# On-body Sensing Systems: Human Motion Capture for Health Monitoring

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## Abstract

On-body sensors capture quantitative data from variety of bio-signals on a subject's body with applications in health, sports and entertainment. With the increase in health costs, a need has arisen to monitor a patient's condition out of hospital in a cost-effective way. In healthcare applications on-body sensing systems can provide feedback information about one's health condition either to the user or to a medical centre. They can also be used for managing and monitoring chronic disease, elderly people, and rehabilitation patients. In rehabilitation applications, such systems can be used to capture patient movement and monitor progress or provide feedback to enhance patients' motor learning and increase rehabilitation effectiveness. Human motion capture systems are expected to generate motion data through several techniques that dynamically represent the posture changes of a human body based on motion sensor technologies. In motion analysis, the human body is typically modelled as a system of rigid links connected by rotary joints. In this paper after describing body models and their approximation by link-segment models, we introduce kinematics and inverse kinematics problems for determining motion. Different sensor technologies and related motion capture systems are then discussed. It is shown how motion data is derived from position and orientation for the different motion capture technologies.

## 1. Introduction

Human body motion is captured through several sensor technologies and techniques for the purpose of health monitoring. Motion sensors involve accurate identification, tracking and post-processing of movement. Visual and non-visual based sensor technologies use different techniques to capture human body motion. In this paper, after describing body models and their approximation by link-segment models, we introduce kinematics and inverse kinematics problems for determining motion. Different sensor technologies and related motion capture systems are then discussed. It is shown how motion data is derived from position and orientation for the different motion capture technologies. Considering their limitations, we review the wearability challenges of these systems. Their drawbacks will be considered in terms of portability: portable motion capture systems should be less sensitive in accurate positioning of sensors and have more battery life time or less power consumption for their wider adoption as an assisted rehabilitation platform [1].

Motion capture attempts to approximate human motion by a rigid-body model with a limited number of rotational degrees of freedom (DOF). In motion capture, an articulated figure is often modelled as a set of rigid segments connected by joints which are constraints on the geometric relationship between two adjacent segments.

This relationship is expressed with parameters called joint angles measured in a number of planes. With careful selection of joints so that, for example, segments are connected to form a tree structure, a collection of the joint angles of all the joints corresponds exactly to a configuration of a figure. This correspondence provides an immediate computer representation of an articulated figure as shown in Figure 1; it is straightforward to compute the corresponding configuration [2]. Human motion capture techniques could be categorized according to the intended degree of abstraction imposed between the subject and the animated figure. Efforts to accurately represent human motion depend on limiting the degree of abstraction to a feasible minimum. Human body motion modelled by a rigid body model typically is approximated with a limited number of rotational degrees of freedom [3].

A non-rigid or deformable body may be thought of as a collection of many particles (infinite number of DOFs); this is often approximated by a finite DOF system. When motion involving large displacements is the main objective of a study, a deformable body may be approximated as a rigid body (or even a particle) in order to simplify the analysis.

In motion analysis, modelling techniques determine the positions of bones of the subject or fitting of the skeleton. Depending on which activities are going to be modelled, there are several body segment representations of human motion [4]. Also if we assume that nearly all parts in the human body can move, it means that all movements of the human body are coordinated movements of the joints, and all movements can start independently from any one joint. A local coordinate system is established at the ends of the inboard bone centre, which is located near the body mass centre, for each joint. The movement of the outboard bone is represented as an orientation with respect to this local coordinate system creating a hierarchical structure. All the joints are organized in a hierarchical tree structure with the root node located at the lower back especially in gait analysis [5].

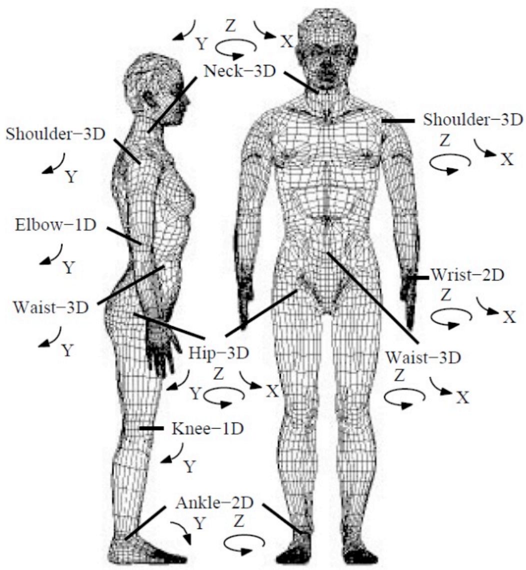

**Figure 1, The controlled degree of freedom of human model [6]**

## 2. Human body modelling for motion capture

In general, there are two kinds of modelling technique: dependent and independent of sensor or marker placement. In modelling techniques that are dependent on marker placement, marker placement should be precise. In modelling techniques that are independent of marker placement, there is no need for the precise marker set-up, but they require a calibration process, which takes time.

