anatomic bench models can be equipped with sensors as will be illustrated.

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6.2 History of Mechanical Simulators

Primitive forms of physical models were used for medical training for centuries before the introduction of plastic mannequins (Rosen 2008). From that point on, there have been attempts to simulate real-life experiences whenever a task has been considered too dangerous, expensive or distant in time or place to physically experience (Satava 1993). Like many technological advances, simulation has its origins in the military and aviation industries. The principle of providing flight training in a captive aircraft without actually taking off originated early in the twentieth century, with one of the earliest devices being the Sanders Teacher. The 1910 issue of Flight stated:

> the invention of a device which will enable the novice to obtain a clear conception of the workings of an aeroplane and conditions existent in the air without any risk personally or otherwise is to be welcomed (Haward 1910)

Other similar devices were created but were unsuccessful, mainly due to the unreliable and irregular nature of the wind, and so attention turned towards developing synthetic flight training devices.

The most successful flight simulator was the Link Trainer designed by Edwin Link in 1929 as a safe means of teaching new pilots how to fly and to reduce the cost of learning to fly by allowing students to learn some of the core skills on the ground (Engineers AASoM 2000). It was based on the vacuum technology used in automatic musical instruments and was seated on a series of organ bellows that would inflate or deflate to cause the trainer to bank, climb or drive. In this way, it was a mechanical device that translated physical movement of the control devices to pneumatic signals in order to move the trainer as an actual aircraft would.

The trainer was upgraded a few years later following the introduction of instrument flying to allow pilots to practise flying by using the instruments when the exterior conditions rendered it unsafe to rely on outside visual references alone. The US Army first showed interest in the Link Trainer in 1934 after a series of highly publicised air crashes occurring due to the inability of pilots to fly by instruments in poor visibility. The era of simulation-based training on the grounds of safety started to take off and the first Link Trainer for commercial use was bought by American Airlines in 1937.

We performed an inventory of available box trainers and anatomic bench models by searching literature databases (PubMed and Scopus), but also by searching Internet engines (Google and Yahoo) in an effort to be as complete as possible. We searched for the combination arthroscopy with model, trainer, phantom, dummy, mannequin, mock-up, teaching, learning, education, skill, psychomotor, dexterity, handiness and eye-hand coordination. They are presented in the following categories: box trainers, anatomic bench models per joint and models with sensors.

6.3 Box Trainers

6.3.1 Basic Psychomotor Skills

General dexterity testing products can be used by healthcare professionals, physiological researchers and human resource staffing personnel to assess the basic psychomotor skills of residents and surgeons (Kaufman et al. 1987). Several tools have been designed and manufactured that allow training-specific psychomotor skills such as reaction time, triangulation, manual dexterity and eye-hand coordination, which can be purchased at different supplies such as Lafayette Instrument Company (www.lafayetteevaluation.com), North Coast Medical (www.ncmedical.com) and ProHealthcareProducts (www.pro-healthcareproducts.com) (Fig. 6.1). Unalan and coworkers have studied the prognostic nature of such basic dexterity tests for proficiency in arthroscopy and found that there is evidence (Unalan et al. 2010).

6.3.2 Dome Holder for Rotator Cuff and Labrum Repair

For training of specific surgical suture skills, a training environment is developed that consists of a transparent plastic dome (100 mm in diameter) that contains (segmented) discs with different

Fig. 6.1 Examples of instruments for dexterity tests. Starting in the left top corner and turning clockwise: Mirror tracer, purdue pegboard, two arm coordination tests, O'Connor Tweezer test, Minnesota manual dexterity test, Roeder manipulative aptitude test (© Lafayette Instrument Company, 2014. Reprinted with permission from www.lafayetteevaluation.com)

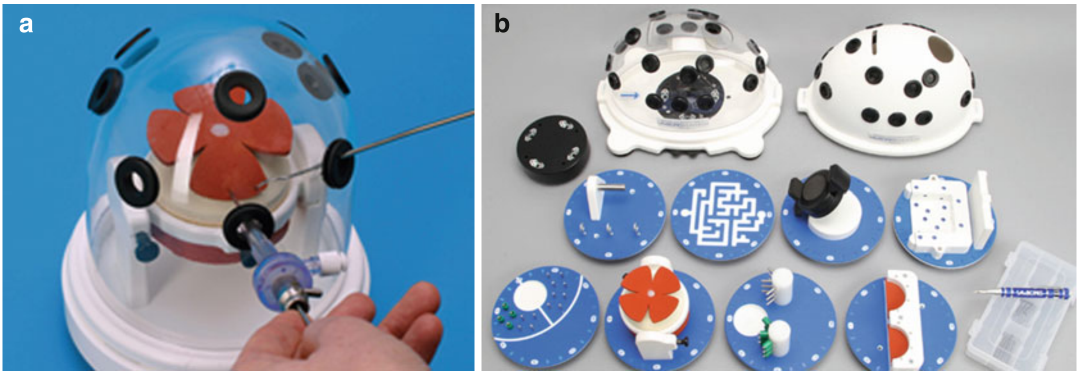

Fig. 6.2 (**a**) Dome holder for rotator cuff and labrum repair. (**b**) FAST Arthroscopy Training Workstation (© Sawbones Europe AB, 2014. Reprinted with permission from www.sawbones.com)

shapes and material densities that can be sutured (Fig. 6.2a) (www.sawbones.com). Multiple entry ports are present all around the dome to reach different locations on the disc. The discs can be locked under multiple angles to train different scenarios. The system can be used for training of standard suturing and anchor placement and be elaborated into the FAST Arthroscopy Training Workstation, involving additional basic training exercises to stimulate the psychomotor skills (Fig. 6.2b).

