



Quantitative Assessment of Upper Limb Rehabilitation through Digital Motion Acquisition

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Abstract. Motion capture (Mocap) systems are considered more and more interesting for the assessment of rehabilitation processes. In fact, medical personnel are increasingly demanding for technologies (possibly low-cost) to quantitatively measure and assess patients' improvements during rehabilitation exercises. In this paper, we focus the attention on the assessment of rehabilitation process for injured shoulders. This is particularly challenging because the recognition and the measurement of compensatory movements are very difficult during visual assessment and the movements of a shoulder are complex and arduous to be captured. The proposed solution integrates a low-cost Mocap system with video processing techniques to allow a quantitative evaluation of abduction, which is one of the first post-surgery exercises required for shoulder rehabilitation. The procedure is based on a set of open-source software tools to measure abduction and evaluate the correctness of the movement by detecting and measuring compensatory movements according to the parameters commonly considered by the physicians. Finally, a preliminary results and future works are presented and discussed.

Keywords: Motion Capture, Microsoft Kinect v2, Embedded Knowledge, Medical assessment, Post-surgery shoulder.

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1 INTRODUCTION

During rehabilitation processes the orthopedic physicians, surgeons and physiotherapists have to perform several assessments to evaluate the patients' condition. Usually, they assess the improvements through the evaluation of the rehabilitation exercises the patient has to do for recovering his/her physical abilities after an injury or a surgery. Typically, this evaluation is based on several parameters, which are consolidated by the experience obtained during daily practice; however, their assessment heavily depends on the physicians' subjectivity due to an observational approach.

Nowadays, one of the most promising approaches for motion analysis is based on the use of Motion Capture (Mocap) systems. Among the available technologies, the markerless solutions are attracting more and more attention. However, introducing a markerless system for patients' movements evaluation requires facing technological issues to guarantee the accuracy of acquired measurements, such as the number of devices and the acquisition layout. For this aim, a roadmap has to be defined for solving technical problem and making the use of a Mocap system a repeatable and accurate procedure.

In this paper we focus the attention on the rehabilitation of a shoulder after trauma or surgery. The shoulder articulation is considered one of the most complex human body districts to be rehabilitated since it comprehends several muscles, tendons and bones, which perform a specific task according to the motions of the respective arm. Therefore, visual assessment has to be very specific to clearly understand if the patient is performing the exercise in the correct way. There are several exercises for shoulder rehabilitation; abduction and adduction are the first steps for recovering the normal use of the shoulder. They are basic exercises but hard to be evaluated through a visual approach because the error consists of small translations of the shoulder. In particular, the medical assessment is based on the identification of compensatory movements performed during the exercise and this is a challenging issue using a marker-less Mocap system.

The objective of this research is to provide the physiotherapist with a tool that allows him/her to analyze and quantify some aspects of the patient's movements in order to avoid exercises incorrectly performed and define a personalized and effective rehabilitation plan. The solution has to be at low-cost both as far as concerns devices and software. The use of open-source libraries is preferred to make the application easily portable on different platforms, such as Microsoft Windows and Apple iOS. The solution should also be portable, quickly installed and set-up in a rehabilitation center, and, even at patient's home.

First, the scientific background is introduced as well as the general framework we refer to develop and implement the specific solution. Then, we introduce the exploited solution based on the integration of low-cost markerless Mocap system and image processing techniques. Finally, the preliminary tests carried out in collaboration with the medical personnel and the outcomes are presented and discussed.

2 SCIENTIFIC BACKGROUND

At present, literature shows many contributions involving Mocap systems and software platforms to study the kinematics of human body articulations for rehabilitation purposes [4], [12]. For example, Colyer et al. [2] describes the evolution of MOCAP systems through a wide state of art, which underlies how MOCAP solutions have been improved from the first manual approaches of optoelectronic marker-based systems to the last generation of markerless motion capture systems. Proença et al. [14] present a systematic review of serious games mainly based on low-cost Mocap systems for upper limb rehabilitation.