### *2.1. Dependent on marker placement*

In modelling techniques, which are dependent on marker placement, data may be acquired unilaterally or bilaterally for the calculation of internal joint centres, e.g. for the hip, knee, and ankle joints in case of modelling gait. Their 3D internal rotations can be calculated in addition to the 3D orientations of the pelvis and foot. This process can be done by using a special marker set which includes a pelvic frame, thigh wands and shank wands. Additional data is required for the calculation of internal joint centres and for the inverse dynamics calculation of joint moments and powers. This can be acquired from subject data and includes subject age and weight, joint widths, and leg-segment data (segment length, mass-ratio, centre-of-mass position, radius of gyration) [5].

### *2.2.Independent of marker placement*

Modelling techniques independent from marker placement are decomposed into three stages: partitioning the markers into rigid segment sets, estimating the position of joints, and deriving the corresponding skeleton dimensions respectively [6]. In the first stage it needs to be specified which marker belongs to which segment. This can be done manually by reference to the anatomic skeleton and making associations, or automatically. In the automatic method, an algorithm computes the distances between markers. It selects the biggest sets of markers in which all distance variations between all pairs of markers are under a certain threshold. This condition defines a rigid segment set [6].

The markers that are attached onto adjacent segments theoretically move in a sphere centred on the joint that links the two segments. The position and orientation of a segment in space is completely defined by three points because a segment is modelled as a surface. Afterwards, we can compute the movement of the markers on adjacent segments defined by these markers in the reference model, and we can estimate their centres of rotation. The centres of rotations correspond to the joints. From their position in space we can compute the lengths of the segments as the distances between them. The joint positions are estimated as the centres of rotation weighted by the associated marker weight and the radius of the sphere.

By applying the previously described procedures, the position of a set of joints can be estimated. The next step is to compute the length of each bone in the anatomical skeleton of the subject. One trivial approach is to estimate the length as the average distance between the estimated joints. A more elaborated one is to compute the length that minimizes the square of deviations. A global adjustment of the lengths can be used that minimizes the distance between the joints of a model and the estimated joints in each frame, adjusting in the same step all the other degrees of freedom of the model.

After determining the position of joints in the human body model, joint angles should be calculated. The problem of finding a set of joint angles is referred to as the inverse kinematics problem. In solving the inverse kinematics problem, the main concern is finding a set of joint angles that corresponds to a given configuration. We need the angles which the body segments make relative to each other to quantify the movements of the joint which connect them and therefore the human motion of interest. In inverse kinematics we know position of body and we attempt to find angles of joints. Conversely in forward kinematics, we know joint angles of a body and we try to compute the body configuration or position. So motion data is derived from different techniques depending on which sensor technologies are used for body sensing.

## 3. Sensor technologies for motion capture

Body area sensing systems can capture bio-signals like electrocardiogram, blood pressure, body temperature, respiration rate, oxygen saturation, heart rate, skin conductivity, electromyogram, electroencephalogram, and body movement. The sensors can be skin electrodes, temperature probes, piezoelectric sensors, galvanic skin response sensors, pulse oximeters, gyroscopes, and accelerometers [6]. A wearable system may have a wide variety of components other than sensors like wearable components, smart textiles, processing units and advanced algorithms for data extraction and decision making.There are two categories of sensor technologies for motion capture: visual and non-visual. Visual technologies can be marker-based or markerless, while non-visual tracking sensors are inertial, magnetic, ultrasonic and electromechanical [7], (see figure 2). In this section we review these technologies, their advantages and disadvantages and we discuss their potential for wider adoption in home-based rehabilitation systems. For home-based rehabilitation the reviewed sensor technologies have their own advantages and disadvantages. Visual marker-based technologies have high accuracy but they need camera set up in a motion capture environment which is not suitable for home-based rehabilitation. Similarly, magnetic and acoustic systems need transmitters and receivers, which should be set up in the environment. On the other hand, inertial and mechanical sensors do not need external set up in the environment; however they need precise alignment on the subject's body.