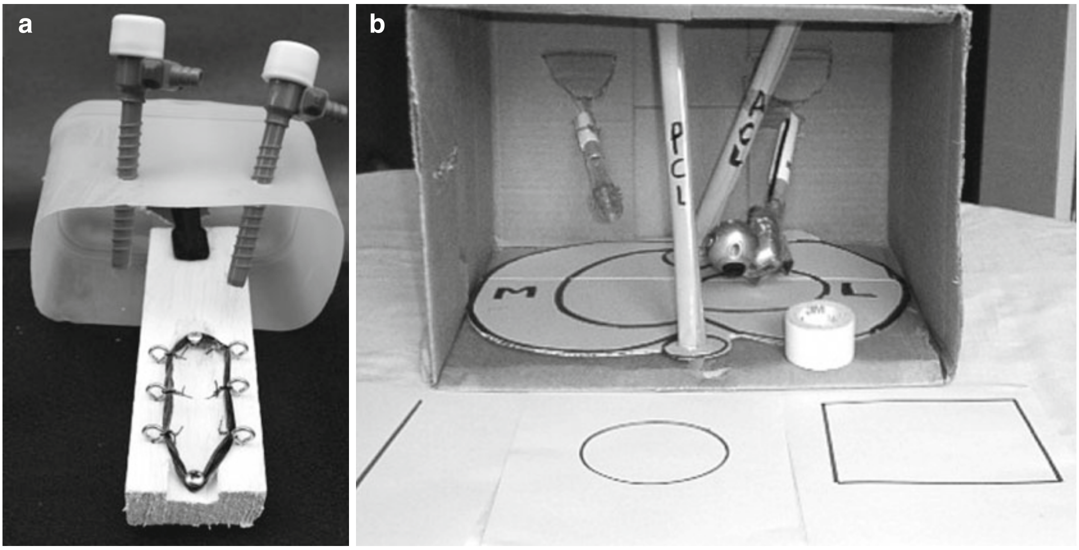

Fig. 6.3 (**a**) A model for developing psychomotor skills in arthroscopic knot tying (© Royal College of Surgeons of England, 2006. Reprinted with permission from Kitson et al. (2006)). (**b**) Simple box to train eye-hand coordination and camera positioning (© Royal College of Surgeons of England, 2009. Reprinted with permission from Patil et al. (2009))

6.3.3 Box Trainer for Arthroscopic Knot Tying

Kitson and coworkers developed a cheap and easy-to-construct jig for practising arthroscopic knot tying (Fig. 6.3a) (Kitson and Blake 2006). Six eyelets were screwed into a piece of wood with a small cut-out on one side. On each side of the eyelets, screws are placed to position two tensioned elastic bands between the two rows of eyelets. The bottom of an empty plastic container is used to simulate the tissue surrounding the entry portals and helps to fixate the trocars. While suturing the elastic band to the eyelets, a loss of suture tension during knot tying is exposed rapidly. This helps the trainee to develop psychomotor skills, to understand the concepts of sliding and locking knots and to practise a crucial step in arthroscopic shoulder surgery. This is a typical example of affordable basic psychomotor training.

6.3.4 Model for Junior Surgical Trainees

In 2009, Patil and coworkers developed a system to train bimanual camera and instrument control for arthroscopic tasks (Patil et al. 2009). A webcam was attached at 30° tilt to one end of the outer sheath of an embolectomy catheter (Fig. 6.3b). After connecting this assembly to a computer, an illuminated cardboard box was used to form an arthroscopic box trainer. A second portal in the box can be used for inserting another rod. Tasks can be performed in this box trainer aiming on bimanual coordination by contour following an instrument tip, and triangulation by manoeuvring the webcam around simulated cruciate ligaments. Although the quality of the webcam is low, the assembly is inexpensive costing around £10. Moreover, it is simple to produce and can be used repetitively with most USB cameras and computers without the necessity of operation theatre facilities. Although the authors claim that this system can hardly be a substitute for performing arthroscopy on real patients, it can improve triangulation skills and hand-eye coordination.