Regarding shoulder rehabilitation, traditional procedures involved trained observers (e.g., physiotherapists and orthopedic physicians) who assess the shoulder rehabilitation by means of goniometers, questionnaires [10], camcorders, or visual estimation [9]. In order to introduce quantitative measurements, optical Mocap systems have been increasingly introduced and considered as an optimal solution to analyze shoulder rehabilitation. Some researchers exploited marker-based solutions, such as Vicon and Qualysis. For example, Tang et al. [18] described the use of Vicon-based system for guiding patients through physiotherapy exercises at home. Sousa et al. [17] developed a software module based on the Optitrack system to evaluate in real-time both abduction/adduction and elevation/depression of shoulders. Even if these solutions have demonstrated good accuracy, they are not easily accessible to the patients due to their high costs and required dedicated space. In addition, the need of markers on the patient's body can cause discomfort and limitation of movements. Other researchers adopted low-cost markerless devices, such as RGB-D sensors [3], [6], [11]. For example, Domingues et al. [3] developed a software

application to detect compensatory movements by using a Microsoft Kinect v2 device. The application, developed in Unity, permits to get various parameters, such as the number of correct repetitions, the path and the targets of the executed exercises. This solution identifies where the compensatory occurs but does not provide a direct measure. Gal et al. [5] and Zhao et al. [22] exploited a single Kinect sensor to evaluate abduction and adduction of an arm. This approach has been adopted to emulate the traditional approach during which the physiotherapist performs a visual assessment by monitoring abduction and adduction only along the frontal plane. In particular, they aim at recognizing specific patterns of the rehabilitation exercises to give a real-time feedback of patient's performance. Anyway, there was no a direct detection and measurement of shoulder movements and in particular for the compensatory movements.

Finally, regarding accuracy, some research works demonstrated how low-cost markerless systems permit to get results good enough for medical applications compared with those obtained with better performing but more expensive solutions. Otte et al. [13] used simultaneously the Vicon system and a single Kinect v2 to record movements of arms during six different movement tasks. The accuracy of Kinect V2 landmark movements was moderate to excellent and depended on movement dimension and performed task. The medical personnel considered the measurement error not relevant to assess motion for clinical purposes. Wilson et al. [20] studied the accuracy of a markerless system composed by a laptop with a Kinect v2 device compared with trained observers and using the Vicon system for the validation of the acquired data. Also, in this case the medical personnel considered the Kinect v2 a valuable tool to assess the shoulder rehabilitation process and acceptable the accuracy of results.

Given our aim, a technical solution based on RGB-D sensors seems to be the most suitable one to direct measure compensatory movements thanks to their flexibility, portability and ease of use. In fact, this kind of solution can be easily installed at a physiotherapy facility or at home and suitable to different needs and rehabilitation exercises.

3 REFERENCE ROADMAP

Medical knowledge and technological solutions have to be correlated in a clear way with the aim to create procedure and applications, which are really useful for improving the medical assessment. On the basis of previous experience carried out to design medical devices and assess gait of hemiplegic patients or pushing cycles of people on a wheelchair [19], we have developed a reference roadmap (Figure 1) to guide the development of Mocap solution for rehab assessment, which can significantly differ in terms of system set-up and data elaboration, depending on the involved body segment and performed activity.

The Roadmap foresees five main steps, not necessarily sequential [16]:

- *Knowledge acquisition.* At first, interviews to domain experts are required to collect and formalize rules and guidelines related to the specific activity (e.g., how to perform exercise and evaluation parameters). This task will heavily influence the following steps since it will contribute to the definition of the Mocap layout, acquisition protocol and medical rules-acquired data correlation.
- *Mocap system setup.* This step consists in defining all what is relevant for setting up the acquisition phase. The volume of acquisition has to be defined according to the space useful for acquiring the whole exercise performed by the patient. Specifically, number of used sensors and their position are identified as well the definition of the best calibration method. It also includes the planning of the acquisitions.
- *Motion acquisition.* This is the most repetitive part and it can be performed almost in the same way for any kind of application. The motion acquisition is more than the action of recording a movement because it has to consider also possible criticalities that could happen. For example, the patients should be advised to wear cloth as skin as possible in order to obtain the best acquisition of their movements. Furthermore, acquired data (e.g. videos,

point clouds and virtual animations) have to be managed through a storage system to make available information requested by medical personnel.