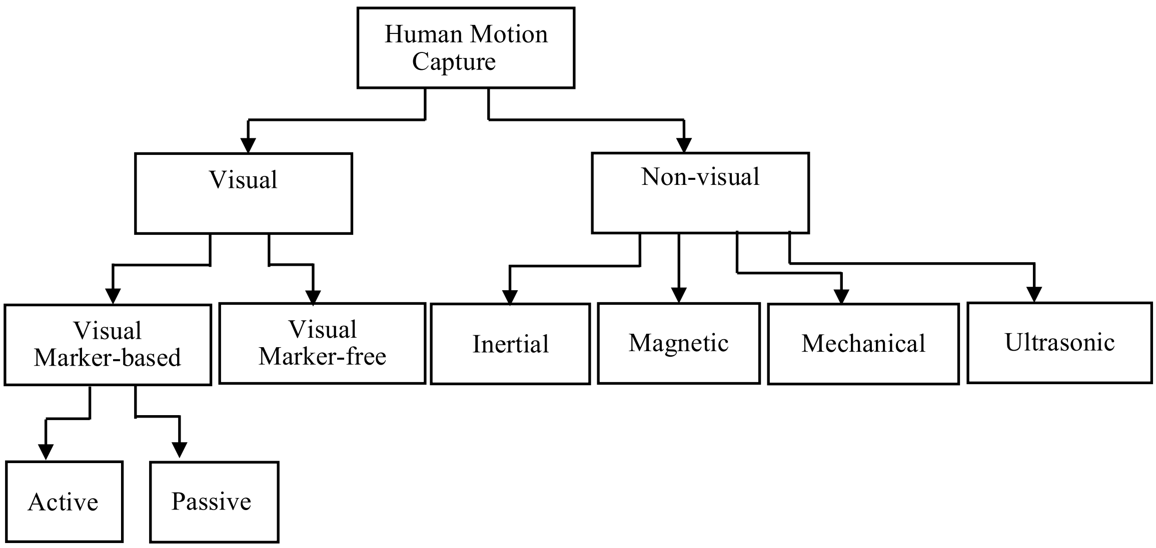


**Figure 2. Motion capture systems using different sensor technologies [6]**

### *3.1 Visual Sensors*

Two classes of visual tracking systems are visual marker-based and marker-free, depending on whether or not sensors or markers need to be attached to body parts. In visual marker-based tracking systems, cameras are applied to track human movements with markers that act as identifiers of the rigid body model landmarks. Marker-based systems are used because of the accuracy of marker position information. They can be active or passive; active marker-based systems use light emitting markers, while passive ones use markers made of reflective material that do not require a power supply. One of the active visual tracking systems is Codamotion which is for 3 dimensional (3D) measurements. Its measurements have been commonly used as ground truth to evaluate motion measurements [6]. Although measurements of these systems are highly accurate with position resolution of about 0.05 mm, they need to be performed in a laboratory and cannot be used in home-based rehabilitation.

Passive motion capture systems usually consist of 1–16 cameras, each emitting a beam of infrared light. Small reflective markers are placed on an object to be tracked. Infrared light emitted by the cameras is reflected back and picked up by the cameras. The system then computes a 3D position of the reflective target, by combining 2D data from several cameras [7]. The two common widely used passive visual motion capture system are Qualisys and VICON. These systems are designed to be used in virtual and immersive environments, and in medical science. Marker-based tracking systems are more accurate in comparison to other motion capture technologies, although they need precise calibration before each motion capture process and it should be performed in laboratory.

Marker-free systems exploit optical sensors to measure movements of the human body without any sensor on the human body. Human body motion can be tracked by cameras and is mainly concerned with the boundaries or features of human body on the images. Image based systems use computer vision techniques to obtain motion parameters directly from video footage without the use of special markers [8]. By using a proper camera set-up, including a single camera or a distributed-camera configuration, motion capture can be performed. A single camera readily suffers occlusion from a human body, due to its fixed viewing angle. Thus, a distributed-camera strategy is a better option for minimizing such a risk. In comparison to marker-based tracking systems, which are a less restricted to limited degrees of freedom due to mounted markers, marker-less based systems are a less restrictive motion capture technology but still the motion capture process are not convenient to be used in home based rehabilitation as they need camera set-up in the motion capture environment.

