Virtual arm for the phantom pain therapy

Submitted paper

Abstract— **Phantom limb pain appears where an amputated limb used to be and is often excruciating and almost impossible to treat. Recently, two experiments on hand amputees in the neuroscience area have shown that if a patient has the visual illusion of his phantom hand in a way that he is able to move it, the phantom pain can decrease. We propose a new augmented reality system aiming to experiment this idea to arm amputees. Our interactive system provides to single arm amputee the image of himself augmented by a virtual arm. Our system is based on the valid arm detection on frame coming from a single camera, in order to use it to create on the image the virtual arm on the amputated side. By giving a immersive sensation and a realistic image of his complete body to the subject, we anticipate that this could lead to a sense of re-embodiment in the virtual limb as with previous system dedicated to the hand. And then, lead to a reduction of the pain. Moreover, by allowing more freedom we could also expect a better impact rate.**

I. Introduction

After amputation of a limb, an amputee continues to have an awareness of it and to experience sensations from it. Phantom limb pain [Flo02] - pain appearing to come from where an amputated limb used to be - is often excruciating and almost impossible to treat. New approaches, based on a better understanding of the brain's role in pain, may be opening the way to new treatments. Recently, by shifting the center of interest from the amputated limb to the center of pain (the brain), new family of potentially valuable treatments have arisen. Ramachandran *et al.* [RRR96] asked people with amputations of the hand and phantom limb pain to place their hands inside a mirror box as shown in Figure 1. In a way, they see their remaining hand mirror-reversed to look like their amputated one. When they moved their remaining hand in the box they are thinking they were moving their amputated one. By practising this duping exercise several time a week, their pain reduces. In the continuity of the Ramachandran's mirror experiment -the remaining hand was filmed and reprojected on the amputated one-, Giraux and Sirigu [GS03] showed that visual beliefs of the amputated limb lead to restore the motor cortex activity. They suggest that these attempts to link the visual and motor systems might be helping patients recreate a coherent body image, and so reduce pain.

Despite these encouraging results, it subsist several limitations on previous systems. First, the natures of the Ramachandran mirror box or the Giraux's system are dedicated to hand amputation. It is thus difficult to use such a system for patients with leg or high level arm amputation. Moreover, third of the subjects does not notice any reduction in their pain. For the other, the pain is reduced but does not disappear completely.

In this paper, we propose a first approach of a new experimental system aiming to increase the mirror process in an augmented reality context. Augmented reality will have the advantage of providing more flexibility in the ability to manipulate the image. We will construct an arm in virtual reality (VR) which subjects with phantom limb pain will be able to move themselves. Augmented reality will allow to overtake the main limitation of the classical mirror box system: movements are constraints to stay in the box, which lead to treat hand amputees only. Moreover, by giving more freedom of movement, our objective is to obtain better impact rate on large number of amputees.

Fig. 1. Ramachandran *et al.* [RRR96] asked hand amputee with phantom limb pain to place their hands inside a mirror box. In a way, they move their remaining hand in the box they are thinking they were moving their amputated one. By practising this duping exercise several time a week, their pain reduces.

II. Previous work

In order to augment image of amputees, the first system developed by Ramachandran *et al.* in [RRR96] was a physical device based on mirror. People with hand amputations placed their arms inside a box with vertical mirror in the middle. In a way, they see their remaining hand mirror-reversed to look like their amputated one. Another device built by Giraux *et al.* in [GS03] consists of a PC computer, a video camera, an LCD screen, and two mirrors. During training subjects seat in front of a table and place the impaired limb below an oriented mirror and the valid hand on the table. A video monitor placed above the mirror projects the image of hand movements onto the mirror. Subjects perceive those hand movements at a location coinciding with their impaired hand. The visualized hand movements are prerecorded movements of the valid hand obtained prior to training. Subjects are asked to produce a hand movement with their phantom limb while watching the hand in the mirror. There are two issues in the use of these two devices. First, by their natures they are dedicated to hand amputation. It is difficult to use such a system for patients with higher arm amputation than the hand. Second, movements are constraint to be perfectly symmetric on the both system. It could be be interesting to give more freedom to patient in order to see if it could improve the impact rate.