6.4 Anatomic Bench Models

6.4.1 Knee Joint Bench Models

This section provides an overview of the commercial knee joint bench models that to the

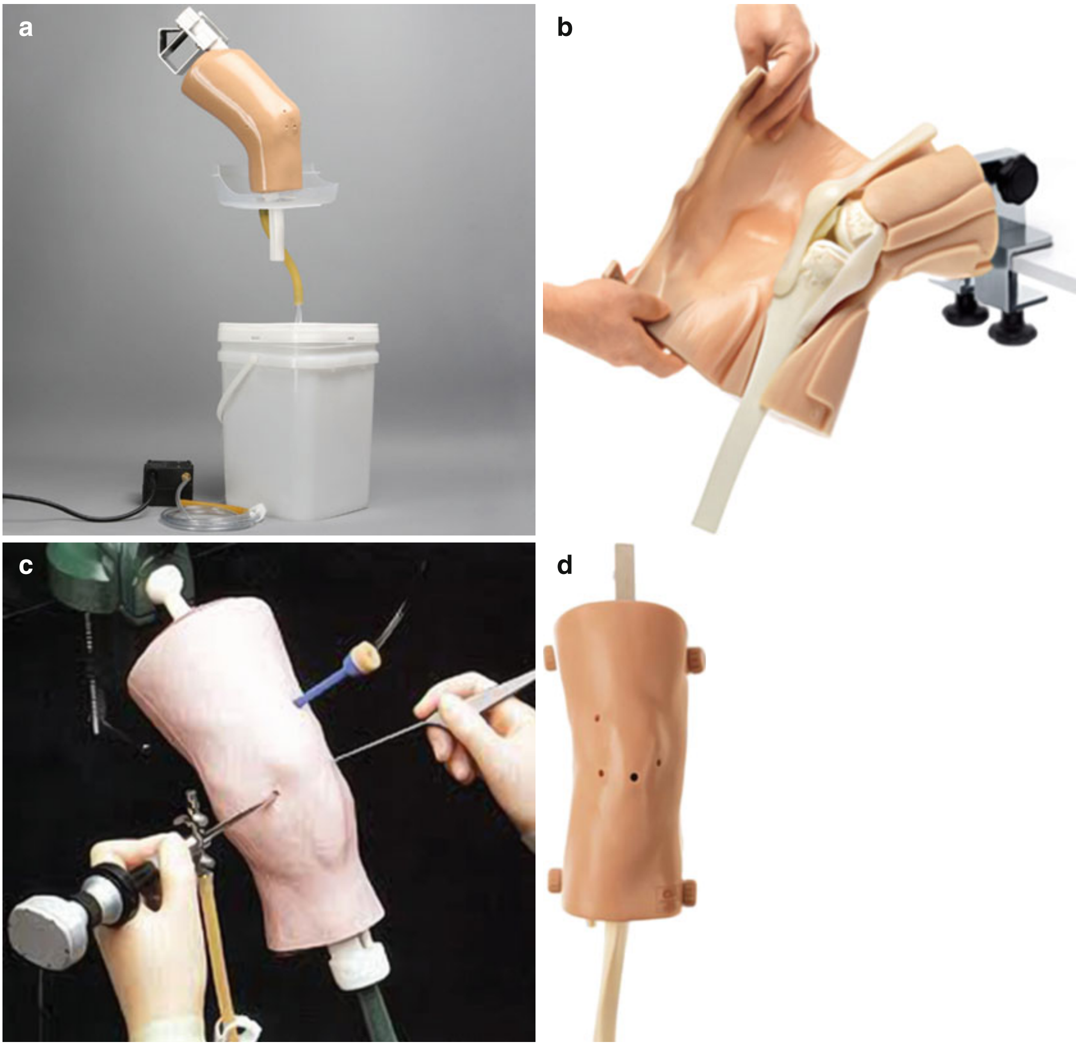

Fig. 6.4 (**a**) Sawbones knee joint bench model (© Sawbones Europe AB, 2014. Reprinted with permission from www.sawbones.com). (**b**) Adam-Rouilly knee joint bench model (© SOMSO Modelle GmbH, 2014. Reprinted with permission from www.adamrouilly.co.uk) (**c**) Hillway Surgical Knee joint bench model (© Hillway Surgical Limited, 2014. Reprinted with permission from www.surgimodels.com). (**d**) CLA knee joint bench model (© SOMSO Modelle GmbH, 2014. Reprinted with permission from www.coburger-lehrmittelanstalt.de)

best of our knowledge are available (Fig. 6.4). For clarity, we will name them by the brand or company name. General characteristics of all knee joint bench models are that they are composed of synthetic material, equipped with a clamp to fixate the model to a solid construction and present naturally sized anatomic structures including at least skin, bones, menisci and ligaments.

Two different types of Sawbones knee joint bench models (www.sawbones.com) are available: dry or wet, which can be purchased in various sizes and can be presented on a left or a right knee (Fig. 6.4a). Both models can be manipulated through valgus and varus and flexion and extension during training. The dry model is designed to train meniscal repair, with the menisci being replaceable. The wet model included a fluid management system and is designed to train diagnostic and operative arthroscopy techniques.

