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GAIT ANALYSIS IN THE ASSESSMENT OF PATIENTS UNDERGOING A TOTAL HIP REPLACEMENT

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ABSTRACT
Nowadays, healthcare centers are not familiar with quantitative approaches for patients' gait evaluation. There is a clear need for methods to obtain objective figures characterizing patients' performance. Actually, there are no diffused methods for comparing the pre- and post-operative conditions of the same patient, integrating clinical information and representing a measure of the efficiency of functional recovery, especially in the short-term distance of the surgical intervention.

To this aim, human motion tracking for medical analysis is creating new frontiers for potential clinical and home applications. Motion Capture (Mocap) systems are used to allow detecting and tracking human body movements, such as gait or any other gesture or posture in a specific context. In particular, low-cost portable systems can be adopted for the tracking of patients' movements. The pipeline going from tracking the scene to the creation of performance scores and indicators has its main challenge in the data elaboration, which depends on the specific context and to the detailed performance to be evaluated.

The main objective of this research is to investigate whether the evaluation of the patient's gait through markerless optical motion capture technology can be added to clinical evaluations scores and if it is able to provide a quantitative measure of recovery in the short postoperative period.

A system has been conceived, including commercial sensors and a way to elaborate data captured according to caregivers' requirements. This allows transforming the real gait of a patient right before and/or after the surgical procedure into a set of scores of medical relevance for his/her evaluation.

The technical solution developed in this research will be the base for a large acquisition and data elaboration campaign performed in collaboration with an orthopedic team of surgeons specialized in hip arthroplasty. This will also allow assessing and comparing the short run results obtained by adopting different state-of-the-art surgical approach for the hip replacement.

INTRODUCTION
Degenerative osteoarthritis of the hip joint (coxarthrosis) is the most common disease of the hip joint in adults. Although research has advanced knowledge of osteoarthritis, none of the known therapies can halt its progression. The elective procedure in the treatment of the hip osteoarthritis is universally recognized to be the prosthetic hip replacement surgery (HRS) known also as Total Hip Arthroplasty (THA) [1]. In 2010, an estimated 2.5 million people in the USA were living with THA, and nearly 332,000 THA were performed annually [2]. In a traditional surgical treatment, the femoral head and damaged acetabulum are removed and replaced with metal, plastic or ceramic prosthetic components. Due to the anatomy of the region, it is possible to access to the hip joint from different directions and literature reports three main approaches [3]:

- Posterior Approach (PA) that is the most common surgical approach used worldwide, known since the end of the XIX century and performed without major variations since the 60's.
- Direct Lateral Approach (DLA), or transgluteal, that was popularized by Hardinge starting from 1982; it is the second most common surgical approach used worldwide.
- Direct Anterior Approach (DAA) known since the middle of last century; thanks to the development of new instruments to make it less invasive and easier to perform, it has gained popularity in recent years and is now the third most common surgical approach.

Recently, the trend is to prefer minimally invasive THA [4]. DAA is one of the most promising minimally invasive approaches in hip arthroplasty [5] because it allows reaching the hip joint capsule without cutting through any muscle during acetabular and femoral preparation. However, minimally invasive surgical procedures have a higher complication rate than conventional techniques [6]. The preservation of the gluteus medius muscle increase the risk of damaging the lateral femoral cutaneous nerve, as stated by Oldenrijk's study on fresh frozen cadaver hips [7]. In recent years, the DAA is gaining consent but it still needs to be supported by further analyses to prove if it actually is the best solution and in order to eventually become the elective surgical procedure.

The aim of this research is to provide an assessment procedure of patients' gait capability in a short term after the THA. Actually, a multidisciplinary approach is needed to understand which are the right gait parameters, when they must be considered, and to interpret the results so that final users can be provided exactly with the information they need. To accomplish this goal a portable Motion Capture (Mocap) system has been configured to be used inside a hospital facility, and any time a patient needs to be evaluated, the system can be quickly set up and used. Then, a gait analysis based on acquired data is performed with the goal of ranking the different surgical procedures. In the hip arthroplasty assessment, patients' short-time recovery performance is crucial to give a feedback to surgeons and to healthcare providers.