On the other hand, virtual reality (VR) is now attractive for both research and real-world applications in neuroscience, cognitive science and psychology as shown by Michael *et al.* in [TW02]. These researches take place in the more general context of cybertherapy [RBLO04]. The crucial element provided by VR is the ability to break the laws of optics and physics, or to disconnect physical reality as specified by a subject's body senses from the world he/she is seeing. As such, VR offers a unique research tool that allows the behavioral neuroscientist an opportunity to address heretofore unanswerable questions. It is not in our scope to survey all existing techniques, nevertheless we mention some of them: special education of learning disabled children [RWM98], schizophrenic patients with virtual hallucinations in an effort to desensitize them to their actual hallucinations [NNC96], phobia desensitization [NNC98], etc.

In this paper, we propose a image-based method aiming at estimating patient posture in order to reproject the valid arm sub-part of the image onto the phantom arm. Hence, we review posture estimation techniques. Since this is an important topic in computer vision, we can not be exhaustive, see [MG01] for a more complete survey. One can also see a survey [ZH04] on human movement tracking for stroke rehabilitation. Many posture estimation systems exist. Most of them are based on a model to perform the tracking. In order to initialize this model, the person is required to perform a set of calibration movements that identify the body parts to the system. Once the model is available in the first frame, a very common approach to tracking is to perform iterations of four steps until good agreement between the model and the data is achieved: prediction of the model position in the next frame, projection of the model to the image plane(s), comparison of the projection with the data in the new frame and adjustment of the model position based on this comparison. Several papers address this problem in real time with multi-cameras [CTMS03], [MTHC03], [HLS04], [CBK05]. The video frames are segmented and the 3D voxel reconstructions of the human body shape in each frame are computed from the foreground silhouettes. These reconstructions are then used as input to the model acquisition and tracking algorithms [MTHC03], [CTMS03]. The problem of occlusions is solved by choosing from the available cameras those that provide visibility of the part and observability of its motion, for every body part at every frame.

However, a broader range of applications can benefit from a single-camera approach. In recent monocular but non real time work from Agarwal and Triggs [AT04] a sparse Bayesian regression method is used to estimate 3D body postures directly from silhouettes. They are able to estimate angles for a 54 degree of freedom human body model. Complexity of the approach forbids application in real time. In real time, Poppe *et al.* [PHNP05] present a method based on silhouette matching with 3D-model in conjunction with hands and head localization by skin color detection. Since in our case the residual limp could be small and partially occluded by cloth, methods based on skin detection were early discarded. Jaegglia *et al.* in [JKG05] propose this year an interesting approach. A sparse 3D reconstruction of the subject to be tracked is made using a structured light system consisting of a LCD projector and a camera. Points of interest, easily detectable features are projected and detected to estimate the body pose. By determining points of interest our method can be joint to this one.

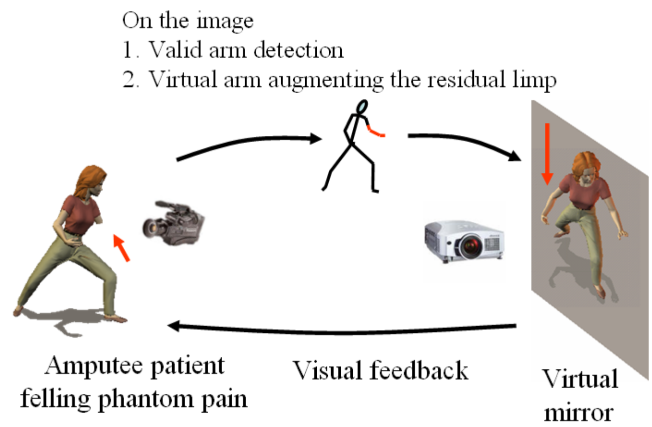

Fig. 2. Our purpose is to setup a magic mirror where an amputee is seeing his reflected image augmented by a virtual limb in order to trick his proprioception. Our system consists of one camera acquiring images of the amputee.

III. Our system: the mirror process in augmented reality

Our system consists of one camera acquiring images of the amputee moving his two arms (valid and residual limp). Our general purpose is to trick the amputee proprioception by interactively showing his image as a mirror except we add a virtual limb moving as the phantom limb (see Figure 1). We decided to use a single camera (instead of several) for the capture since we believe this kind of system could be used, in long term, by amputees at home. Then, simple materials has been preferred. The position values of our camera are constants set manually. Others assumptions are none camera motion, constant lighting and static background.