The Adam-Rouilly (www.adamrouilly.co.uk) knee joint bench model offers, beside the basic anatomic structures, also muscle and the knee joint capsule and allows removal of the cutaneous-muscular cover to show the intra-articular joint (Fig. 6.4b).

The Hillway Surgical Knee joint bench model (www.surgimodels.com) can be applied for dry and wet training. For the latter, bleedings can be simulated. The sacrificed ligaments can be replaced by new ones in a simple manner (Fig. 6.4c).

The CLA knee joint bench model (www.coburger-lehrmittelanstalt.de) has an anterior outer cover with four access points: two lateral, one central and one medial opening (Fig. 6.4d). The Hoffa's fat body is shown and can be taken off and replaced by an adhesive catch. The internal and external menisci are anchored by plug-in threads and can be easily exchanged and replaced. The cutaneous-muscular cover can be removed exposing the bones with the ligaments as a functional knee joint model.

6.4.2 Shoulder Joint Bench Models

This section provides an overview of the commercial shoulder joint bench models that to the best of our knowledge are available (Fig. 6.5). For clarity, we will name them by the brand or company name. General characteristics of all shoulder joint bench models are that they are composed of synthetic material and present naturally sized anatomic structures including at least skin, bones and ligaments.

Similarly for the knee joint models, the Sawbones shoulder bench models offer a wide variety in terms of size, left/right shoulder and dry and wet (www.sawbones.com). Figure 6.5a shows Alex III Shoulder Professor model, which has a characteristic of transparent hard-shell cover with prefabricated portals, and Fig. 6.5b shows the Arthroscopy Shoulder model covered by a soft skin that allows palpation and training of portal creation.

Internal components of the models can be replaced and allow training of various scenarios such as anchor insertion, suture passing and knot tying techniques and repair of various ligaments (SLAP, rotator cuff), tendons (biceps, subscapularis), labrum locations (posterior, anterior) and Hill-Sachs lesions.

The Hillway Surgical Shoulder joint bench model (www.surgimodels.com) can be fixated in any plane such as 'lateral decubitus' or 'beach chair' position due to multidirectional clamp.

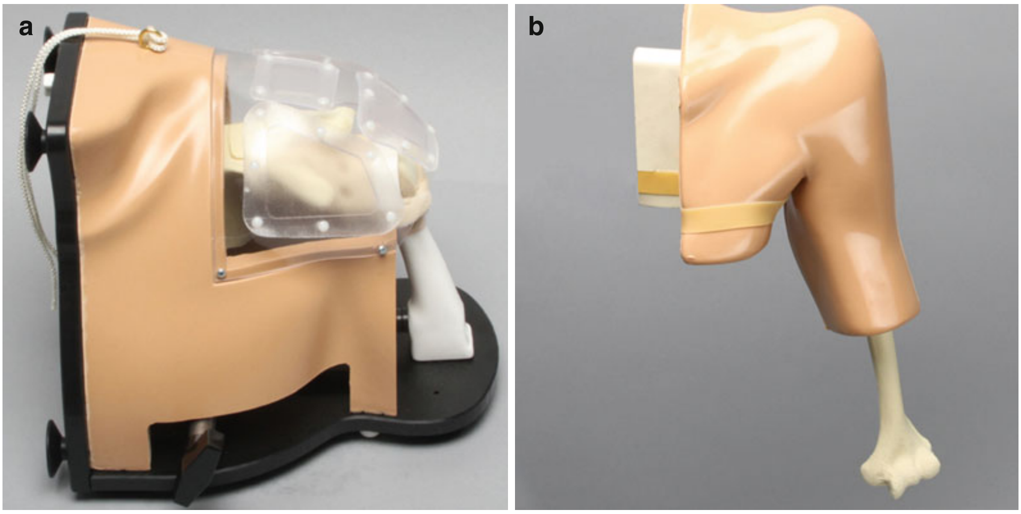

Fig. 6.5 (**a**) Sawbones Alex III Shoulder Professor model (© Sawbones Europe AB, 2014. Reprinted with permission from www.sawbones.com). (**b**) Sawbones Arthroscopy Shoulder model (© Sawbones Europe AB, 2014. Reprinted with permission from www.sawbones.com). (**c**) Hillway Surgical Shoulder joint bench model (© Hillway Surgical Limited, 2014. Reprinted with permission from www.surgimodels.com). (**d**) Adam-Rouilly Shoulder joint bench model (© SOMSO Modelle GmbH, 2014. Reprinted with permission from www.adamrouilly.co.uk). (**e**) CLA shoulder joint bench model (© SOMSO Modelle GmbH, 2014. Reprinted with permission from www.coburger-lehrmittelanstalt.de). (**f**) Beijing Yimo Shoulder Joint