The paper, after this introduction to the research context, shows the state of the art of clinical and innovative ways of assessing patients after the THA. Then, the proposed method and tools are described together with an example of experimentation with patients. Discussions and conclusions end the paper.

BACKGROUND

There are many reasons why moving towards better surgical approach is a key factor for healthcare systems and surgeons. Besides straight economic motivations, the main goal is to provide patients with safer, more effective and quicker path towards the best healing condition. This motivates the number of research studies available in literature, whose aim is to compare and rank the different surgical approaches to THA.

Physicians are prone to measure the effectiveness and risks of a procedure using the general clinical data that are normally collected for any hospitalized patient. This is a common feature for retrospective studies analyzing a high number of patients. For instance, [8] shows a retrospective study on 419 patients undergoing THA for coxarthrosis. The patients are grouped depending on the approach: DLA and DAA. The reported evaluation parameters are: length of the surgical procedure, intraoperative complications, intra- and postoperative blood loss, postoperative pain, postoperative nausea and vomiting, length of stay, and type of discharge. The conclusion stated that patients operated with the DAA approach had a better perioperative outcome but short and long run assessments are required. Some other literature contributions adopt the same evaluation parameters, plus some other, such as in [9], which introduces: length of stay (in hospital), return to theatre and readmission rate after 12 months of discharge. Qualitative results are encouraging to move towards DAA as the elective procedure.

Scores and scales are also well known for assessing patients on their ability to fulfil tasks (e.g., Harris Hip Score [9] or Bartel scale [10]) or that are based on the self-evaluation of pain level (Visual Analogue Scale [11]). Even if clinical parameters and scales above mentioned are widespread, they lack in accuracy for the aim of this work. Actually, it is very difficult to notice the difference due only to the surgical approach, by considering global parameters, frequently only on a long run. This is the reason why a more objective, quantitative and direct approach is required.

Literature shows some examples of direct measures. Mjaaland [12] and Bergin [13] propose the use of biochemical markers for muscle damage and inflammation as an objective measure on invasiveness in anterior and lateral minimally invasive THA. Some other works are available in which patients are assessed by means of a gait analysis in a dedicated structure. In [14] some gait parameters are gathered, but the capture system seems to acquire only the foot position in time and not the whole body movement. This study highlighted no functional benefits of the minimally invasive incision over the standard one in terms of early walking ability. Moreover, also high-end solutions for motion capture and gait analysis are reported in literature. They adopt costly optical marker-based systems developed for the entertainment industry and force plate embedded in the floor of ad-hoc facilities. For instance, in [16] ten infrared cameras and 3D force platforms are used acquire patients' gait; [15] shows a system based on eleven high-resolution cameras to acquire patients' movements from six to twelve weeks postoperatively. These solutions are highly performing but they are extremely costly; most of the times the systems are not portable and the use of markers on the body may introduce positioning errors.

The aim of the present work is to evaluate if patients' gait analysis based on low-cost portable markerless Mocap and ad-hoc data elaboration is suitable to be used together with clinical evaluation methods for short run assessment.

PROPOSED METHOD

The method adopted to acquire the way patients walk before and after the THA surgery is derived from an ad-hoc roadmap. This roadmap [17-18] has been conceived to analyze generic human motion with low-cost Mocap technologies. The approach has been designed so that it can be applied in different contexts and with different purposes. The first part is related to the acquisition of the motion, a second part is related to knowledge management, while in the last part raw data of the motion capture activities are elaborated according to rules and algorithms previously defined. For the application to THA operated patients, the roadmap has been specified as follow.

Scene set up and Motion Capture

The motion sensors adopted are two Microsoft Kinect version 2, exploiting the time-of-flight principle for measuring the depth in addition to RGB data captured at 30 frames per second (fps). The sensors are placed opposite to each other at about 6 meters of distance and diagonally respect to the walking path as shown in Figure 1. This configuration is robust, broadly used and it guarantees a walking length of more than 4 meters, which is enough for acquiring at least two complete step cycles. Figure 2 reports a picture taken in the hospital facility where the Mocap configuration is actually used.