To determine the phantom arm position and movement, the only clue is the position and orientation of the residual limp. We decided to constraint the patient movement to quasi-symmetric one. Since previous systems were based on physical mirror, movement had to be perfectly symmetric to correctly match. Our computer-based system adapts the virtual arm position in order to always provide exact continuity with the residual limp. At shoulder level, the valid arm and the residual limp dose not have to be perfectly symmetric[1] Visual realism is be crucial to augment the belief of the subject. Our first try

[1]Notice that our system accepts any desynchronization between valid and amputated sides. Nevertheless, large one could lead to non realist arm posture, so we forbid them.

was to synthesize the virtual arm with a textured 3D mesh. Nevertheless, lack of visual realism due to differences between synthesized part and real part leads us to discard this solution.

Our posture detection algorithm needs restrictions on the movements of the subject: the subject remains inside the workspace, more or less straight, always facing to the camera and performing quasi-symmetric movement between remaining arm and phantom one. During our algorithm test, we decided to use a blue fabric rolled around the arm, so that we can easily simulate different amputation types.

A. Overview

The preprocess of our method is in two steps. First, we learn background characteristics in order to later extract the subject silhouette from the background during the tracking. Second in section IV, by asking two particular postures to the subject we acquire anthropometric values of the tracked subject.

During the tracking, for each frame, we perform our interactive algorithm. First described in section V, arms posture are estimated from the silhouette. Second described in section VI, the valid arm image is used to create a virtual arm on the amputated side. Finally, we will show some results and conclude in section VII.

B. Background substraction

In preprocessing, our method learns the background in order to extract the subject silhouette from the background. This learning allows to easily use our system in different places (amputee home, etc.). On N frames showing only the background, we compute for each pixel the maximum and minimum of each RGB values. Then, a pixel belongs to the background if his RGB values are all three included into the pre-computed ranges. Background is set to black and silhouette to white. To remove the noise, we perform a connectivity search algorithm starting from the nearest white pixel of the barycenter silhouette which gives an usable silhouette.

IV. Anthropometric measures

Anthropometric measures of the subject will be used later during the interactive arm posture estimation. To determine these anthropometric measures, we ask the subject two particular postures shown on Figure 3. We named these two postures: $pose_1$ on the left and $pose_2$ on the right. We subtract the background to these two images and segment them in order to get two binary images of the silhouette.

A. Head and torso measures

Notations used in this section are described on Figure 4. We use the binary image of $pose_1$ (bottom left of Figure 3) to measure head and torso values. Our algorithm determines the skull highest point which is on the head. Then, it computes head measures in several steps. Starting from the highest pixel our algorithm goes down the image as long as the number of white pixels per line increases. So, we get an approximate width of the head $w_{\tilde{head}}$. Then, it still goes down until the number of white pixels per line will be superior to

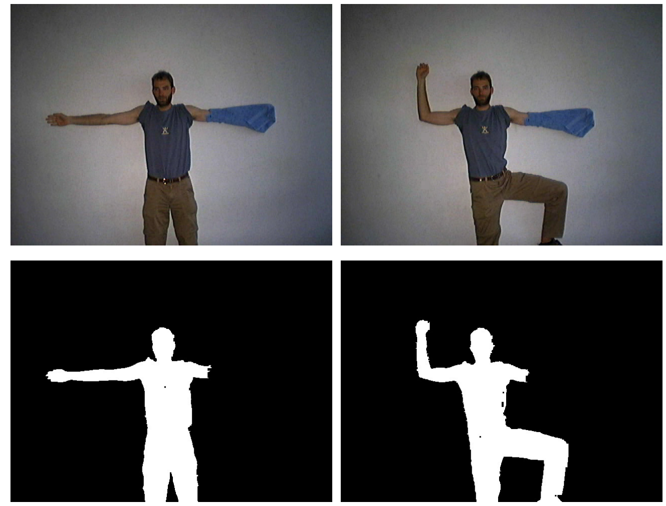

Fig. 3. To automatically measure anthropometric values, we ask to the amputee two particular postures. Note that the blue fabric rolled around the arm is to simulate any level of amputation in order to easily test the robustness of our algorithm.

