Digital Motion Acquisition to Assess Spinal Cord Injured (SCI) Patients

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ABSTRACT

The rehabilitation process of patients after spinal cord injury (SCI) is usually based on subjective visual assessment by medical staff of rehabilitation centers. During the process, the medical personnel train patients to manage wheelchair and they learn how to use their sensible body parts in order to have a satisfactory life-style. Furthermore, physiotherapists and physicians have to control patients to prevent wrong postures that could cause further disorders. This paper describes how a low-cost marker-less motion capture system can be exploited to create an objective assessment procedure. Three Microsoft Kinect v2 sensors have been used to track patients using their wheelchairs along a straight path. The three sensors are arranged to optimize the acquisition. Thanks to the collaboration with the medical staff, we identified the set of parameters necessary to monitor patients' performance. An *ad hoc* application has been developed to provide the physicians with the right set of data easy readable to assess the patients along the rehabilitation process. The application has been tested involving twenty volunteers. Finally, results reached so far and further developments are summarized and discussed.

Keywords: Spinal cord injury, assessment of rehabilitation processes, low-cost marker-less motion capture system, Microsoft Kinect v2.
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1 INTRODUCTION

The rehabilitation process of post-injury patients requires a continuous monitoring by medical staff, who has to understand if rehab exercises have been executed in correct way by the patient to improve his/her motoric conditions.

At present, the assessment is based on several parameters well known in literature and on subjective knowledge of the physicians, who base the evaluations also on their experience. This subjectivity may affect the steps of the rehabilitation process and this usually happens when the medical staff is composed by young practitioners with not enough experience or when the assessment has been done by different physicians with discordant points of view.

Another bottleneck is relative to the inaccurate measurement of parameters useful for evaluating patient's improvements. Usually, medical personnel measure improvements through a visual evaluation, which permits only to identify huge improvement or worsening. However, some research works highlight that small errors relative to postures and use of upper and lower limbs can create problems in the long term [5], [9].

This is the case of rehabilitation processes relative to patients who have been subjected to spinal cord injury (SCI). SCI patients follow a precise rehabilitation workflow that comprehends their motor capability and the learning process about the use of wheelchair in order to live in an autonomous way. A wrong use of the wheelchair creates harms, such as pain in arms and shoulders as well as bedsores along legs and back.

Several medical feedbacks report about the possibility to introduce innovative technology, which can be used as instruments to make the assessment of the rehabilitation process more objective and easy for medical personnel. Furthermore, the use of technology allows taking more precise and accurate measurements for evaluating rehab exercises. In literature, motion capture (MOCAP) systems are shown as technological solutions for facing these issues. Among the several types of MOCAP solutions, optical ones are increasingly exploited for human motion analysis in medical assessments relative to both the analysis of the correctness and completeness of motions after surgery and the evaluation of rehabilitation paths. Optical systems consist of cameras as well as other optical sensors to track light sources or reflections or to detect profiles from video frames. The costliest and most performing solutions are infrared cameras using a marker-based system, such as Vicon [14] and Qualisys [13]. On the other end the most interesting and emerging optical solutions adopt a marker-less based system. The low-cost and ease of use make marker-less systems an interesting base for innovative solutions. Marker-less MOCAP systems are composed by RGB-D cameras and this technology is attracting the interest of both research and medical communities. The most diffused are Microsoft Kinect v1 and v2 [2],[10]. Literature reports applications in several medical contexts, for example for virtual ergonomics [8] and preventing of musculoskeletal diseases (MSDs) [1], [4] or for evaluating rehabilitation exercises [1], [12], or for monitoring different disability as strokes [15] and elderly [3]. Moreover, research works have been carried out to assess accuracy and reliability of Microsoft Kinect v2 in medical contexts and the results reached so far have been considered adequate for both technical and medical personnel [11].

This research work aims at presenting the use of a marker-less motion capture system to evaluate rehabilitation process for SCI patients. The contribution concerns not only the adoption of three Kinect sensors in a new configuration but, especially, the automatic elaboration of acquired data according to medical knowledge in order to generate an ad hoc report for an objective evaluation of the wheelchair use. To this end, we developed a software tool, which makes also available information about patient's data and measurements relative to the wheelchair set-up.

