Virtual Testing Laboratory for Lower Limb Prosthesis

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ABSTRACT

This paper presents an environment, named Virtual Testing Lab-VTL, where the orthopedic technicians can test the prosthesis replicating the traditional procedures. It is part of an innovative design framework centered on digital models of the whole patient or of his/her anatomical districts, which constitute the backbone of the whole prosthesis design process. The virtual lab permits to realize a complete amputee's digital model, an avatar, by which it is possible to execute prosthesis set up and evaluate its functionality simulating postures and movements. First, we describe the state of art of techniques used, i.e., virtual humans and motion capture systems. Then, the application of virtual humans for the prosthesis design and simulation is presented as well as preliminary results.

Keywords: **virtual human, prosthesis design, virtual testing.**

1   INTRODUCTION

Custom-fit products characterized by a strong interaction with human body, such as artificial prostheses, can profitably benefit from the use of computer-aided tools during the development process. In the case of artificial prosthesis this should permit not only to reduce development times and costs and improve quality but also decrease the psychological effects on the patients, especially those cases requiring rehabilitation. In this work we put the attention on lower limb prosthesis, both below-knee (also called transtibial) and above knee (also called transfemoral).

In 2010 in Europe there were 216,000 amputees and 760 certified prosthetics, while in the U.S.A. an estimated 185,000 people undergo an amputation of a lower limb each year, mainly because of diabetes mellitus, dysvascular disease, trauma and bone cancer [1]. Nevertheless amputations due to trauma are decreasing; the overall number of lower limb amputation is growing due to a huge increase of vascular diseases [2].

Considered prostheses are realized with the state of the art components to obtain the maximum comfort and usability for the amputees. A correct configuration of lower limb prosthesis is

fundamental to allow amputees having the highest level of mobility permitted by their physical and life conditions. In fact, an appropriate prescription and/or design of prosthesis components help patients to have a good quality of life, a normal leading of daily activities and social outcomes.

At present, most orthopedic labs produce lower limb prosthesis following a hand made procedure that heavily relies on the orthopedic technician's skill and experience. The prosthesis is made by standard components, such as foot, knee and tube, selected from commercial catalogues according to patient's characteristics (e.g., anthropometric measures and life style) and the socket realized around the patient's residual limb. Typically, socket manufacturing involves the manual realization of negative and positive plaster casts of the residual limb. A check socket is realized on the positive cast and tested, assembled with all other components, with the patient. Then, positive cast shape is modified accordingly to test results, and the definitive socket is manufactured. Usually it is necessary to realize more than one check socket up to five in worst cases. Once realized the definitive socket, all components, standard and custom-fit, are assembled and the whole prosthesis is tested with the patient for the final check and set-up.

In this context, we are developing an innovative software platform for prosthesis design where the patient's digital models play the central role.

In previous works [3,4], the authors have focused the attention on the socket since it is the most critical component. They first demonstrated the feasibility of a totally computer-based approach to design and manufacture the socket integrating virtual prototyping techniques [3] and, then, developed a knowledge-based modeling and simulation environment, named Virtual Socket Lab-VSL, specifically targeted for the mentioned highly customized part [4]. The main scope is to provide a direct support to the technicians embedding within the system their knowledge and guiding them step by step applying in automatic or semiautomatic way rules and design procedures.

At present, the authors have moved the attention to the whole prosthesis. Precisely, in this paper, we consider the last step of the prosthesis deign process and we present an environment, named Virtual Testing Lab-VTL, where the orthopedic technicians can test the prosthesis replicating the traditional procedures using the patient's biomechanical model to validate lower limb prosthesis design and functioning and simulate postures and movements.

Herein, we first describe the state of art on virtual humans techniques and motion capture system. Then, the main features of the Virtual Testing Lab are presented. Finally, the application of virtual human for the prosthesis set-up is presented as well as preliminary results.

2   STATE OF THE ART

The implementation of the Virtual Testing Lab is based on two key issues: patient human modeling and simulation of postures and movements. The procedures have to be coherent with those carried out by the orthopedic technicians. This requires the analysis of prosthetic patients during motion to acquire motion laws of the different joints and simulate postures and movements with the avatar. This analysis can be done out using motion capture techniques. In the following we briefly reports state of the art in mentioned fields.