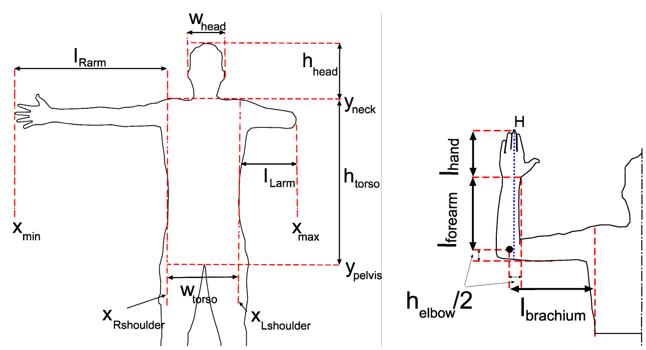

Fig. 4. Anthropometric measures of the subject will be used during the tracking of the movement.

$1.3 * w_{\tilde{head}}$ which should be the beginning of the shoulders. This horizontal line y_{neck} just found corresponds to the base of the neck. So, we get the head height h_{head} thanks to the top of head and the base of the neck. Finally, we determine the head width w_{head} as the maximum width of lines between the top of the head and y_{neck}.

Our algorithm then computes the height of the torso h_{torso} which is defined by the length between the base of the neck and the beginning of the legs separation. On posture $pose_1$, the subject has to separate a bit his legs. To get the beginning line of the legs our algorithm starts from the barycenter, goes down until it gets two separates white segments. This line is named y_{pelvis}. Thus, $h_{torso} = y_{neck} - y_{pelvis}$. The torso width w_{torso} is obtained by taking the width of the line $(y_{pelvis} + y_{neck})/2$. We deduce from this width and from the column of the top of the head the columns $x_{Rshoulder}$ and $x_{Lshoulder}$.

B. Arms measures

Always on the $pose_1$ binary image, our algorithm finds x_{min} and x_{max} corresponding to the minimal and maximal columns. The length of the left arm l_{Larm} and the right arm

l_{Rarm} are then given by

$$l_{Rarm} = x_{Rshoulder} - x_{min} \quad (1)$$
$$l_{Larm} = x_{max} - x_{Lshoulder} \quad (2)$$

These two values indicate the side and the proportion of the amputation. To simplify our notation, in the following of the article we will note symbol with the factor v for the valid side (where the remaining intact arm is) and with a for the amputated side. We also compute the diameter of the elbow h_{elbow} by counting the number of white pixels of the middle column between $x_{min|max}$ (depending on the amputated side) and $x_{shoulder}$.

Then, we use the posture $pose_2$ to compute forearm, brachium arm and hand measures. On the valid arm side, we determine the more distant column from the shoulder. This column is on the forearm or on the hand which does not matter for our computation. Then, from this column, our algorithm goes toward the shoulder by counting the number of white pixels in each column. It keeps the maximum y value and stops when the column size significantly decreases which means we have left the forearm. This maximal y value gives the upper point H on the hand (See Figure 4 on the right). The height of the column going through H is $l_{hand} + l_{forearm} + h_{elbow}/2$. We subtract this value to the arm length l_Rarm to get the brachium length $l_{brachium}$. Then, to get the hand's height, our algorithm goes down starting from H, counts the line width and stop when it significantly decreased to find the border line between the hand and the forearm. Thus, we compute l_{hand} and $l_{forearm}$.

V. Real time valid arm posture detection

The previous section describes preprocess of our algorithm. Limbs measures will not change so we can use them during the tracking. On each frame the silhouette moves so the values $y_{neck}, y_{perlvis}, x_{min}$ and x_{max} can not being used. For each video frame, we have to estimate the valid arm posture in order to use it in the generation of the virtual arm. In this section, we describe how during the capture we track the valid arm posture.

A. Head and torso detection and segmentation

The first step of this part is to determine the head and the torso in order to be able to work only on the arms. Basically, this step is to segment arms. One can see an example of head and torso segmentation on Figure 5.

By considering the barycenter column of the silhouette, we obtain a point on the top of the head. Starting from this point, a connectivity search algorithm fills the head by taking into account head sizes w_{head} and h_{head} computed during the preprocess (See section IV). This step allows to compute Y_{neck} which defined the line between the torso and the head. We use the x value of the head barycenter as medial column X_{medial} because the barycenter of the whole silhouette is corrupted by the amputation. We segment the torso in a similar way we have done with the head: starting from the silhouette barycenter we apply a connectivity search algorithm constrained by the box

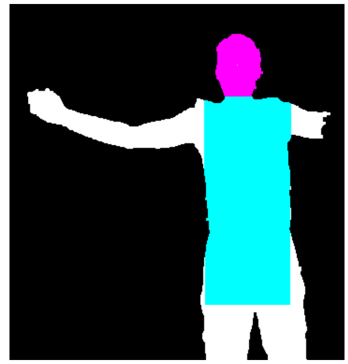

Fig. 5. The first step of our algorithm is to determine the head and the torso in order to be able to work only on the arms.