- *Knowledge elaboration*. This step is the most challenging because it has the goal to translate guidelines and rules into algorithms and routine able to extract the right information from the Mocap data in automatic way. The algorithms have to be able to extrapolate from raw data the useful parameters defined in the first step.
- *Data elaboration*. Elaborated data are presented through an ad-hoc designed user interface, which permits to graphically visualize the outcomes so that the medical staff can easily identify problems and corrective actions and, at the same time, the patient can understand when and why he/she executes the rehab exercise in a wrong way. Usually, the user interface makes available a feature for generating medical report in standard file format, such as PDF and CSV.

The next sessions describe the application of the roadmap for a specific rehabilitation procedure to verify the technical feasibility of the proposed solution. In particular, after the two first two steps we focused the attention on the motion acquisition and knowledge elaboration, which are most critical ones due to the complexity of the shoulder articulation.

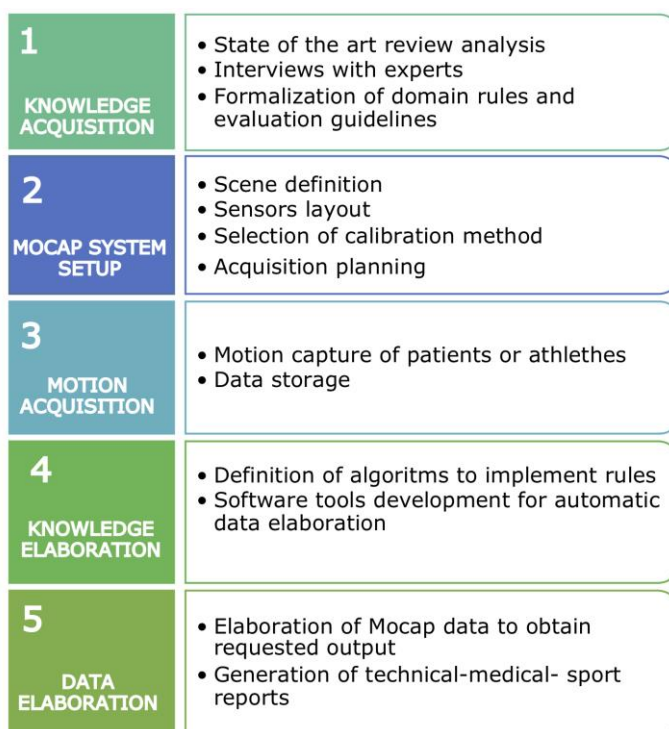


Figure 1: Reference roadmap.

4 KNOWLEDGE ACQUISITION

The medical knowledge has been acquired through the collaboration with a rehabilitation center and the relevant scientific literature [7], [15]. A shoulder articulation comprehends three bones, i.e. the scapula, the clavicle and the humerus. Furthermore, there are many muscles and tendons connected to these bones, which are activated in a very complex way for performing movements. One of the basic movements of a shoulder articulation is obtained through the abduction of the arm. The

abduction exercise consists in rising the extended arm on the frontal plane from the rest position along the body (Figure 2(a)) to a horizontal position (Figure 2(b)) and up to the limit the patient can reach (Figure 2(c)). Therefore, the correctness of an abduction is strictly correlated with movements performed by the scapula (namely scapular elevation).