Human modeling is playing more and more an important role and related applications within the product development process can be various [5-6]. At present, various frameworks for virtual humans of different complexity can be found on the market or in academia and many research activities are under development to fulfill the requirements coming from different industrial sectors to solve specific problems.

Analyzing the state of the art and types of application we have grouped virtual humans into four main categories (Fig. 1):

- *Virtual human/actors for entertainment* **[6–8], used to populate scenes for movies and videogames production. Virtual crowd simulators, belonging to this group, can be also adopted to simulate emergency situations and for training purpose.**
- *Mannequins for Clothing* **[6,9–16] used to create virtual catwalks, virtual catalogues, and virtual try-on show rooms and to design garments.**
- *Virtual humans for ergonomic analysis* **[17–20], three-dimensional models of the human body used to study human-machine interaction that can be used to define complex scenes, analyze postures, simulate tasks and optimize working environments.**
- *Detailed biomechanical models* **[21–25], usually more complex than previous ones, structured into three distinct components: the skeleton with deformable elements and joints, skin and muscle tissues, tendons and ligaments. Applications concern ergonomics analysis, medical equipment, study of safety in transport, and human performance during sports activities, etc.**

The range of application domains is huge and some examples are: automotive [26,27], aeronautics [28,29], architecture and civil engineering [6], bioengineering and medicine [30,31], videogames and movies, education and training. However, depending on the target application, different models of the human body or of its parts are required with different levels of detail depending on the target application. In our case we decided to adopt a biomechanical model of the amputee with a detailed 3D model of the residual limb reconstructed from MRI (Magnetic Resonance Imaging) images [32].
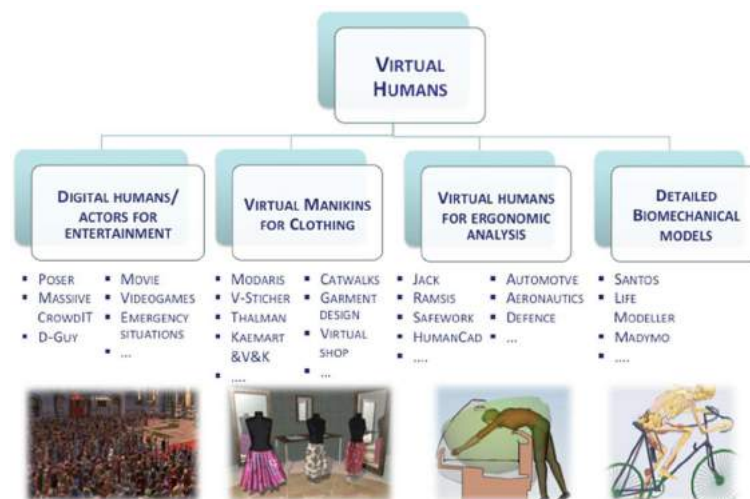

Fig. 1: Classification of virtual human models.

Motion capture (Mocap) techniques, appeared in the 70's as a branch of imaging techniques applied to biomechanical processes and have been developed till nowadays with several different applications such as military, entertainment, sports, and medical applications.
From literature, Mocap systems can be grouped in four categories according to the working principles (Fig. 2) [33]:

- *Optical***, considered the high-end technology. They extrapolate the position of body joints by triangulation between images taken from different cameras. We can have system with active or passive markers [34] or marker less [35–37]. In the first case markers are placed in the remarkable points of the body while in the second case a dedicated software module recognizes human figure.**

- *Mechanical*. **They adopt a deformable exoskeleton that, once worn by the actor, measures his/her movements [38]. The exoskeleton is composed of segments connected by metal or plastic goniometers and potentiometers on the joints. The movements are derived from the movements of the exoskeleton joints and transformed into electrical signals; data can be transferred to computer using cables or wireless. This technique is relatively low cost and appropriate for complex movement acquisition requiring large areas.**

- *Inertial*. **These system use accelerometers and gyroscopes to send to a calculator data about actor's movements to associate them to a virtual skeleton. This technique is good for portability and the satisfying dimension of the area of the scene, but is quite poor in accuracy and suffers of position drift for long acquisitions [39].**

- *Magnetic*. **In these systems the relative magnetic flux of three orthogonal coils on both the transmitter and each receiver is used to determine position and orientation [40]. This solution is quite inexpensive but the sensor response is nonlinear, especially toward edges of the capture area and the wiring from the sensors tends to preclude extreme performance movements**.