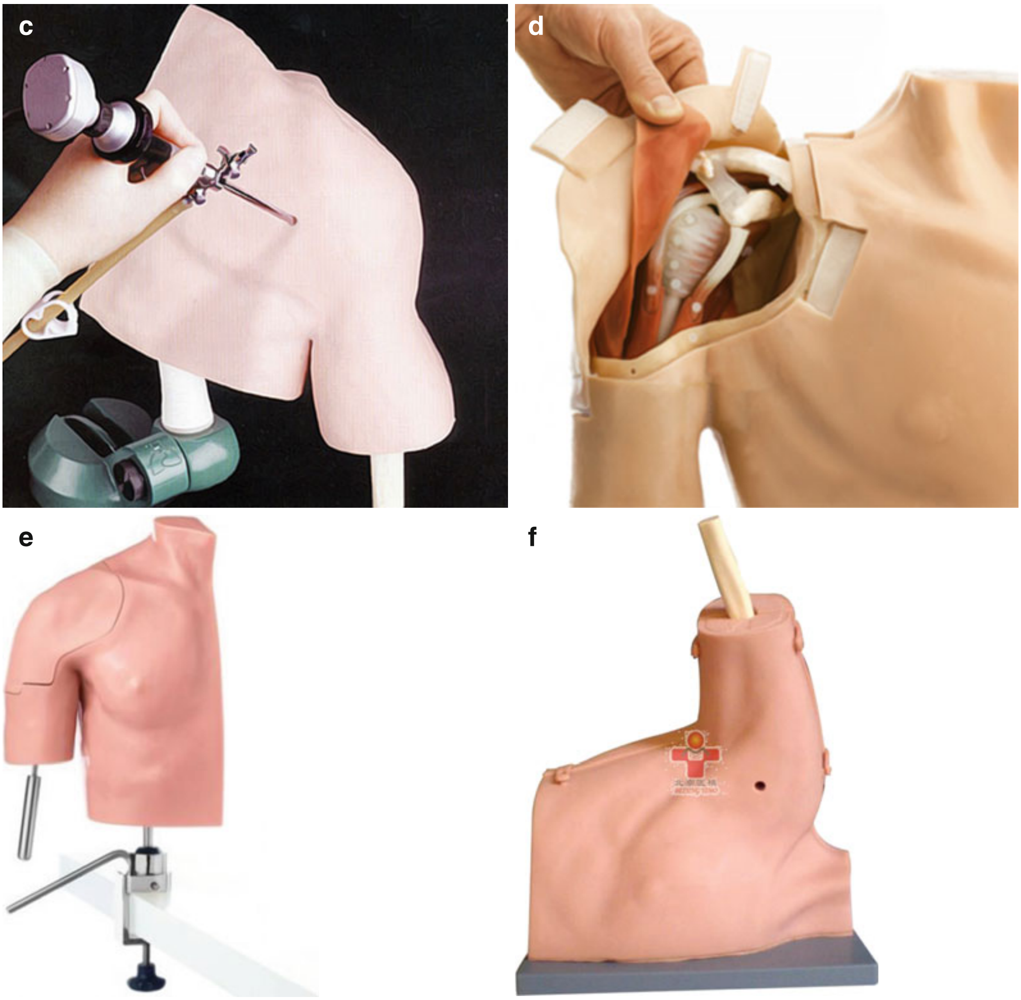

Fig. 6.5 (continued)

Removal of loose bodies, Bankart repair, labrum or biceps tendon repair and subacromial decompressions can be trained multiple times by replacing the sacrificed components with new ones (Fig. 6.5c).

The other three types of shoulder joint bench models (Adam-Rouilly Shoulder www.adamrouilly.co.uk, CLA Shoulder www.coburger-lehrmittelanstalt.de, Beijing Yimo Shoulder Joint www.chinamedevice.com) have a similar build which consist of a removable cutaneous-muscular cover to show the intra-articular joint (Fig. 6.5d–f). This allows the models to be also used as functional anatomic models during lectures. The same type of procedures as mentioned for the Sawbones models can be trained again by replacing sacrificed components.

6.4.3 Wrist Joint Bench Models

This section provides an overview of the wrist joint bench models that to the best of our knowledge are available (Fig. 6.6). If applicable, we will name them by the brand or company name. General characteristics of all wrist joint bench models are that they are composed of synthetic material and present naturally sized anatomic structures including at least skin and bones.

The Sawbones Arthroscopy Wrist Bench Model

The Sawbones Arthroscopy Wrist bench model (www.sawbones.com) is used for diagnostic techniques (Fig. 6.6a). The model contains colour-coded proximal and distal bones with volar ligaments attached.

Fig. 6.6 (**a**) Sawbones Arthroscopy Wrist bench model (© Sawbones Europe AB, 2014. Reprinted with permission from www.sawbones.com). (**b**) CLA Arthroscopy Wrist bench model (Sources: websites of the companies. © SOMSO Modelle GmbH, 2014. Reprinted with permission from www.coburger-lehrmittelanstalt.de). (**c**) Intra-articular structure AMC-TU Delft wrist model (© GJM Tuijthof, 2014. Reprinted with permission) (**d**) Special design of the skin of the AMC-TU Delft wrist model, which is placed on the back side (© GJM Tuijthof, 2014. Reprinted with permission)

The CLA Arthroscopy Wrist bench model (www.coburger-lehrmittelanstalt.de) consists of a plastic hand in which the carpal bones, the radius and ulna, together with the carpal disc and the intra-articular ligaments are visible (Fig. 6.6b). On the extensor side of the hand, two access portals are available to the inner cavity of the joint: a radiodorsal and an ulnodorsal portal. The carpal disc can be attached to the ulna and the carpal ligaments on both the flexor and extensor sides. This structure can be exchanged or replaced as required. The model allows training for diagnosis.