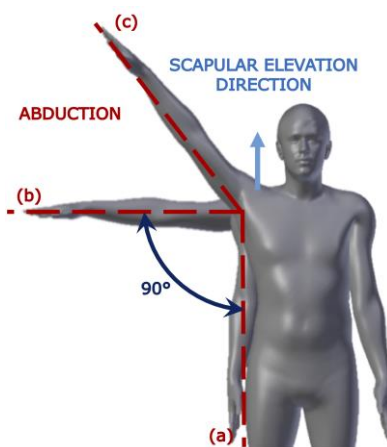


Figure 2: Abduction exercise.

The scapular elevation involves different muscles that should not be used for executing abduction movement. Therefore, the scapular elevation is considered a compensatory movement when it happens during an abduction. This usually happens because the patient has pain when he/she moves injured shoulder using correct muscles for abduction. Thus, the goal of the rehabilitation is to re-activate all muscles to perform the basic movements in an as natural as possible way. According to the physiotherapists' knowledge, the arm abduction is correctly executed if there is no scapular elevation before reaching the horizontal position (Figure 3(a)). The physiotherapist provides us with an empirical threshold: if the scapular elevation is more than 2 cm, the abduction is affected by a compensatory movement (Figure 3(b)).

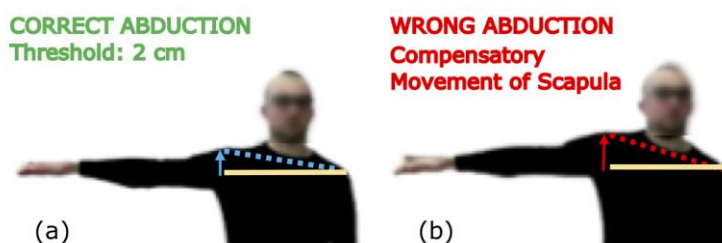


Figure 3: (a) Correct abduction; (b) Wrong abduction.

5 MOCAP SYSTEM SETUP

The low-cost markerless Mocap system should be based on one or multiple Microsoft Kinect v2 devices. The number and the placement of Kinect v2 depend on its technical features [21] and the way the rehabilitation exercises have to be recorded to get the best accuracy.

Since the abduction is visually assessed only in the frontal plane, the system has been configured with a single Microsoft Kinect V2 sensor. Its placement has to guarantee a full body acquisition

during the exercise. The device has a field of view that allows an accurate full body acquisition when the person is positioned to a distance between 2,1 meters and 4 meters in front of it; moreover, its height has to be defined in order to be aligned with the upper part of the human body. According to these requirements, the Kinect V2 has been positioned at a distance of 270 cm and a height of 122 cm in front of the patient (Figure 4).



Figure 4: Layout of the Mocap system.

6 MOTION ACQUISITION & KNOWLEDGE ELABORATION

Motions acquisition is performed using a software platform that manages data acquired by the Kinect v2 sensor connected to a laptop by an USB 3.0 port. There are several software packages that can be adopted for each step to create the virtual skeleton of the recorded person. In this case, we decided to use a low-cost commercial solution named iPiSoft suite [8]. It is mainly composed by two software applications, iPi Recorder and iPi MOCAP Studio. iPi Recorder allows managing the motion acquisition by a user interface that permits to easily execute the recording of the motions. iPi MOCAP Studio exploits recorded data (i.e., RGB videos and depth point cloud) to generate the virtual skeleton.

The next section describes the limits of a system based only on RGB-D data and on an oversimplified skeleton model as well as the new proposal based on the integration of video and image processing techniques considered to overcome identified limits. The new acquisition procedure is based on an open-source software, namely Blender [1], in order to be in line with the low-cost philosophy. Finally, the application developed to automatically assess the abduction is presented.