Cited techniques can be used for testing and validation also combined one each other [41].
Nowadays on the market we can find several solutions, especially optical ones. For our purposes we decided to adopt an optical system markerless based on webcams since this solution is not expensive and easy portable.
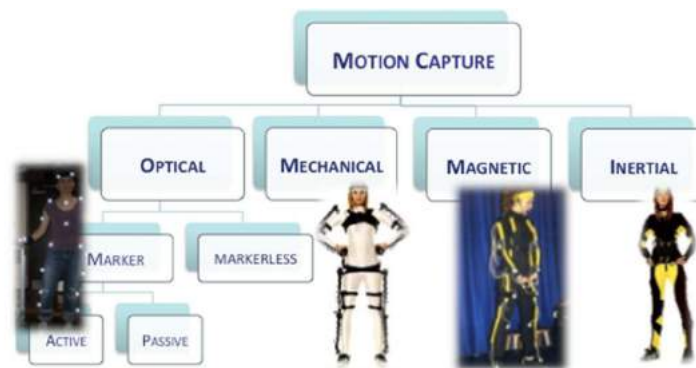

Fig. 2: Motion capture systems classification.

3   VTL-VIRTUAL TESTING LAB

The Virtual Testing Lab–VTL is part of a new software platform devoted to the design of lower limb prosthesis and centered on the digital model of the patient [4]. Two main environments compose this software platform: the *Prosthesis Modeling Lab* **and the** *Virtual Testing Lab-VTL*.
The first permits to generate the 3D assembly of the whole prosthesis that has to be validated with VTL. It guides the technician during the 3D modeling phase and the selection of standard and custom-fit components of the prosthesis on the base of the digital mock up of the anatomical district, the patient characteristics (e.g., anthropometric data) and the prosthesis use (e.g., daily use or sport activities). It comprises: (i) a commercial 3D CAD system to generate the parametric models of the standard parts and the final prosthesis assembly and (ii) the Virtual Socket Lab – VSL, already mentioned, to create the 3D model of the socket. This last step foresees the use of an ad hoc socket modeler, named Socket Modeling Assistant - SMA, integrated with FE tools to study the stump–socket interaction [4]. The orthopedic technician generates the socket model around the stump digital model (acquired with Reverse Engineering equipment [32]) applying in automatic or semiautomatic way rules

and procedures that replicate operations performed by the technicians during the traditional manufacturing process.

Once created the prosthesis model, VTL, allows the technician to realize a complete amputee's digital model, the patient's avatar, onto which s/he can execute the prosthesis set up and evaluate its functionality simulating postures and movements. This permits to validate the prosthesis configuration created using the Prosthesis Modeling Lab. The underlying idea is to provide an environment where the orthopedic technicians can test the prosthesis replicating the traditional procedures. For this purpose, we are collaborating with the technical staff of a qualified orthopedic laboratory since they can provide the domain knowledge about prosthesis development process.

Fig. 3 portrays the main steps of the procedure identified for the virtual testing. We can distinguish two main phases: (i) patient's avatar characterization from anthropometric and geometric point of view and (ii) gait analysis, both described in the next sections.

To create and simulate the patient's virtual human we decided to use LifeMOD, a biomechanical simulation package based on MSC ADAMS solver. It permits to create a detailed biomechanical model of a human body using rigid links connected through joints to simulate the skeleton and flexible elements to represent soft tissues (muscle tissue, tendons and ligaments). As said, we will present preliminary results of the tests performed to verify the feasibility of the approach.

3.1   Characterization of the Patient's Avatar

Virtual testing of prosthesis requires an avatar of the patient able to wear the prosthesis and simulate deambulation. To this end, we have created two reference avatars, one for transfemoral amputee (Fig. 4(b)) and another one for transtibial amputee, from which it is possible to generate a customized model for the specific patient modifying anthropometric measurements of the default model.