First, we introduce the aim of the research work, then, the designed solution is described and clinical tests carried out at an Italian Hospital is discussed. Finally, results and further developments are summarized.

2 DESIGNED SOLUTION

The proposed solution is based on a low-cost maker-less MOCAP system composed by Microsoft Kinect v2 sensors connected to a laptop. The MOCAP data are acquired and managed through the commercial software platform iPiSoft, which is composed by two software tools: iPi Recorder and iPi Mocap Studio [6]. The first one records data acquired by all connected Kinect devices (Fig. 1.(a). and Fig. 2.(b).) and iPi Mocap Studio manages raw data in order to create the virtual avatar (Fig. 1.(c).) and the kinematic data, which will be used as input to the developed application.

State of the art configuration of Kinect MOCAP system uses two sensors and allows acquiring a 5 meters long path. To acquire patients on a wheelchair, a longer path is required to record at least two complete pushing cycles. Thus, we consider three Kinect sensors disposed to permit a longer volume of acquisition without varying the system performances.

The layout of the three Kinect devices has been defined in order to guarantee the whole acquisition of occluded parts. In fact, for the seated position, the presence of the wheelchair creates much more occluded zones during the acquisition rather than during a standard gait analysis. Furthermore, it is really important to track also less visible human body parts, such as hips and trunk, with an adequate quality and reliability. This has been realized even if the MOCAP system with three sensors imposes a minimal common volume of acquisition for the calibration. It is required for all the Kinect devices to detect the light marker during the calibration and the distances among the Kinect devices have to guarantee a calibration zone in which the light maker can be properly moved. Therefore, the layout of the MOCAP system has been designed to guarantee both mandatory features.

(a) (b) (c)

Figure 1: Depth data (a) and RGB data (b) acquired with Kinect devices through iPi Recorder and the virtual avatar computed by iPi Mocap Studio (c).

In order to monitor SCI patients and the wheelchairs use, the distance of the horizontal path has to be more than 6 meters long. Fig. 2 depicts adopted layout, which permits to obtain a horizontal acquisition path of 7 meters and the area with internal oblique lines defines the zone in which the light marker can be moved in order to be detected by all Kinect devices during calibration phase.

3 DEVELOPED APPLICATION

The developed application allows medical personnel to get information by starting from kinematic data extrapolated by iPiSoft MOCAP studio. Furthermore, the software embeds a set of medical rules, which permit to make available information according to patient data and measurements relative to the wheelchair setting. The application requires as input the following data:

- Two CSV files that are exported from iPiSoft MOCAP Studio containing kinematic data of SCI patients during wheelchair pushing. The first file contains information relative to virtual skeleton and its motion according to absolute coordinate system of the 3D environment of iPi Mocap Studio. The second file contains kinematic information and motion data for each virtual bone of the virtual skeleton according to its parent joint.
- Patient's data: in addition to personal information (i.e., name, surname, age and gender), the level of the injury is asked to each patient [8]. Furthermore, the diameter of the wheel is required to perform pushing analysis.

The application computes and makes available both phases of pushing cycles and angles of the upper limbs. The user interface of the application has been designed as a medical report, which can be exploited as a further tool to improve the monitoring of the rehabilitation progress. All data and graphics may be exported in PDF file format for sharing information with other physicians.

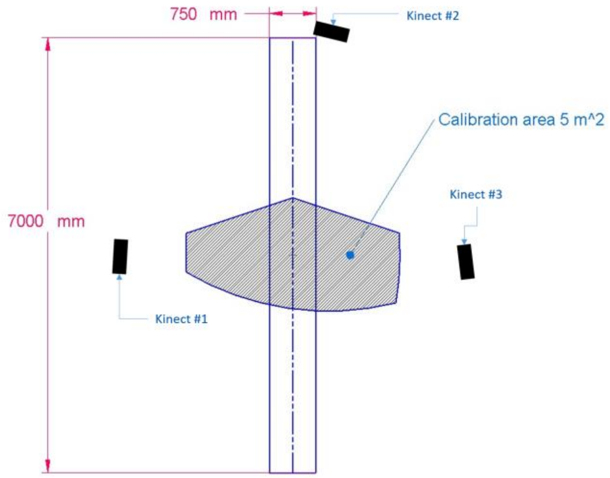


Figure 2: Layout of the MOCAP system and calibration area.