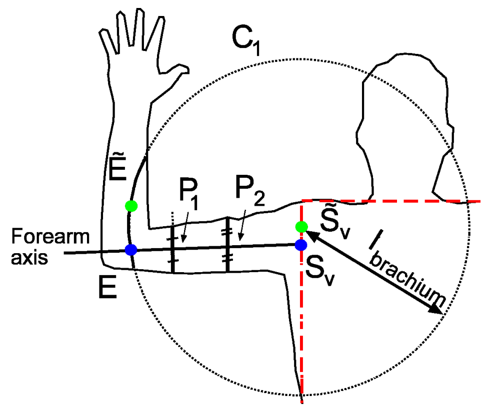

Fig. 6. Our tracking process consists in the determination of the shoulder, the elbow and the wrist positions of the both side: the valid-arm side and the amputated side.

y_{neck}, $y_{neck} - h_{torso}$, $X_{medial} - w_{torso}/2$ and $X_{medial} + w_{torso}/2$.

B. Shoulder, elbow and wrist detections

The segmentation of the head and the torso allows to work without any perturbation on the arms. We detail now the way we determine shoulder, elbow and wrist positions. Let define $\tilde{S}_v$ and $\tilde{S}_a$ two approximal shoulder positions: $\tilde{S}_v$ on the valid limp side and $\tilde{S}_a$ on the amputated limb side. Later we will refine these values to get better shoulder positions S_v and S_a. According to anthropometric statistics [TA93], we assume that shoulder positions are about $h_{torso}/12$ under the neck line Y_{neck} and half of the torso width $w_{torso}/2$ on each side of the medial column X_{medial}.

Once those approximal shoulder positions defined, we analyze the posture of the valid arm. We consider the circle C_1 center on $\tilde{S}_v$ and of radius $l_{brachium}$ as shown on Figure 6. Since the head and the torso were segmented in order to not being considered, this circle only intersects the valid arm on an arc of circle. We set the middle of this arc as our approximal elbow position $\tilde{E}$. Thus, to better estimate $\tilde{S}_v$ and $\tilde{E}$, we define two points P_1 and P_2 on the axis $\overrightarrow{\tilde{S}_v\tilde{E}}$:

$$P_1 = \tilde{S}_v + \overrightarrow{\tilde{S}_v\tilde{E}}/3 \quad (3)$$

$$P_1 \quad = \quad \tilde{S}_v + 2\overrightarrow{\tilde{S}_v \tilde{E}}/3 \qquad (4)$$

¿From those two points we search the intersection between the brachium and the column. The two centers of those intersections give a precise forearm axis. We then deduce a better elbow E and shoulder positions S_v. E is the intersection between the brachium axis and C_1. S_v is the intersection between the brachium axis and the column of $\tilde{S}_v$.

Finally for the valid limb, we search the wrist. We define a circle center on E and of radius $l_{forearm}$ which intersects the forearm silhouette. We use the middle of this intersection as wrist position W.

C. Residual limb detection

Depending on the level of amputation we have two different schemes detection.

If the amputation is above-elbow, we compute the middle of the column going though the residual limp barycenter. The residual limb axis is then the line starting from S_a and going through this middle point.

If the amputation is below-elbow, we compute the elbow and the shoulder positions similarly than for the valid arm side. Then, we search the most distant white pixel from the elbow position limited by the forearm length. The line going through the elbow position and this point is the residual forearm axis.

VI. Arm mirror

In this section, we describe how we create the virtual arm image based on a valid arm copy. Arm movement detection described previously on section V gives several positions as described on Figure 7. We assume the camera is orthographic in order to reproject the valid arm without any perspective correction. We define a 2D coordinate system for the valid side and for the amputated side. First, we set the origin O_a of the amputated coordinate system on the barycenter of the residual limb which could be the residual brachium or the residual forearm. The distance between O_a and S_a or E_a depending on the amputation type (below or above elbow) is reported to the valid side to set the origin O_v of the valid side coordinate system.