6.1 Motion Acquisition Issues

The measurement of the scapular elevation can be done by considering the vertical translation of the virtual clavicle joint on the frontal plane; however, an important limit has been identified about the accuracy of tracked motions. The virtual skeleton generated by iPi MOCAP studio does not correctly emulate the movement of the shoulder and thus, the measure of the scapular elevation is not coherent with the real one. Figure 5 illustrates the point cloud and the virtual skeleton of a patient. Figure 5(a) depicts the time-frame before performing the abduction and the position of the virtual clavicle joint can be considered overlapped to the real one. Figure 5(b) and Figure 5(c) show the patient rising the shoulder as in a compensatory movement. In this case, the point cloud shows a high scapular elevation, but the position of the clavicle joint is remarkably lower. Therefore, the conventional solution is not adequate for measuring the scapular elevation and detecting the compensatory movement.

To solve this problem, a new procedure has been designed by integrating image processing techniques to improve the measurements accuracy.

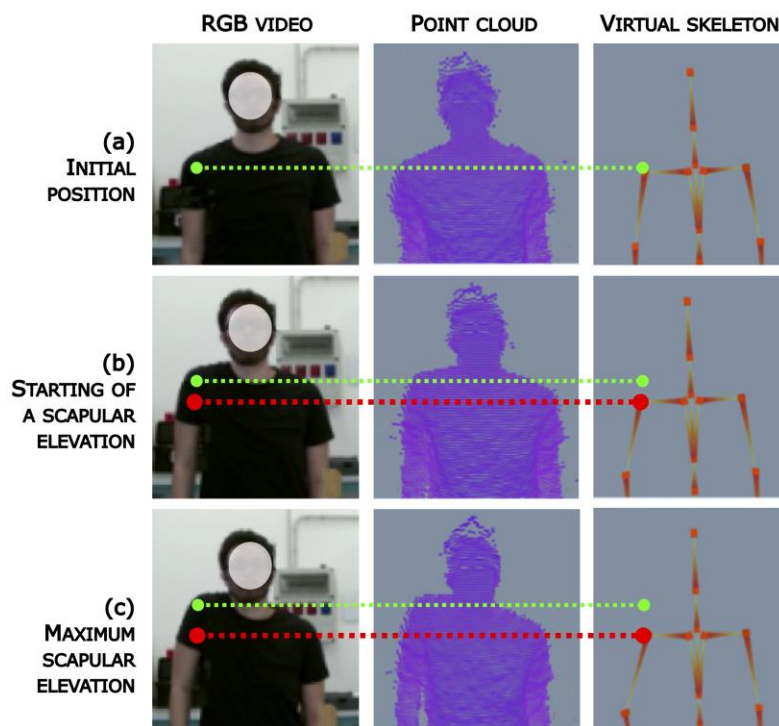


Figure 5: The images show a temporal sequence during which the generated virtual avatar does not follow the point cloud of human body during the scapular elevation.

6.2 Proposed Solution for Scapular Elevation Detection

RGB images and 3D point cloud acquired with the Kinect v2 sensor can be exploited in an alternative way. The RGB data (i.e., the recorded video) can be used to find the vertical translation of the scapula through image processing techniques to track the movement of an object in a video sequence. The proposed solution exploits 2D motion tracking techniques by starting from the recorded video. The 2D motion tracking is possible through video processing algorithms that are used to detect movements of simple shapes (e.g., a square or a circle). In particular, we have adopted Blender, an open-source software, since it makes available a powerful motion tracking tool. This tool permits to detect the movement of a single point on the body; however, the evaluation of a rehabilitation exercise requires multiple body segments (e.g., shoulder, arm, neck and spine) connected in a virtual skeleton. To achieve this result, the tracked point movement has to be associated to the bone of the virtual skeleton and this is possible if the camera's position is known as in our case. The acquisition based on iPi Soft Studio allows us to automatically calibrate the position and the orientation of the device and the data can be used in Blender to create a virtual camera with the same features. Then, the motion tracking tool exploits 3D information to compute the 3D motion of the tracked object. Finally, the 3D motion can be associated to an existent 3D object such as the clavicle joint of the animated skeleton, that can be imported in Blender in BVH file format.