3.1 Pushing cycle analysis

The recorded motion of the patient with wheelchair has been analyzed in order to automatically detect each pushing cycle and the main sub phases, which are pushing and recovery phase for both left and right sides.

The first step is relative to the identification of those virtual joints of the avatar that better describe the main phases of wheelchair propulsion. They have been defined by the medical staff as the grasping point (i.e., when the hands start pushing the handrail), and the release point of the hands, which occurs when the hand ends the pushing phase and the charging phase begins. Figure 3 shows the various phases of the propulsion movement available in the literature [15].

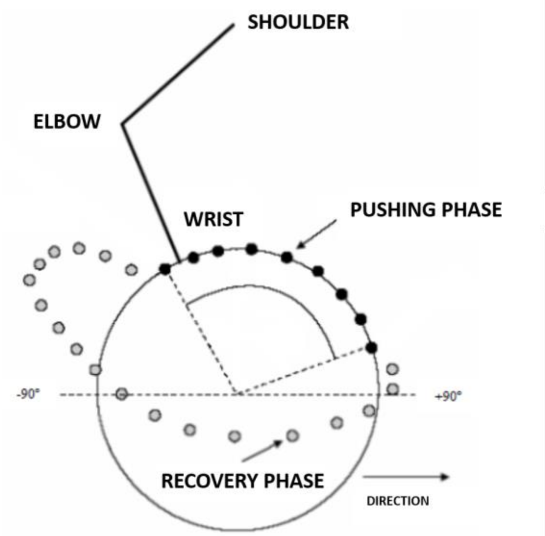


Figure 3: Basic template of phases of a schematic pushing cycle.

The application is able to extrapolate only the propulsion movement of wheelchair in order to evaluate pushing cycles of the patient from the data of the whole movement along the path. In fact, the tracked motion can be subdivided into two motions: the horizontal translation of the patient on wheelchair along the path and the one relative to the pushing of wheelchair using hands (Fig. 4.). The horizontal motion must be removed from motion tracked data otherwise the plotted graph, as the one shown in Fig. 5., cannot be easily interpreted.

In order to calculate the horizontal motion, the position of the two frontal Kinect devices gives the advantage of obtaining an excellent acquisition of the upper right and left limbs. Thanks to this feature it was decided to study the shoulder joint. The high precision of the motion acquisition of the shoulder gives consistent data very realistic with respect to the real case, without unnatural and discontinuous movements. Furthermore, the low mobility of the upper limbs during the pushing phase allows us to conclude that the horizontal translation of the whole body and, thus, of the wheelchair, can be consider as the translation of the shoulders.

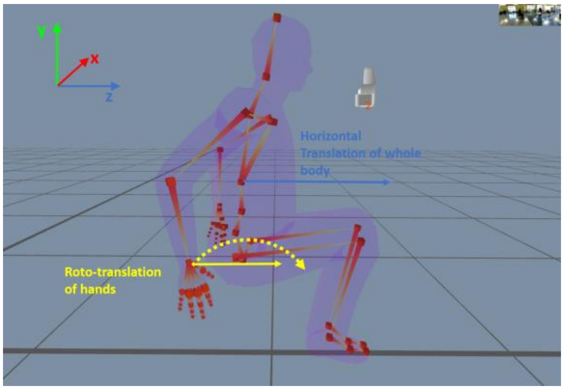


Figure 4: Absolute and relative motions of the patient executed during the use of the wheelchair.