### *3.2 Non-visual based*

Non-visual sensors such as inertial and electromechanical sensors are used in non-visual tracking systems. They enable motion capture without the need for external emitters and cameras. These sensors can be fitted in a garment or attached directly to the body. The advantage of non-visual tracking systems over visual tracking systems is that there can be ambulatory motion tracking, which means motion tracking by a portable motion tracking system outside the laboratory to capture daily activities, so they are applicable in home-based rehabilitation and there is no need for doing the experiments in special laboratories.

Miniature inertial sensors, which are small, relatively cheap and have low energy consumption, are categorized into accelerometers and gyroscopes. Accelerometers measure acceleration and gyroscopes measure angular velocity. By integration and double integration of gyroscope and accelerometer signals, respectively, one obtains some measure of orientation and position [6]. By knowing the initial position and orientation, we can find sensor orientation and position changes [9]. The position and angle of an inertial sensor cannot be correctly determined, due to the fluctuation of offsets and measurement noise, which lead to integration drift. Therefore designing drift free inertial systems is a challenge. On the other hand, these sensors can be used in home-based rehabilitation as there is no need for cameras to be set up.

Mechanical sensors provide joint angle data to determine body posture. A goniometer is a sensor with attachments to the proximal and distal limb segments that span a joint to be measured. The sensor operates on the assumption that the attachment surfaces move with (track) the midline of the limb segment onto which they are attached and thereby measures the actual angular change at the joint. These devices provide an output voltage proportional to the angular change between the two attachment surfaces. Mechanical sensor accuracy should be carefully evaluated by testing them on individuals of various statures. Attachment and positioning of goniometers present several problems; in addition alignment of the goniometers with body joints is difficult [10] so it needs experts for system set-up in home-based rehabilitation.

Strain and stress sensors have been developed for fabrics from piezo-electric to polyvinylidene fluoride (PVDF) polymer films. These sensors can be integrated within textiles, or securely attached to them. Most are based on the principles that the electrical resistance of the flexible sensor changes during stretching. Many of the developed flexible strain sensors are based on using coated fabric technology [6]. The limitations of these kinds of sensors are their sensitivity to temperature and electromagnetic interference, tensile stiffness and transient output signals, which preclude their use in wearable garments.

Motion capture data such as position and orientation of sensors can be generated from magnetic sensors as well. Magnetic motion tracking systems have been widely used for tracking user movements in virtual reality, due to their size, high sampling rate, and lack of occlusion. One of the common motion tracking systems with electromagnetic sensors is MotionStar by Ascension Technology Corporation. The system detects the position and orientation of the sensors by the magnetic field (either the Earth's magnetic field or the field generated by a large coil). These systems offer good accuracy with no line of sight problems, so are more applicable for home-based rehabilitation. However, they are expensive, have high power consumption, and are sensitive to the presence of metallic objects in the environment [6].

Acoustic systems collect signals by transmitting and sensing sound waves, where the flight duration of a brief ultrasonic pulse is timed and calculated. These systems are used in medical applications, but have not been used in motion tracking. This is due to the drawbacks such as; (a) the efficiency of an acoustic transducer is proportional to the active surface area, so large devices are desirable; and (b) to improve the detected range, the frequency of ultrasonic waves must be low (e.g. 10 Hz), but this affects system latency in continuous measurement. In addition, acoustic systems require a line of sight between emitters and receivers [6], which is not suitable in assisted home-based rehabilitation.

## 4. Derivation of motion data from sensors' signals

As introduced before, different sensor technologies are used for motion capture. Depending on which of these sensors categories are used, there are different techniques to derive angles of joints on the modelled human body. Some sensor technologies like visual marker, magnetic and ultrasonic based systems derive the position of sensors and other ones like inertial and mechanical systems derive the orientation of sensors. Techniques for motion capture try to solve the inverse kinematics problem to find the angles of joints from position of sensors or to solve the kinematics problem to find the posture of body segments from the position of sensors. In next Section, we explain how angles of joints can be derived from sensors' position and orientation.