To characterize the amputee's avatar wearing the prosthesis following data are necessary: (i) patient's anthropometric measures, (ii) digital models of the lower limb and (iii) of the assembled prosthesis representing three different levels of the avatar characterization (Fig. 3).
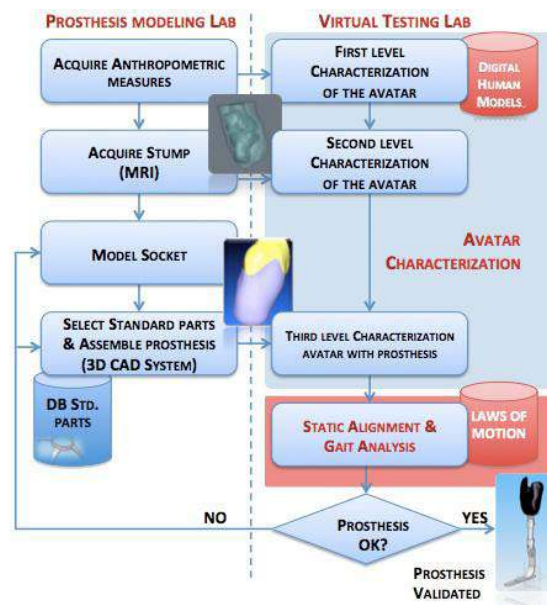

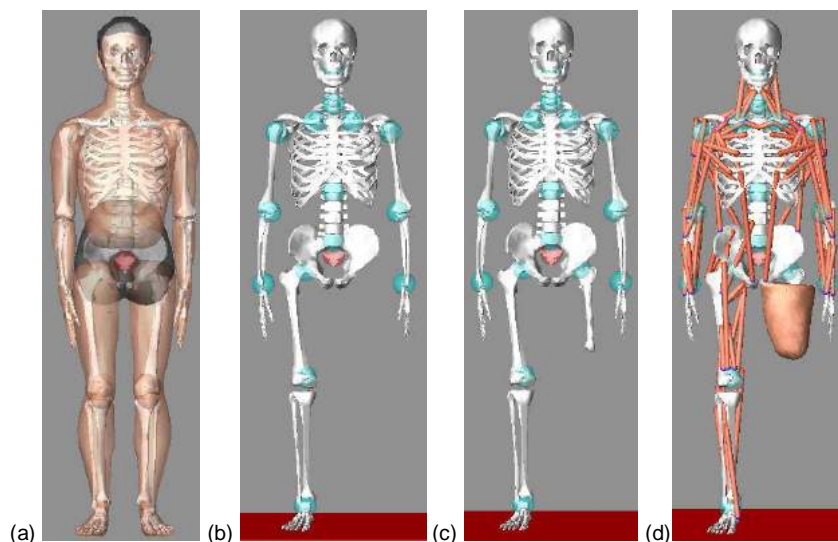**Fig. 3: Virtual testing procedure.**

Fig. 4: Avatar characterization: (a) standard virtual human model; (b) reference transfemoral model; (c–d) patient's avatar.

Patient's anthropometric measures are meaningful for correct dimensioning of the avatar, a key factor for the prosthesis set–up. We have distinguished between general patient's data to size the avatar and stump measures to position and link the prosthesis to the avatar. Tab. 1 summarizes measures required for the patient. Some of them are already available and directly acquired from the Virtual Modeling Lab since they are used to guide the technicians during the prosthesis design tasks. Some examples are hip joint (transfemoral) or knee joint (transtibial) height and weight, height, and foot length of the amputee. Remaining ones can be acquired using a measuring tape or a motion capture system.