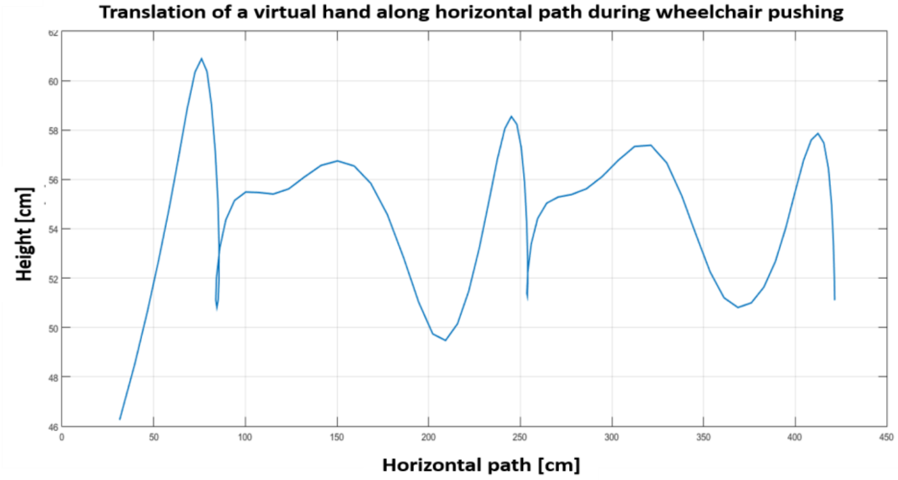


Figure 5: Trajectory of hand along the straight path.

Burning and Schmeler [7] propose as a measure of correctness of patient positioning on the wheelchair the distance along the z-axis between the scapula-humeral, i.e., the shoulder, and the axis of the wheel. This confirms that the choice of the shoulder joint is appropriate.

Using this joint to calculate the relative movement of the hand we can plot the graph shown in Fig. 6. This graph depicts the distance along the z-axis between the hand and the shoulder. The most significant points can therefore be identified, which correspond the upper and lower peaks.

The upper peaks coincide with the position and frames in which the hand is in the most advanced position relative to the shoulder. On the other side, the lower peaks represent the position and the frames in which the arm and forearm are in the position of maximum backward extension respect to the shoulder.

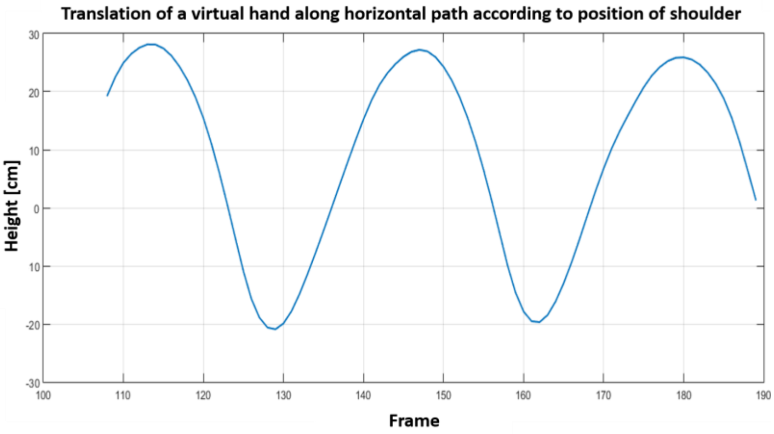


Figure 6: Standard sinusoidal trend of virtual bone relative to right hand along the straight path.

Once the information plotted in Fig. 6. had been calculated and the diameter of wheel is known, it is possible to determine angles and phases of the pushing cycle (Fig. 3.).

3.2 Patient's evaluation

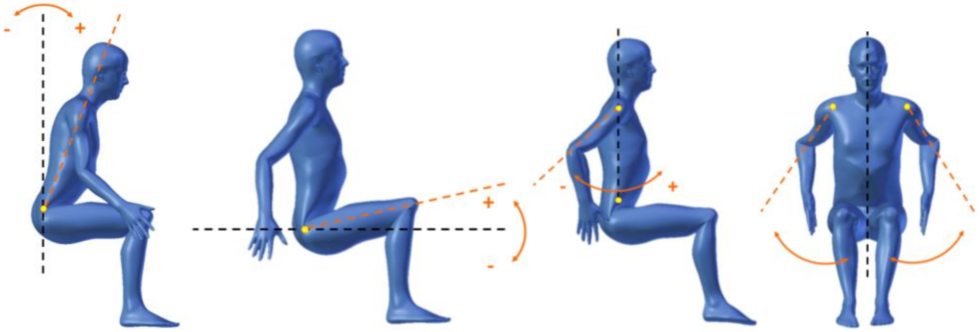
The collaboration with the physicians of the ASST Special Rehabilitation Unit of Papa Giovanni XXIII Hospital, Bergamo allowed to gather indications on the parameters to keep into account in order to assess the patients. Some conditions that are conventionally evaluated by physicians have been translated into a set of parameters (mainly angles) and range of values. Comparing acquired data with references values allows creating an evaluation tool to support patients' assessment. Fourteen characteristic angles have been defined. Among them, the most important are described in the following.