Figure 6 shows the implemented procedure. First, a simple square of white adhesive tape has to be applied on the extremity of the injured shoulder as tracking marker. The marker can be applied

either on the skin or tight clothes near to the acromial end of the clavicle because its movement reproduces what happens during the abduction. Once the acquisition is executed, the initial virtual skeleton is generated from the video and the depth data by using iPi Soft Studio. The scapular elevation is detected through the 2D motion tracking tool, which automatically detects and tracks the white marker.

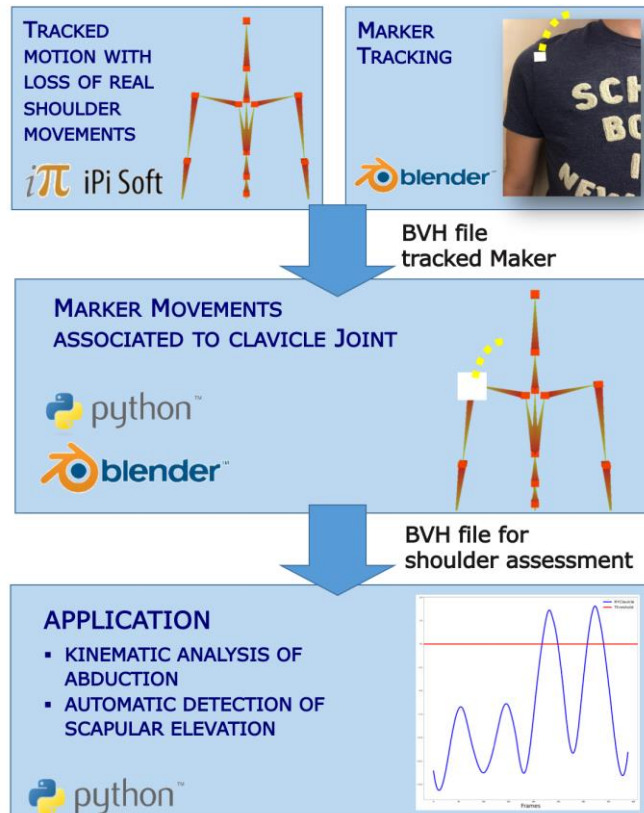


Figure 6: Workflow of the new solution.

After the 2D tracking, a virtual camera is created in Blender according to the Kinect device position and orientation computed in iPi Soft Studio. The marker tracking movement lies on a plane that has to be overlapped to the plane defined by the skeleton in the T-Pose. The translation of the marker describes the trajectory of the patient's clavicle joint. Therefore, the recreated 3D scene permits to associate the 2D motion of the marker to the virtual clavicle joint of the initial virtual skeleton to get the correct 3D movement (Figure 7). The modified virtual skeleton is exported in BVH file format by Blender and is used as input data in an ad-hoc developed application.

6.3 Developed Application

A software module has been developed in Python language to automatically execute the procedure above-described. The application permits to elaborate data coming from an acquisition including several arm elevations and graphically plot outcomes.

The motion data of the clavicle joint is used to evaluate the scapular elevation according to the threshold defined in section 4. If the scapular elevation is higher than the threshold, the application automatically highlights that the abduction is performed in a wrong way.

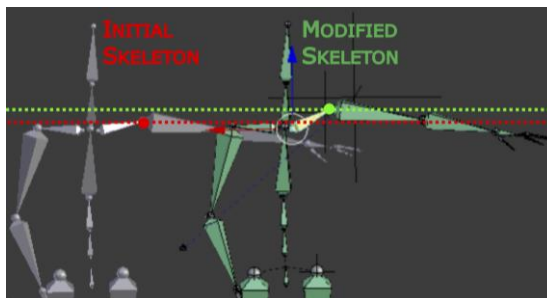


Figure 7. Comparison between the initial skeleton from iPiSoft and the modified skeleton using marker tracking.