LifeMOD - Body Segment Measurement Table

BODY MEASUREMENT TABLE (length data displayed in inches)

⦿ Male ○ Female ○ Child ○ Non-Human   ⦿ Hands Gripping ○ Hands Open

Age (months)	288.0	Waist_Depth	8.6170494179	Left Knee Ht Seated	21.99618541
Weight (lbs)	169.7530864199	Waist Breadth	12.0108018073	Right Thigh Circum.	22.8035602827
Standing_Height	70.0	Buttock Depth	9.2819317031	Left Thigh Circum.	22.8035602827
Right Shoulder Ht	57.2869888644	Hip Breadth Standing	13.7771791722	Right Upper Leg Circum.	15.1023275299
Left Shoulder Ht	57.2869888644	Right Shoulder To Elbow Ln	14.1932000816	Left Upper Leg Circum.	15.1023275299
Right Armpit Ht	51.2785570284	Left Shoulder To Elbow Ln	14.1932000816	Right Knee Circum.	15.3455677064
Left Armpit Ht	51.2785570284	Right Forearm Hand Length	19.4876759288	Left Knee Circum.	15.3455677064
Waist Height	42.076585549	Left Forearm Hand Length	19.4876759288	Right Calf Circum.	14.4814201753
Seated Height	36.7411964749	Right Biceps Circumference	12.2228582717	Left Calf Circum.	14.4814201753
Head_Length	7.817658576	Left Biceps Circumference	12.2228582717	Right Ankle Circum.	8.7574689033
Head_Breadth	6.1304445084	Right Elbow Circum.	12.2362368667	Left Ankle Circum.	8.7574689033
Head To Chin Ht	8.9732999206	Left Elbow Circum.	12.2362368667	Right Ankle Ht Outside	5.4214689807
Neck Circum.	14.9737716209	Right Forearm Circum.	10.9894194781	Left Ankle Ht Outside	5.4214689807
Shoulder Breadth	19.1977283936	Left Forearm Circum.	10.9894194781	Right Foot Breadth	3.8371722689
Chest Depth	9.517462803	Right Wrist Circum.	6.8898925689	Left Foot Breadth	3.8371722689
Chest Breadth	12.7675659397	Left Wrist Circum.	6.8898925689	Right Foot Length	10.6540185017
		Right Knee Ht Seated	21.99618541	Left Foot Length	10.6540185017

Close   Apply

Tab. 1: Patient's anthropometric measures (in inch).

Once entered and/or automatically acquired the necessary data, LifeMOD automatically applies the first level of customization to the virtual amputee generating skeleton, masses, joints and soft tissues on the basis of anthropometric measures.

The residual limb is necessary for a complete characterization and for the gait analysis; therefore, the second level of customization consists in linking the detailed stump model to the virtual amputee. The stump model, acquired using MRI equipment, is directly imported from the Prosthesis Modeling Lab (using Parasolid format) in two steps:

▪ The bone segment is linked to the virtual hip (transfemoral), as shown in Fig. 4(c) or to the knee (transtibial) using, respectively, the hip joint and the knee joint height;

▪ The residual limb soft tissues are properly positioned (Fig. 4(d)).

In the last step the digital amputee has to wear the assembled prosthesis modeled using the Modeling Prosthesis Lab. While assembling the components, the alignment of the prosthesis parts must be similar to the skeletal structure of the other leg. Traditionally, this operation is called bench alignment or plumb line alignment. Once properly aligned, the digital prosthesis is imported from the Virtual Modeling lab and taking into account the prosthesis height and foot rotation respect to the vertical line makes the correct positioning. In particular, the prosthetic foot has to be aligned to the other one and the socket has to hold entirely the residual limb. Fig. 5 portrays either a transfemoral or a transtibial avatar wearing the prosthesis.

Now, the amputee's avatar can be used to perform static alignment and gait analysis during various patients' activities.
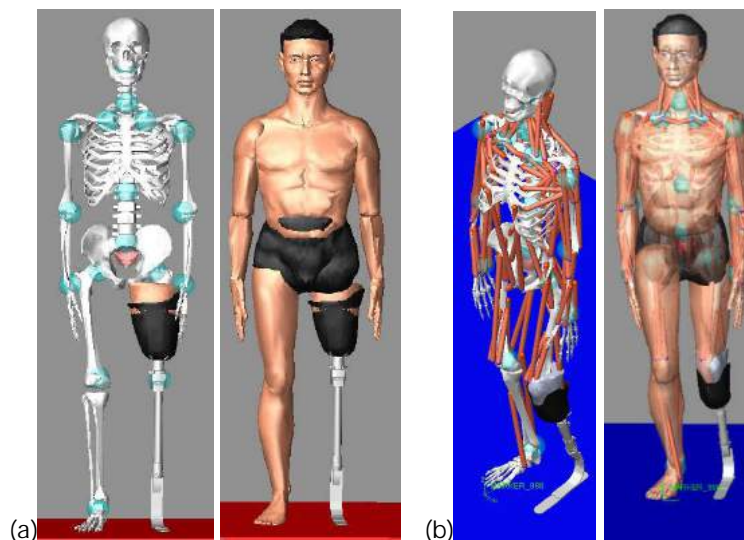