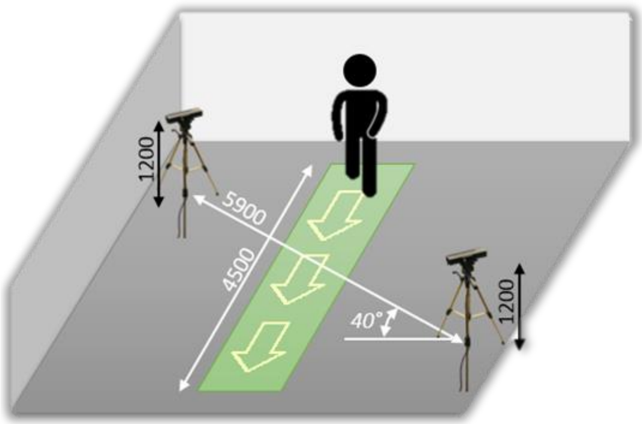

Figure 1. MOTION CAPTURE SYSTEM CONFIGURATION

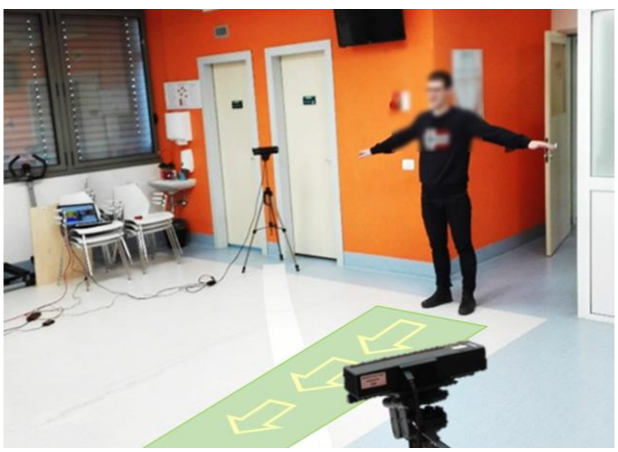

Figure 2. MOTION CAPTURE SYSTEM IN A REAL ACQUISITION LOCATION

The software solution used for capturing Kinects data is provided by iPisoft [19] and it allows recording, tracking and analyzing 3D motion data. A cloud database is set up to conveniently organize and store raw data obtained with the acquisition sessions.

Using Kinects as Mocap devices has several pros and cons. The most relevant reasons that lead to this choice are:

- The portability of the system that can be carried and set up in almost any place having, at least, the sizes shown in Figure 1.
- The ease of use of both hardware and software.
- The low cost of the entire system that encouraged the diffusion of Mocap technologies outside specialized Mocap laboratories.

Portability is required because Mocap sessions are organized according to patients' availability and clinical schedule. Any time an acquisition is needed, in less than half an hour the system can be mounted and calibrated to be ready for capturing patients' gait. Thus, no dedicated spaces are necessary for fixed devices. Mocap session can be done inside the hospital at a few meters from patients' rooms.

Having a flexible and easy to use solution is the key for planning a campaign of acquisition in which any patient selected for the study can be tracked, before the surgical procedure and exactly seven days after, right before discharge. Being compliant with hospital schedule would have never been possible with different technological solutions requiring long set up, or the use of markers on the body.

For capturing the gait, the patient is simply asked to walk on a straight path marked on the floor without wearing bulky cloths. A normal RGB video and depth data are acquired simultaneously at 30 fps (Figure 3). Patients using crutches are acquired with no problems. Each acquisition is done twice to have a backup in case of acquisition errors. Room light is checked while calibrating the system to avoid extreme conditions such as direct sunlight or reflections on the floor. Patients stay in the motion capture room for just a couple of minutes.