One non-commercial wrist bench model is presented, which is a joint development performed by the Academic Medical Centre in Amsterdam and Delft University of Technology (Fig. 6.6c). The model is focused on training of ‘portal creation' and 'navigation and identification' tasks using the arthroscope and a probe. The bony structure is a 3D print of a normal human wrist imaged with CT in distraction. To connect the carpal bones and keep them aligned while still allowing for limited movement between the bones, they were fixed in a volar plate made of silicone. Effort was put in a realistic feel of the skin and repetitive training of portal creation. Therefore, we fabricated two instead of one single skin layer. The top layer was made of silicone and 1 mm thick. The second layer was 2.5 mm consisted of silicone as well but was reinforced with medical gauze to increase tear strength. In between the silicone layers, oil was added that allows skin shifting upon palpation. The silicon material has a shore A hardness of 10, which is in the predetermined range of human skin (Kissin et al. 2006), and offers a realistic sensation of the skin. This configuration was attached around the carpal bones with a lacing system to allow adequate tensioning and quick replacement. This prototype is further developed and validated.

6.4.4 Other Joint Bench Models

Arthroscopy is performed on many more joints than the knee, the shoulder and the wrist, but to the best of our knowledge, the only company that offers anatomic bench models to train arthroscopic skills in specific other joints is Sawbones (www.sawbones.com). In Fig. 6.7, joint models of the ankle, hip and elbow are shown. They show a similar set up as presented for the other Sawbones products and provide training for the treatment of cartilage erosion of the capitellum, fracture of the radial head and loose bodies in the elbow, transcondylar fracture at various locations of the talus, chondromalacia and a osteochondral loose bodies in the ankle and labrum tears and cartilage erosion in the hip.

6.5 Models with Sensors

6.5.1 Anatomic Bench Models Combined with Sensors

For validation purposes of the use of anatomic bench models or determination of what metrics are able to discriminate between expert and novice arthroscopists, these bench models have been combined with sensor systems. We specifically use the term combine as the sensors were not physically integrated with the anatomic bench models. We provide an overview.

The most straightforward application is the use of a stopwatch to measure the completion time of a task. Scientific literature does present studies where only task time was measured, but usually the other sensors give task time as an accompanying measure when monitoring other metrics, such a motion of force metrics.

Motion metrics including path length, instrument velocity and smoothness are related to instrument or hand motion for which electromagnetic

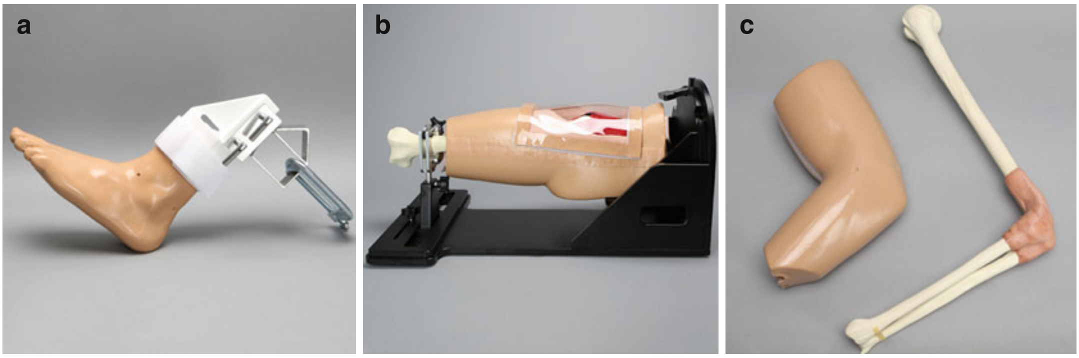

Fig. 6.7 (**a**) Sawbones ankle bench model. (**b**) Sawbones hip bench model. (**c**) Sawbones elbow bench model (© Sawbones Europe AB, 2014. Reprinted with permission from www.sawbones.com)