Flexion of trunk is a useful parameter to describe patients' stability on the wheelchair. Very often medical staff inclines the seat backwards to increase the support of the trunk and improve the patient's sense of safety. An excessive negative inclination can lead to the wheelchair overturning during pushing cycle (Fig. 7(a).).

The angle described by the direction of the femur and z-axis is used to increase the feeling of safety in the patient. This setting allows patients to hold the entire body on the seat and not letting it slip, but an excessive inclination can cause problems in the buttocks and thighs (Fig. 7(b)).

This angle is useful because it highlights the maximum and minimum extensions of the rotational movement of the scapula-humeral articulation. In fact, observing the value of the angle in the point of beginning and end push, the medical staff can deduce any defects in the positioning of the seat on the wheelchair and, in particular, if the patient is positioned too far forward or vice versa. It is also important to analyze the asymmetries between the right and left arm to evaluate their motor abilities (Fig. 7(c).).

The distance of the elbows from the trunk determines the abduction and adduction angles. These are crucial to determine the pushing performance of the patient (Fig. 7(d).).



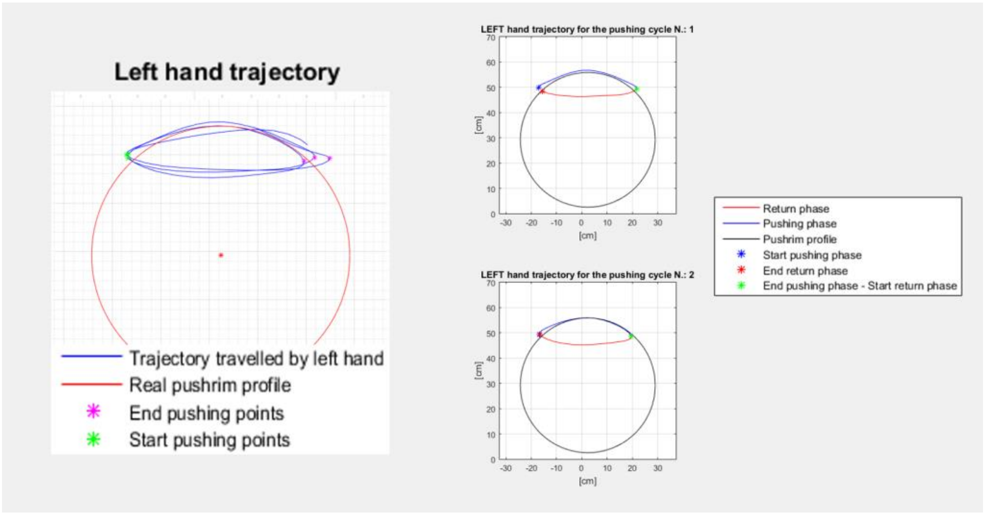
(a) (b) (c) (d)

Figure 7: Measured angle of trunk (a). Measured angle relative to the extension of hip along femur (b). Measured angle about back-arm position (c). Measured angle for evaluating abduction/adduction of arms (d).

4 CLINICAL TEST

The MOCAP system and the application have been tested involving 20 SCI patients with different levels of injury. The testers are 4 females and 16 males who are from twenty-five to seventy years old.

The optimized layout of MOCAP system has been replicated in the rehabilitation gym of the Hospital and each step of the workflow to acquire motion of SCI patients on wheelchair has been executed. The acquisition of twenty patients has been done in 16 hours spread over 12 acquisition sessions. Motion and kinematic data have been computed by iPiSoft Mocap Studio and have been used as input file in the developed application. The first part of the application leads to the definition of pushing cycle and graphs are automatically generated to show the trajectories of the hands (Fig. 8.).