Data can be differently shown depending on the user. If the user is the physiotherapist, the user interface shows the total number of detected abductions, the presence of compensatory movements of the scapula and its relative measurement in centimeters. Furthermore, a graph is plotted to show the scapular elevation (Figure 8(a)). On the other end, if the user is the patient, it has been implemented a simplified user interface with an intuitive colored and smiley feedback (Figure 8(b)). The green smile means that all the detected abductions have been correctly performed and thus, there are no compensatory movements. The yellow one indicates that some abductions exhibit a scapular elevation, whose value is below the threshold less than 5 mm. Finally, a red smile means the presence of a remarkable compensatory movement.

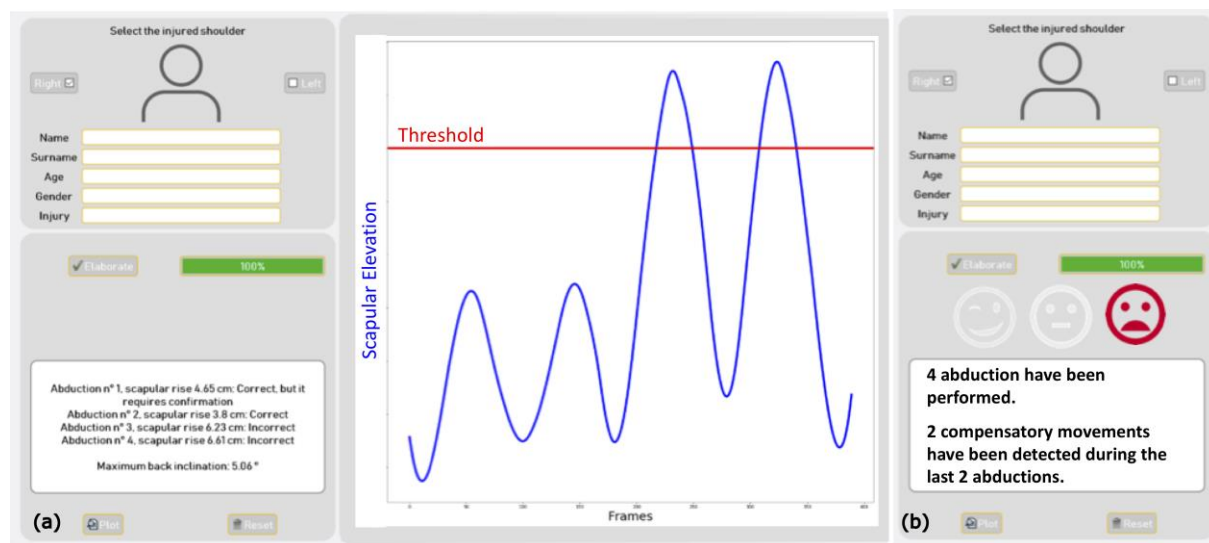


Figure 8: (a) User interface for medical personnel; (b) User interface for patients.

7 PRELIMINARY TEST

A preliminary campaign has been performed to test the procedure. We involved a physiotherapist for the medical assessment and fifteen volunteer engineering students. The testers were between 23-26 years old without shoulder injuries. Each of them has been asked to execute a simple shoulder

rehabilitation exercise composed by 4 arm abductions, the first two done in a correct way and the last two rising the shoulder before 90° rotation (i.e., performing a compensatory movement of the scapula) of the arm. During the acquisitions of each volunteer, the physiotherapist assessed the abduction movements by means of the traditional observational method and his evaluations were compared with the results automatically gained with the proposed solution.

The average end-to-end processing time of the workflow is approximatively 5 minutes for each acquisition.

Table 1 reports the 60 measured scapular elevations.