The arm axis normalized define the X axis. For the valid side: the origin is O_v, the first axis X_v is the vector $\overrightarrow{S_v E_v}$ or $\overrightarrow{E_v W}$ normalized and the second axis $\overrightarrow{Y_v}$ is the normal vector to $\overrightarrow{X_v}$. The amputated side coordinate system (O_a, X_a, Y_a) is determined similarly and with a mirror effect to choose the Y_a direction. Indeed, the sign of the angle between X and Y has to be opposed between the valid side and the phantom side. A pixel A_v of image coordinates (x_I, y_I) has for coordinates (x_v, y_v) in the valid-side coordinate system:

$$x_v \quad = \quad \overrightarrow{S_v A} \cdot \overrightarrow{X_v} \qquad (5)$$

$$y_v \quad = \quad \overrightarrow{S_v A} \cdot \overrightarrow{Y_v} \qquad (6)$$

These coordinates are then reported in the amputated side coordinate system to find the pixel A_a of image coordinate

$$A_a = \overrightarrow{S_a} + x_v \times \overrightarrow{X_a} + y_v \times \overrightarrow{Y_a}$$

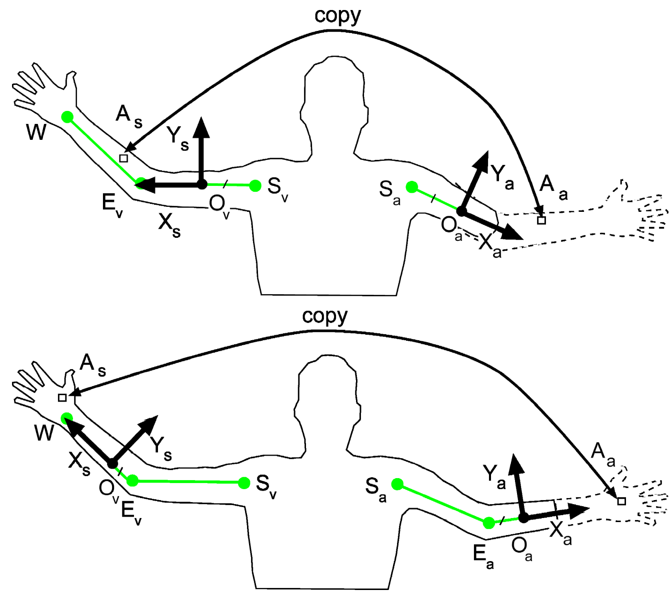

Fig. 7. The valid arm sub-image is used to create a virtual arm on the amputated side depending on the level of amputation (amputation between the shoulder and the elbow on the top and after the elbow on the bottom). For that, we define two coordinate systems for the both sides and each pixel of the valid arm side is copied to the amputated side.

To reproject the whole valid arm we perform a connectivity search algorithm on the valid arm silhouette without considering pixels between S_v and O_v. For each pixel A_v of this arm, we reports the RGB value to the corresponding pixel A_a. To avoid discontinuity between the real limb and the virtual one we apply a Gaussian filter on pixels around O_a.

VII. Results and conclusion

We implemented our method on a Pentium 4 2.8Ghz; the graphics board was a GeForce FX5200; the camera was a web cam Philips ToUCam Pro. To simulate an amputation we use a blue fabric rolled around the arm. This has the main advantage to easily test our algorithm with different levels of amputation in order to sustain the robustness of our method. Figure 8 shows a sequence coming from a video capture. The first line shows the original image without the blue. The second line shows the head and torso segmentation and the tracked skeleton. The third line is the final result with the valid arm copied on the the phantom side. Our implementation is interactive and process a frame in 160 to 180 ms:

- silhouette computation: 50 to 60 ms
- movement analysis: 50 to 60 ms
- mirror process: instantly
- Gaussian filter: 10 ms

The preprocess of computing anthropometric measures (See section IV) takes around 1.2 seconds.