Fig. 5: Amputee's avatar wearing the prosthesis: (a) transfemoral and (b) transtibial.

3.2   Virtual Amputee's Simulation

Once created the patient's avatar, the prosthesis can be validated simulating situations traditionally analyzed by the orthopedic technicians. The underlying idea is to develop a library of laws of motion specialized for amputees wearing the prosthesis. To this end, it is necessary to acquire patients' movement and posture during typical daily-activities.

At present, the approach has been tested using a motion capture system to acquire the motion laws of the patientÑ joint and simulate posture and movement with LifeMOD¦ .

Fig. 6 shows the acquisition environment composed of:

- Four Sony-eye cameras, resolution 640x480 pixels at 60 Hz;
- The markerless motion capture technology iPi Desktop Motion Capture¦ [42];
- A portable work station Dell Precision M6500 with dual core CPU;
- A rehabilitation stair.

Fig. 6: Markerless Mocap system.

The adopted Mocap solution is non-invasive and based on the acquisition of synchronized video sequences obtained with common cameras without having to apply any type of physical markers on the patient's skin. It automatically recognizes the different body segments and, then, calculates the position and orientation in three-dimensional space. iPi Desktop Motion Capture¦ includes two main components: *iPisoft Recorder* for the motion capture phase that synchronizes images recorded from the four webcams and *iPisoft Desktop Motion Capture* for the recognition and segmentation of body and tracking of movement.

The rehabilitation stair has an inclined ramp (about 17°) and three steps; it is used to acquire amputeeÑ movement when walking along a sloping floor and going up stairs.

To reproduce the movement with the patientÑ avatar, two issues have to be considered: data conversion and mapping of acquired data onto the amputeeÑ avatar defined in the previous phase.

First, we have implemented a software module, named BVHtoSLF, which converts acquired data from .BVH (Biovision Hierarchical Data) format used by iPi Mocap to the .SLF one used by LifeMOD. Then, it has been necessary to create a set of markers in LifeMOD coinciding with those used by Ipisoft since LifeMOD considers external markers placed on skin surface. To make easier this operation we have implemented an automatic procedure, through a LifeMOD script, which relocates parametrically the position of the markers in the LifeMOD human model.

Both operations are performed automatically and data captured and imported can be used to study and analyze, in virtual, the behavior of the prosthesis during daily activities.

Typically, to achieve accurate simulations of muscle and joint movement, an inverse dynamics simulation is first run to record angulations and muscle-contraction histories for the target body segments (links). ÎMotion agentsÏ (yellow spheres in Fig. 7) are positioned on the model to drive the movement and "teach" the joints and soft tissues how to move. In our case, to replicate the functionality of the residual limb, we have inserted Îaugmented motion agentÏ linked to the prosthesis segments (Fig. 7): three associated to the prosthetic foot, one to tube below-knee representing the lower part of the leg, one to the knee and another one to the socket. Once movements have been

recorded in an inverse dynamics simulation, the compiled movement histories are ready to drive the forward dynamics simulations.
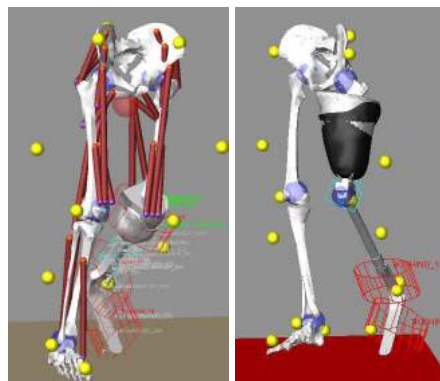

Fig. 7: Prosthetic avatars with motion agents.