		Subjects														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Scapular elevations (cm)	Abd. 1	1.2	1.4	1.3	1.4	1.2	1.3	1.4	1.3	1.1	1.4	1.1	1.6	1.5	1.6	1.5
	Abd. 2	1.1	1.3	1.2	1.2	1.4	1.4	1.6	1.7	1.2	1.2	1.3	1.6	1.4	1.3	1.6
	Abd. 3	2.5	2.3	2.6	2.8	2.2	2.8	2.9	2.7	2.5	2.7	2.6	2.3	2.2	2.8	2.6
	Abd. 4	2.7	2.5	2.4	2.5	2.7	2.9	2.7	3.1	2.9	2.9	2.8	2.7	2.8	2.6	2.8

LEGEND: value < 1.5 cm
 1.5 cm ≤ value < 2 cm
 value ≥ 2 cm

Table 1: Scapular elevations.

We can observe that all the exercises performed in the wrong way, according to the physiotherapist, have been correctly evaluated as “wrong” (red cells, abduction 3 and 4) by the application. We have considered an uncertainty range (from 1.5 to 2.0 cm) in which the physiotherapist should further investigate patient’s performance. This is because there could be an estimated error below 0.5 cm. Therefore, concerning abductions 1 and 2, which are correctly executed for the physiotherapist, the system classifies them in two groups:

1. Exercises, which are surely performed in a correct way (green cells) and the measured value is significantly below the zone of uncertainty, i.e., 1.5.
2. Exercises, which the physiotherapist has considered correctly executed but the measured value is in the zone of uncertainty.

The second group of values has been highlighted to give a warning to the physiotherapist about potential critical conditions that could require further assessments.

The use of the marker has been necessary to measure the exact elevation of the scapula because using only the Kinect sensor we were not able to reproduce the movement of the virtual shoulder joint. The accuracy of the automatic marker detection has been determined comparing the shoulder silhouette displacement with the marker displacement along the vertical direction. This has been done comparing manually different video frames and the maximum error measures is below 0.5 cm.

Regarding the threshold, the value we have used is empirical and comes from physiotherapist experience and sensibility. Anyway, both the threshold value and uncertainty range can be easily according to considered exercise without the validity of the propose approach. Furthermore, in order for a better tuning a large campaign of acquisition is necessary to properly set the right threshold level.

8 CONCLUSIONS

This research work presents a feasibility study about the introduction of low cost markerless Mocap system for the assessment of shoulder rehabilitation. A roadmap was used to organize the workflow,

including the set-up of the RGB-D acquisition system, the acquisition of rehabilitation exercises and the elaboration of gained data according to the domain knowledge.

Due to the high anatomical complexity of the shoulder joint and to the detailed analysis requested by physiotherapists, the conventional Mocap procedure, successfully applied for different aims, is not suitable for the shoulder analysis. Thus, a new solution has been proposed, exploiting motion captured data and RGB video, by means of the open-source software Blender. This resulted in a 2D motion tracking module that, together with the known 3D tracking solutions, enables to interpret small shoulder movements, e.g., the scapular elevations during arm abduction. On this basis, an ad-hoc application has been developed, which uses a modified virtual skeleton to automatically evaluate if the movements are done in the correct way. In particular, the application automatically detects and measures the vertical rising of the scapula during a series of arm abductions. The application can be used with two different styles of interface, intended for physiotherapists and patients.

A preliminary test highlighted that the developed solution is able to distinguish between abduction performed in correct and wrong way as well measuring motions relative to compensatory movements, which are the main cause of bad execution of exercises. Even if the evaluations done by the physiotherapist and by the applications are coherent in terms of a right/wrong score, the system would benefit from an empirical refinement of the threshold level. This will be achieved using the presented solution on an elevated number of patients and comparing the results achieved with those gathered in the conventional observational way. On the methodological side, further developments have been planned for improving the 2D marker tracking accuracy, because some other small shoulder movement could be even more demanding.

The physiotherapist involved in the research highlighted the importance of having an objective measurement of compensatory movements and supports the introduction of low-cost markerless Mocap systems in everyday rehabilitation tasks. The presented approach can be easily applied to other rehabilitation exercises for shoulder or for any other anatomical district.

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