As firstly shown in [RRR96], [GS03] with a physical mirror or with prerecorded movement movies, giving an image of his complete body to an amputee leads to a sense of re-embodiment in the virtual limb and hence to a reduction of the pain. In the same way, we developed a system in a augmented

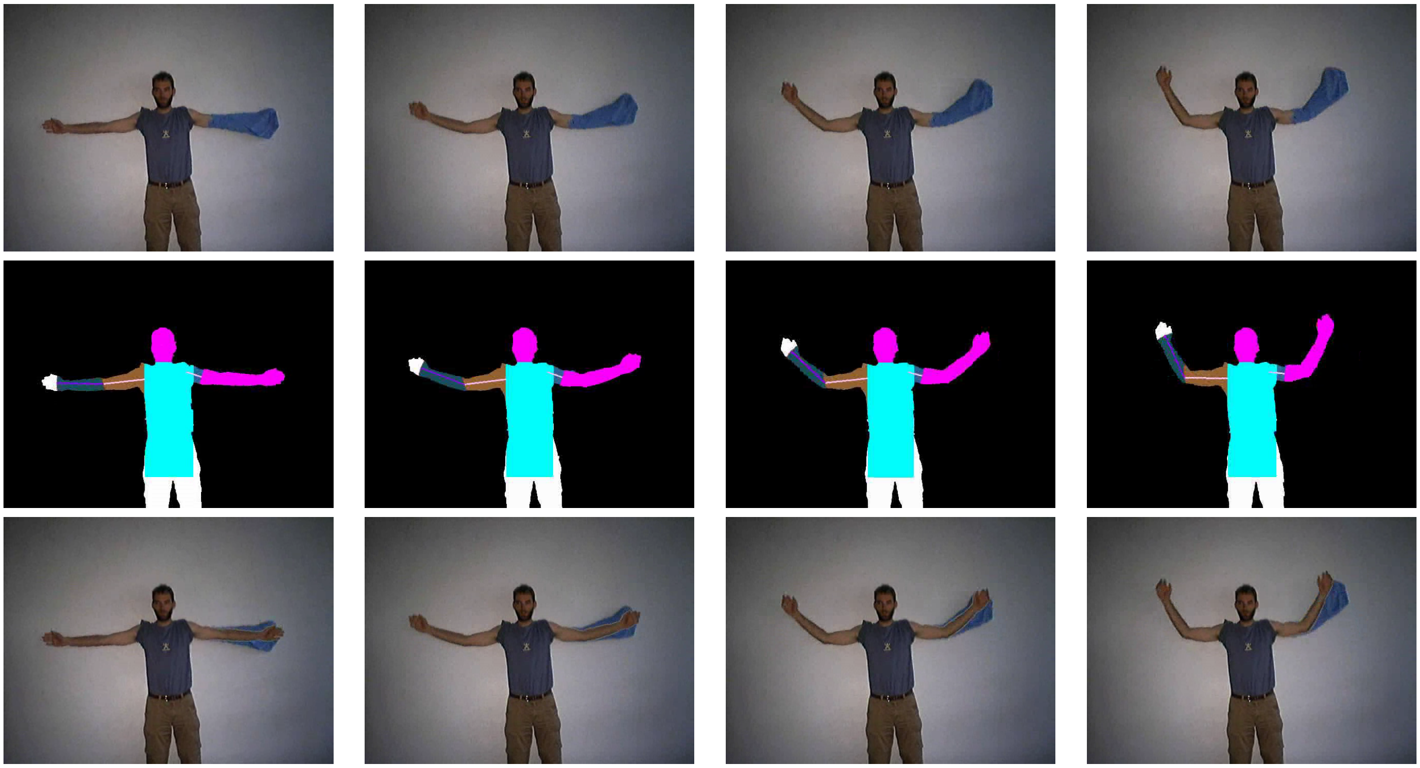

Fig. 8. The first line shows the original frames with the blue fabric. The second line shows the head and torso segmentation and the tracked skeleton. The third line shows the valid arm copied on the phantom side.

reality context. Comparing to previous system, our technique is able to treat higher level of arm amputation than the hand and allows desynchronized movements between the valid and the phantom arm at shoulder level. These two improvements should allow to address this kind therapy to larger scale of amputees.

Currently, we are working with Pascal Giraux and Angela Sirigu -from the Cognitive Science Institute in Lyon- who have leaded previously mentioned experiment on hand amputation [GS03]. We are planning to test our system with arm amputees very soon. Thus, we hope to demonstrate the potential of our system to subjects which were stayed insensitive to previous system dedicated to hand only amputation. Moreover, by allowing more freedom we could also expect a better impact rate.

According to amputee feedbacks we will work at increasing our system. In particular, we are conscious that the strong movement constraints of our method can be a limitation. So, we are planning to use texture information in conjunction with the silhouette to solve ambiguous posture *i.e.* where the arm is confounded with the trunk.

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