(a) (b)

Figure 8: All pushing cycles in relation to the push rim profile (a). Pushing phases for each detected pushing cycle(b).

The second part of the application has been used to obtain the final results to be interpreted by the medical staff. To start testing the effectiveness of the application comparisons have been made with the traditional evaluation approach.

In general, the precision of a MOCAP measure depends on the distance from the person, on occlusions, on the intrinsic sensor sensibility, and other parameters. What we decided to do has been to define the best MOCAP configuration and evaluate the final results in terms of medical indexes for rehabilitation assessment.

Kinect v2 sensors provided adequate measurements of hands, arms and shoulders movements, which are the key anatomical districts involved in the pushing cycles. The maximum error of 2 cm has been detected for the body districts occluded by wheelchair during the acquisition, such as the lower back. The acquisition of the other interested districts is affected by an error of 7-9 mm that could be relevant for a single frame, but it is negligible for the overall medical assessment. Then, detected issues relative to pushing phase of some patients have been directly evaluated by medical personnel after the use of designed solution and these defects have been effectively confirmed. In particular, the maximum angle obtained when arms achieve maximum backward extension has been the most important parameter for evaluating if the SCI patient executing pushing phase in the correct way. As depicted in Fig.9., the acquired patient moves the right arm backward with an average value related to chest of -23 degrees (maximum 5 degrees, minimum -44 degrees). These values have been confirmed by medical personnel by direct observations and using recorded videos. Therefore, proposed solution can be considered for further testing and validation.

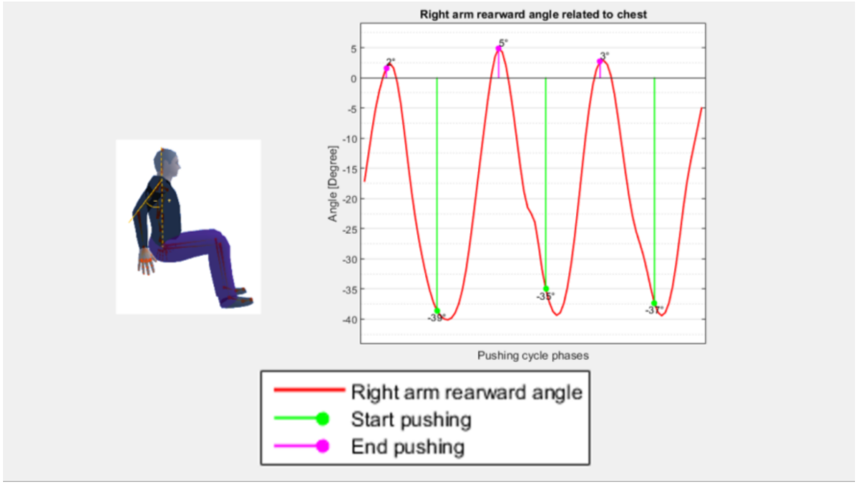


Figure 9: Right arm rearward angle in relation to pushing cycles of wheelchair.

5 CONCLUSIONS

The paper describes an innovative procedure based on the use of low cost MOCAP systems and an ad-hoc developed knowledge guided application, which helps medical personnel to objectively assess the rehabilitation paths of SCI patients. The designed solution has been developed in collaboration with medical staff of ASST Special Rehabilitation Unit of Papa Giovanni XXIII Hospital in Bergamo, who made available medical knowledge for creating the rules embedded in the application.

The main limits of the system derive from the quality of acquisition we can reach with the Kinect V2 sensors. In fact, due to the higher speed of movements respect to other acquired tasks (e.g., gait), the low frame-rate does not allow recording with desired precision. As a consequence, it is difficult to obtain a high-quality evaluation of the parameters for the data processing of the application. At the same time, the presence of light sources in the acquisition environment disturbs the infrared sensors. Despite these limitations, the acquisition quality is adequate for data analysis and the results obtained have been evaluated by the medical staff adequate for future support to patients' rehabilitation process. Although the Kinect devices present some limits, we have designed an innovative system with a new layout and calibration method to obtain good data for reaching a more objective medical evaluation.

New tests have been planned in order to try the application with a bigger number of patients to identify further improvements of the proposed hardware and software solutions.

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