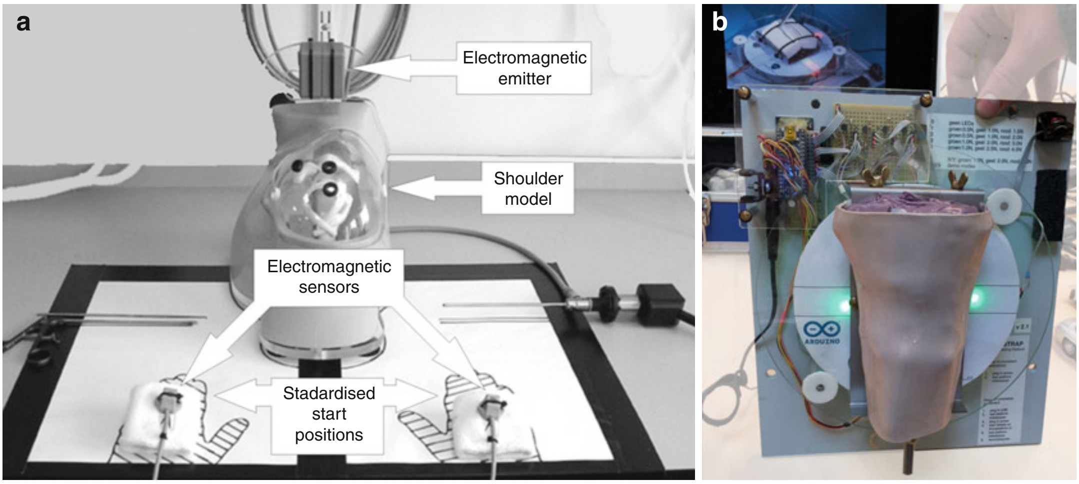

Fig. 6.8 (**a**) Alex Shoulder Professor bench top model combined with an electromagnetic motion tracking system (Reprinted from Howells et al., Copyright (2008b), with permission from Elsevier) (**b**) Force measurement system connected to the AMC-TU Delft wrist bench model (Horeman et al. 2010; © Tim Horeman, 2012. Reprinted with permission)

motion tracking systems were used (Howells et al. 2008a, 2009; Tashiro et al. 2009) (Fig. 6.8). These electromagnetic markers were attached to the instruments or the dorsum of the hands during task training on a bench model. The models that were used are the Alex Shoulder Professor (Howells et al. 2008a; Howells et al. 2009) and the knee joint bench model (Howells et al. 2008b; Tashiro et al. 2009), both from Sawbones. All four studies showed a significant difference in performance between experts and novices, and it was concluded that the motion analysis system could subsequently be used to track performance progression when practising arthroscopic skills on bench top models.

Force metrics include peak forces, average force and overall force over time. Such metrics can be determined when measuring with a six-degree-of-freedom sensor that measures the force in three directions and moments in three directions. The force sensor was attached in between the fixation table and the knee joint bench model (Tashiro et al. 2009). The results indicate that the three force metrics were also able to discriminate between experts and novices.

A similar type of 3D force sensor has been designed by Horeman and coworkers (Horeman et al. 2010) specifically for training of endoscopic skills. This platform is accurate and affordable, can be attached to various anatomic bench models and offers the possibility to record task time and all exerted forces on a computer and to provide direct feedback when manipulation forces are exceeded (Fig. 6.8b). A commercial version called ForceTRAP v2 © is available via MediShield (www.medishielddelft.com).

6.5.2 Practice Arthroscopic Surgical Skills for Perfect Operative Real-Life Treatment (PASSPORT)

The PASSPORT is a co-development project between the Academic Medical Centre in Amsterdam and Delft University of Technology (Tuijthof et al. 2010). The philosophy of PASSPORT was to combine the strong features of virtual reality systems and physical models into one design and provide sufficient clinical variation, natural visual and haptic feel and direct feedback on performance. To this end, standard arthroscopic equipment was maintained and the human knee joint was replaced by a realistic dummy in which sensors are integrated to provide feedback and registration of training