Figure 3. DEPTH MAPS OBTAINED DURING THE MOTION ACQUISITION

Knowledge acquisition and data elaboration

The following steps are not necessarily performed in the location where the motion is captured. They are related to the capture of domain knowledge and to the elaboration and interpretation of collected data. Actually, before starting analyzing data, meetings with caregivers are organized. The aim of the meetings is to clearly define which are the parameters to be extracted for patient's performance assessment. Physicians and engineers are collaborating in this step to share the knowledge about quantities that have to be taken into account. A clear definition of such parameters is crucial for the success of the entire procedure. Physicians' requirements are formulated in natural medical language and they have to be mapped onto the joints movements acquired in time. For instance, the simple "step length" quantity is translated into "the distance between two homologous foot joint positions"; where "homologous" must be further defined as a particular repeated condition, e.g. heel strike or toe off on two consecutive step cycles. According to this logic, a list of parameters, each on a specific time frame, is defined and validated. Literature can be searched to compare data with eventual existing related works. Afterwards, it is possible to determine how to extract automatically or semi-automatically the relevant values from the considerable amount of raw data stored for each acquisition.

Table 1 shows the complete list of parameters that were considered for performing the gait analysis of patients having a THA procedure.

Table 1. SELECTED PARAMETERS FOR THE ASSESSMENT OF GAIT

GAIT PARAMETERS		
NUMBER	DESCRIPTION	
1	Duration of the step cycle [s]	
2	Frequency of the step cycle [steps/min]	
3	Duration of stance phase and rate towards the entire step cycle [s]	
4	Duration of swing phase and rate towards the entire step cycle [s]	
5	Duration of double support phase and rate towards the entire step cycle [s]	
6	Step length normalized to patients height	
7	Step cycle length normalized to patients height	
8	Step width [cm]	
9	Maximum swing speed [m/s]	
10	Gait average speed [m/s]	
11	Maximum knee flection during the swing phase [°]	
12	Lateral displacement of center of mass respect to the pelvis in mid stance/swing phase [cm]	
13	Hip rotation in the sagittal plane	At first heel contact [°]
14		At toe off [°]

Parameters from 1 to 5 are related to time and are useful to determine the proportional duration among the three parts of a step:

- Stance: time frame in which the considered foot is on the ground.
- Swing: time frame in which the considered foot is not touching the ground.
- Double support: time frame in which both feet are on the ground.

A step cycle is composed by a right and a left step. Parameters 3, 4 and 5 refers to the three phases of a step and are normalized respect to the entire step cycle duration.

Parameters 6, 7 and 8 are linear dimensions referred to the step and step cycle. Number 6 and 7 are lengths of the steps normalized to patient's height, while 8 is the width of the walking base. Parameters 9 and 10 refer to speed of the swing and of the entire gait. Last four parameters are much more detailed and have been considered to investigate specific walking deviations relevant for this context. For each parameter, we defined a way to calculate the associated value. For instance, details are reported for parameters number 11 "Maximum knee flection during the swing phase" (Figure 4) and number 12 "Lateral displacement of center of mass respect to the pelvis in mid stance/swing phase" (Figure 5). At first, for each parameter the proper moment of the walking cycle must be defined so that the correct value can be extracted. For the knee flection, the maximum value generally corresponds to the transition from the stance phase to the swing phase. To gather the correct frame of the acquisition the curve trend related to the knee rotation in the sagittal plane is observed.