4   PRELIMINARY EXPERIMENTATION

The Virtual Testing Lab has been preliminary tested with two case studies: a transtibial amputee, 35 years old, 170 cm tall and a transfemoral amputee, 49 years old, 175 tall.

The prosthesis for both the amputees has been modeled using the Virtual Modeling Lab on the base of patients' characteristics and around the residual limb model [4, 43]. Fig. 6 shows the virtual avatars corresponding to the transfemoral and transtibial amputees.

Before starting the acquisition, the VTL needs a number of setup steps, such as webcam configuration and the calibration to initialize the system and properly locate each webcam in the space.

Tests have been carried out in collaboration with the technical staff of an orthopedic lab. We have acquired and simulated the amputees walking on a flat floor and going up a step. The amputees were asked to move as much as possible as if they were in the real environment and to avoid fast movements since the system has some known limits in tracking fast movements due to the frequency of acquisition of cameras. Fig. 8 shows the images recorded by the Sony-eye camera for the first step of a transfemoral amputee walking along a regular flat floor and corresponding simulation with the amputee's avatar. Fig. 9 portrays subsequent steps as recorded by the second webcam and the related simulation. Fig. 10 reports four frames of the simulation of the avatar going up the step.

Preliminary results permitted to verify the capability of the motion capture system to acquire data necessary to replicate movements with the patient's avatar and the functionality of data exchange (conversion algorithm) as well. No meaningful problems have been identified and results have been considered encouraging. However, we have planned to use six cameras instead to obtain a more precise acquisition and to perform a campaign to acquire and define a customized library of motion laws to simulate amputee's movement.
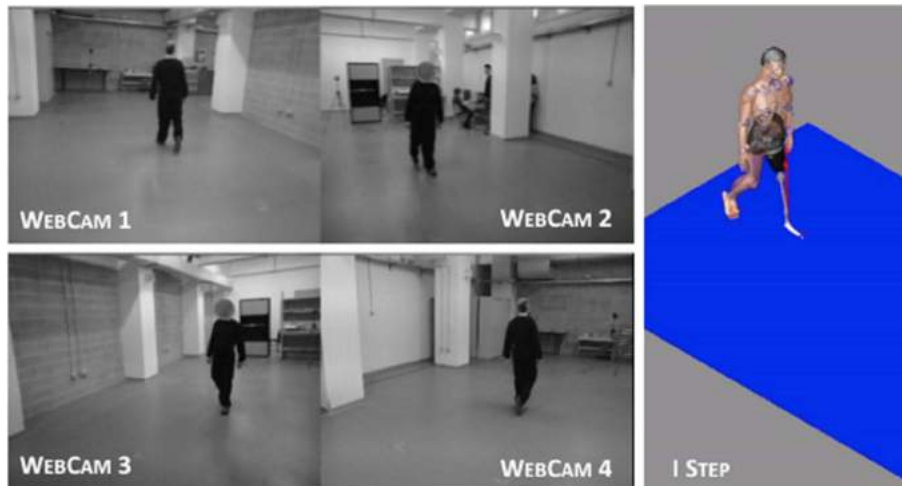
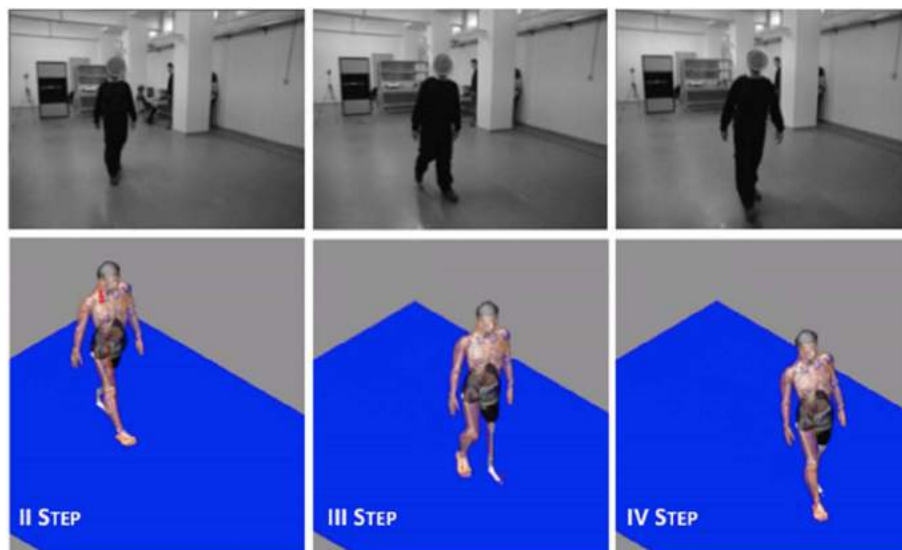Fig. 8: Recorded images from the four webcam and amputeeʼs simulation.