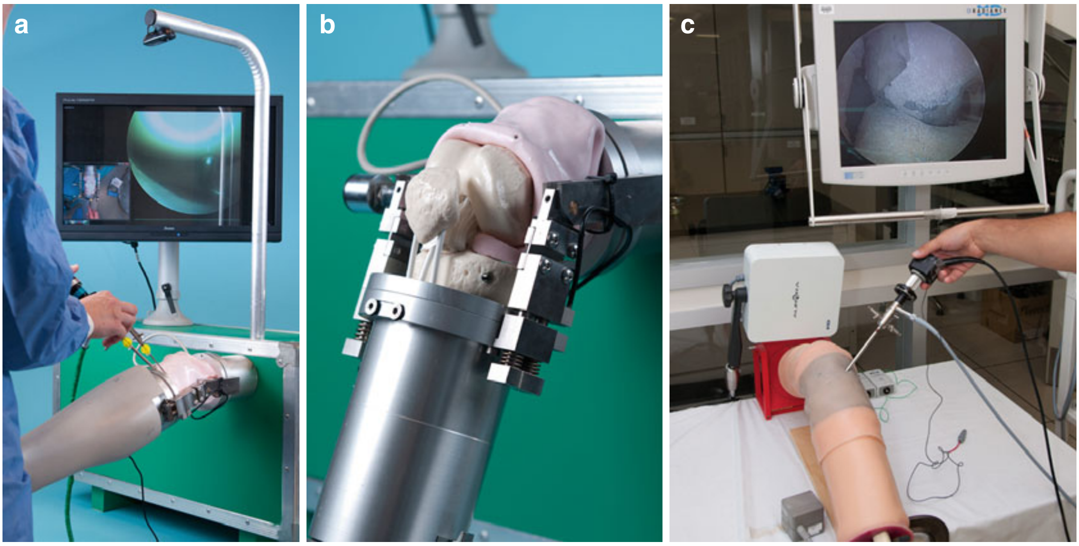

Fig. 6.9 (**a**) PASSPORT arthroscopic simulator showing the leg, instruments inserted in the joint, a webcam that tracks instrument motions and a user interface that provides the arthroscopic image and offers real-time force and time feedback during training (© AJ Loeve, 2012. Reprinted with permission). (**b**) Intra-articular joint space of PASSPORT with two forces that are connected to the tibia and femur bone to measure safe tissue manipulation (© AJ Loeve, 2012. Reprinted with permission). (**c**) Knee Arthroscopy Simulator offering motion tracking by electromagnetic sensors and allowing performance of wet arthroscopy (© 2013 IEEE. Reprinted, with permission, from Escoto et al. (2013))

sessions. After the validation of the first prototype (Tuijthof et al. 2010), PASSPORT v2 has been substantially improved (Fig. 6.9) (Escoto et al. 2013; Tuijthof and Horeman 2011; Tuijthof et al. 2012). The outer appearance of the lower leg was made from a dummy leg of a mannequin. The patella, tibia and femur bones are present, the patella moving in line with the flexion-extension motion of the lower leg. The hard plastic tibia plateau was modified for easy fixation of the menisci, which can be removed after sacrificing. This feature makes it possible to train meniscectomies and meniscus suturing. The cruciate ligaments are made of white-coloured woven rope and anatomically attached, but in such a manner that they remain in place while replacing a set of menisci. All anatomic structures match the human shape and geometry and the intra-articular joint volume was made waterproof for usage in combination with irrigation. A unique feature of PASSPORT is the special hinge that allows both flexion-extension and joint stressing in a natural manner to imitate natural knee joint stressing. Instrument motions are detected by a webcam and coloured markers attached to the instruments, and forces exerted on the condylar femur and tibial surfaces are recorded with a special version of the 3D force sensor and directly processed for real-time feedback and performance progression (Fig. 6.9).

Similarly as when using virtual reality simulators, exercises can be designed including digital instructions and video and selection of proper metrics, as the sensors are coupled to a computer that provides a graphical user interface.

6.5.3 Knee Arthroscopy Simulator

Escoto and coworkers developed a high-fidelity knee joint bench model with performance tracking (Knee Arthroscopy Simulator) following the same line of reasoning as presented for the PASSPORT (Escoto et al. 2013). The Knee Arthroscopy Simulator is composed of modular and replaceable plastic elements which is possible with quick release clamps that uncover the intra-articular joint space (Fig. 6.9c). The lower leg is moveable and covered by a custom-made foam that holds hard plastic bones. Quick-release clamps were designed and built to tightly secure the skin surrounding the joint to the calf and the thigh, preventing water from leaking. The same electromagnetic motion tracking system as introduced above is implemented to track instrument motions, and forces are measured with a commercially available six-degree-of-freedom force sensor and by modifying the arthroscopic instruments with strain gauges. It is unclear if the simulator offers a graphical user interface that allows autonomous training.

6.6 Discussion

Dexterity tests and box trainers can be very well used to train basic psychomotor skills including eye-hand coordination, precise manipulation and bimanual tasks. Since the scientific evidence is marginal, it is recommended to extend the research with these trainers and provide additional evidence, as such tests are affordable and can be very easily translated to tests in training curricula.

Training environments in which anatomic bench models are used allow for physical interaction between the user, the instruments and the model. This immediately highlights the strong characteristic of these types of simulators: the presence of normal everyday life sensory feedback. This implies that the relevant human senses (vision and proprioception and to a lesser extend sound and smell) can be used by the trainee to acquire feedback on their performance in a natural manner. That is why anatomic bench models allow for arthroscopic therapeutic training including tissue cutting or punching and tissue reconstruction using anchors and sutures. A necessary precondition is that the simulation environment as offered by the anatomic bench models is sufficiently realistic for the intended skills training, which is so far not the case. Thus, many of these models do not present a sufficiently challenging intra-articular joint space that would allow more widespread integration of these models in the training curricula. The work done by Tuijthof and Escoto and coworkers (Escoto et al. 2013; Tuijthof et al. 2010) indicates that engineers are aware that improvements are needed. The challenge is to keep these models affordable, which is their second biggest asset.

Both studies also indicate another disadvantage of the use of anatomic bench models, which is the lack of performance registration. This hampers individual-independent training and skill progression monitoring. Although this chapter offers several options as indicated in literature on how to combine sensors or to implement them in the anatomic bench models, most of the trainers lack a proper functioning graphical user interface that automatically processes all data and gives meaningful feedback on performance to a trainee. If physical trainers are used for educational purposes, this is definitely required for the future.

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