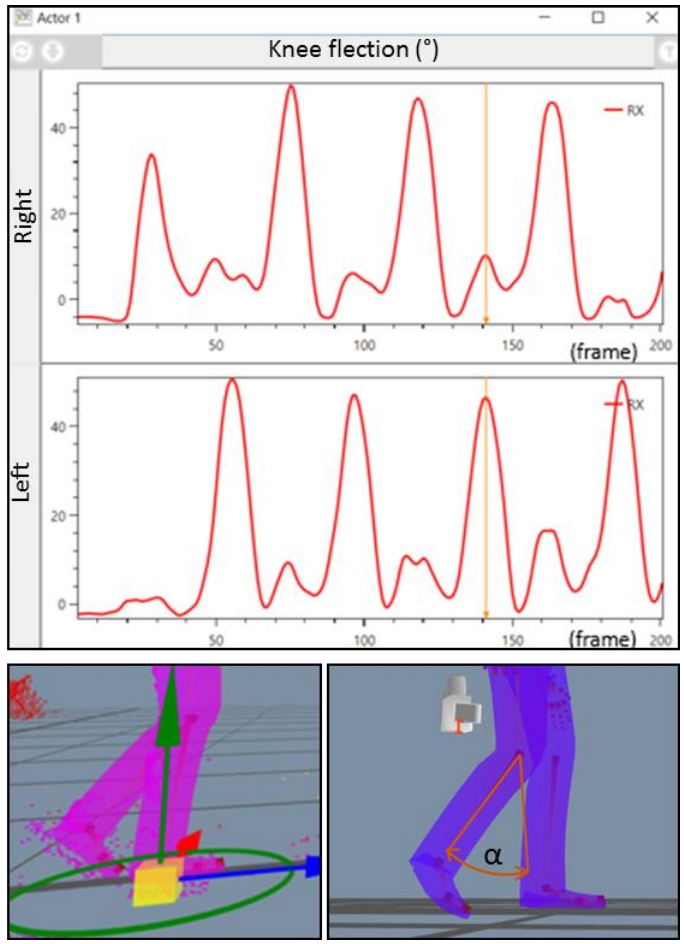

Figure 4. MAXIMUM KNEES FLECTION

The maximum value for each step is the value we are looking for. Figure 4 shows the plot of right and left knee flection angle and the avatar in the reference position.

Considering the lateral displacement of the center of mass respect to the pelvis, the maximum value is near the mid-point of the swing phase, when the two legs are overlapped in the sagittal plane. As for the previous example, the curve trend of the desired parameter is plotted and maximum values are identified. Figure 5 shows the plot of the lateral displacements of center of mass and pelvis and the reference model and avatar.

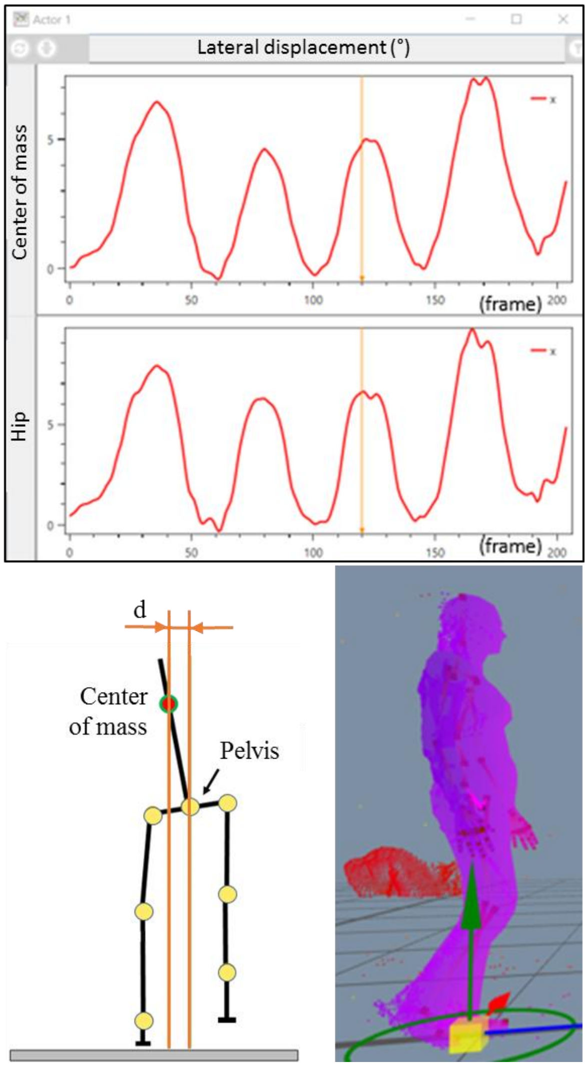

Figure 5. CENTER OF MASS - PELVIS DISPLACEMENT

The same approach is adopted for all the parameters listed in Table 1.

PRELIMINARY EXPERIMENTATION

In order to test the feasibility of the presented method and tools, 4 patients (2 male and 2 female) after 5 days from the THA surgery participated as volunteers. The acquisition showed no difficulties even if performed in a general-purpose room. Data were elaborated manually using a spreadsheet and Matlab [20], but the automatization of the procedure, or even the development of software tool, is perfectly feasible. The whole procedure has been run successfully and a draft report has been generated to show results to physicians. Table 2 reports the values for each parameter of Table 1 related to the acquisition of a 68 years old man who had the hip replacement on the left side. Both left and right legs are evaluated and, except for the average speed, a percent difference is calculated and shown in the last column.