Fig. 9: Subsequent steps.

5   CONCLUSIONS

In this paper we have presented VTL–Virtual Testing Laboratory for lower limb prosthesis centred on the amputeeʼs avatar and integrated with a Prosthesis Modelling Lab to generate the 3D model of the whole prosthesis. The virtual lab should allow the prosthetic to virtual test the prosthesis simulating traditional procedures (e.g., the prosthesis set–up) and amputeeʼs daily activities, such walking in different environments (e.g., flat or sloped floor), sitting on a chair and going up stair accordingly to the patientʼs life–style.
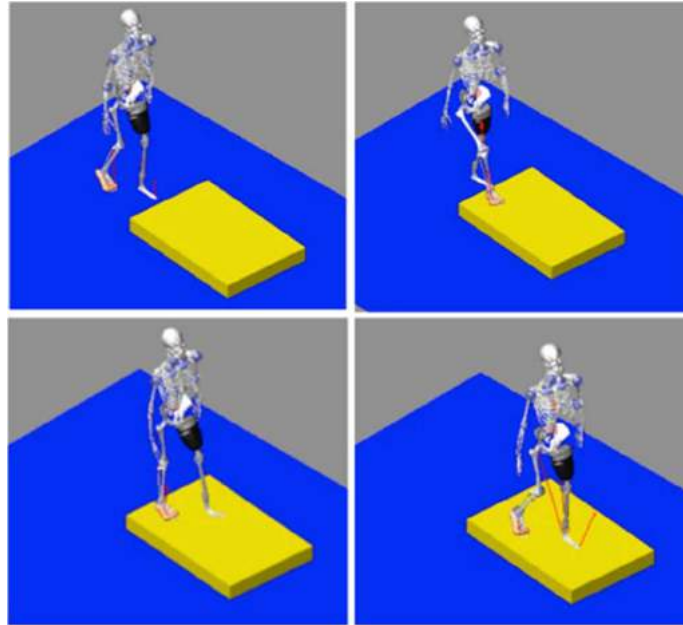
Fig. 10: Simulation of avatar going up a step.

VTL includes a commercial DHM (Digital Human Modelling) tool, LifeMOD, which permits to create a detailed biomechanical model of the amputee and simulate the behaviour. At present, we have identified a procedure to characterise a patientʼs avatar wearing the prosthesis and adopted a markerless motion capture system to acquire the laws of motion for each joint characterising the patientʼs avatar. The approach has been validated with two test cases, one transfemoral and another one transtibial and involving an orthopaedic laboratory. Preliminary results have been considered interesting; however further enhancements and system refinements have been envisaged. First of all, plan a campaign to acquire to acquire motion laws of joints during daily activities accordingly to the patientʼs life-style. In fact, life-style is one of the key parameter that guides the selection of prosthesis components, both standard and custom-fit. Then, a set of simulation tests will be performed to verify the performances of the framework and implemented procedures. Finally the new prosthesis design environment will be experimented results obtained with the proposed approach will be compared with the prosthesis traditionally manufactured.

We think that the new development process could improve the prosthesis design. It should permit to reduce number of prototypes and lower the psychological impact on the life of the patient since many tests, very bothering for the amputees, can be performed virtually.

ACKNOWLEDGMENTS

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