Table 2. DRAFT REPORT WITH THE EVALUATION PARAMETERS OF THE GAIT ANALYSIS

N.	GAIT PARAMETERS		PATIENT'S NAME M - 170 cm THA - LEFT LEG SX		
			LEFT	**RIGHT**	|Δ%| |z|
1	Duration of the step cycle [s]		1,53	1,56	2%
2	Frequency of the step cycle [steps/min]		39	38	2%
3	Duration of stance phase and rate towards the entire step cycle [s]		0,7 48%	0,8 51%	7%
4	Duration of swing phase and rate towards the entire step cycle [s]		0,8 52%	0,8 49%	7%
5	Duration of double support phase and rate towards the entire step cycle [s]		0,2 13%	0,2 13%	2%
6	Step lenght normalized to patients height		0,37	0,39	5%
7	Step cycle lenght normalized to patients height		0,73	0,77	5%
8	Step width		14	14	0%
9	Maximum swing speed		2,65	2,48	7%
10	Gait average speed		0,8		---
11	Maximum flection during the swing phase		136	129	5%
12	Lateral displacement of center of mass respect to the pelvis in mid stance/swing phase [cm]		0	2	2
13	Hip rotation in the sagittal plane	At first heel contact [°]	22	23	4%
14		At toe-off [°]	-14	-15	7%

The test allowed us checking the entire process going from motion capture with a low-cost portable system, to the elaboration of data according to domain knowledge define together with physicians. The capture, elaboration and visualization of data reached with the experimental test is coherent with the aim of the research project.

Defining the right parameters to investigate and the exact values to give back to the physicians is the most challenging phase and it requires some iterative cycles before final validation. By the way, once knowledge is consolidated, the rules to acquire key values can be embedded in the process, requiring no further changes.

On the hardware side, the major but not critical limitation is due to the performance of sensors, in terms of resolution and frequency of acquisition. This does not affect the assessment process for this kind of application in which the person moves relatively slow. Moreover, similar optical sensors, but with improved performances, are likely to appear on the market soon. Since then, the flexibility, portability and ease of use make the Kinect v.2 sensors the best choice available. Indeed, the Mocap configuration based on Kinect is suitable for large-scale acquisition campaign on THA patients.

CONCLUSIONS

Growing access to diverse 'real-world' data sources is enabling new approaches in different medical fields from medical devices development, to drug usage and estimation of benefits or risks. Besides test and validation required before any product, protocol or drug that is considered convenient, the evaluation of real-world data is a key factor to determine its actual benefits and risks. In this context, the research work described in this paper fulfils the goal of proving the feasibility of an experiment-based method to evaluate the outcome of a surgical procedure. On the long run, different procedures for THA reach the same level of success for the patients, which are equally satisfied by anterior, lateral or posterior approach, either conventional or minimally invasive. On the short run, both surgeons' effort and patients' recovery time are highly impacted by the procedure adopted. There are many researchers observing these differences with undirected measures based on clinical indicators.

The approach presented in this paper addresses the need for objective and quantitative evaluations on the patients' performances after a total hip replacement procedure. Using only low-cost motion capture devices, it is possible to track patients' movements whenever it is required, depending on physicians' requests or hospital schedule. The portability of the system allows tracking patients on a predetermined time before and after the surgery to gather comparable results on the pros and cons of a given procedure.

The first experimentation has been conducted successfully working side by side with caregivers to fulfil their requests and needs. At this stage, we are confident in the feasibility of the process and of the results gathered. The natural prosecution of the project will bring to the development of a software solution to automate the process. An increased level of automation will involve primarily data exchange issues among the difference software modules involved in the process. The solution will deal with the captured data, allowing motion tracking, gait recognition and data processing to create an easily readable report. Actually, no computer scientists must be requested to run the system and usability will be highly kept into consideration. This will allow adopting the method on large scale for ranking not only the different access a THA procedure may have, but also any other procedure whose outcome affects patients' gait.

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