### *4.1. Deriving motion data from the position of sensors*

Motion capture systems which derive position of sensors in space, like optical, magnetic and ultrasound systems use similar techniques to determine the angles of joints and therefore kinematic parameters. As explained in Section 2.1, a skeletal model is built or adjusted by using a special calibration motion that highlights all the necessary degrees of mobility once per session [11]. Then the model is used to derive the motion trajectories of all the captured motions. Finally angular data are adjusted to adapt the motion to a virtual character. The process can be described in the following pipeline: calibration and capturing, knowing positions of cameras and markers, skeleton estimation, inverse kinematics processing, and determining the angle of joints.

After installing the cameras, attaching markers to the subject is the second step. To obtain accurate results, markers should be positioned on the subject at specific anatomical locations. The cameras capture the movement of the markers rather than the body to which they are attached. Determining the skeleton of a subject means to find the 3D positions of joints from the 3D marker locations and therefore determine the 3D positions of the bones of the subject.

After deriving the 3D position of segments and joints from marker placements, finding the set of joint angles is the next step. The problem of finding a set of joint angles that corresponds to a given configuration is referred to as the inverse kinematics problem. We need the angles which the body segments make relative to each other to quantify the movements of the joint which connects them. A single marker can represent no more than a single point on a body segment as its motion is tracked. A pair of markers mounted upon a rigid segment presents sufficient information to describe both translational and rotational movement, though not fully, as rotations about axis joining the two markers remain undefined.

The arrangement is typical of a simple stick-figure description of the human form where limb segments are indicated as straight lines between markers placed over joints. Though not very sophisticated, it is obviously far better than representing each limb segment by a single marker bearing no spatial relationship to markers on adjacent segments.

To calculate the angles which the body segments make relative to each other, a rotation matrix is used which describes the orientation of the moving coordinate system on each body segment in comparison to a fixed coordinate system. The rotation matrix will translate movement from the fixed coordinate systems to the moving local coordinate system associated with the signals. This allows the angle between two segments to be calculated. So the rotation matrix between the coordinate systems of a proximal segment and the coordinate system of distal segment relative to the proximal segment can be achieved by producing the corresponding rotation matrix of the two segments coordinates [12].

To calculate the orientation of a segment and its embedded coordinate frame, Euler angles are used. Euler angles are set of angles corresponding to rotations about given axes, usually orthogonal axes. The meaning and validity of the derived anatomical angles are determined by the choice of axes and rotation sequence. In order for limb segment angles to be clinically relevant we can define the orientation of the distal segment relative to the proximal segment by comparing the corresponding axes of the segment-embedded co-ordinate frames [6].

### *4.2. Deriving motion data from the orientation of sensors*

Each body segment's orientation and position can be estimated by integrating the gyroscope data and double integrating the accelerometer data in time. By using the calculated orientations of individual body segments and the knowledge of the segment lengths, rotations between segments can be estimated and the position of the segments can be derived under strict assumptions of a linked kinematic chain [13]. This process may have drift because of gyroscope offset, measurement noise, integration and so forth. Although these sensors give some measure of orientation, it is stated in [6] that inertial sensing cannot be used on its own to estimate relative position and orientation of sensors with respect to each other. The estimation of displacement and relative distances between sensors need to be determined using different methods.

In [6], relative distances between sensors were measured by acoustic signals. In this work each unit consists of inertial sensors and miniature microphones, which are used to record distances between pairs of sensors on the body. These distance measurements reduce the drift in purely inertial systems. The reconstruction algorithm estimates body posture by combining inertial and distance measurements with an extended Kalman filter that incorporates estimation of the body's joint structure and poses.

Another way of measuring the relative distance between sensors is using magnetic sensors. By combining inertial sensors with magnetic sensors, an ambulatory 6 degrees of freedom human motion tracking system has been designed in [14]. The magnetic system consists of three orthogonal coils with a magnetic field source fixed to the body and 3D magnetic sensors, which measure the fields generated by the source. Based on the measured signals, a processor calculates the relative positions and orientations between the source and sensor. Since accelerometers and gyroscopes can only measure changes in position and orientation and suffer from integration drift, an improved solution for position and orientation estimation is obtainable by combining measurements from both systems in a filtering structure [15]. In this method a 3D source of magnetic signals is used which can consist of one or three [16]-[17] circular coils that are mounted orthogonally with respect to each other [18].

## 5. Home Based Motion Capture Challenges

### *5.1. Variability*

Variability in movement patterns plays a fundamental role in motion analysis. Inconsistencies due to placement errors of on-body sensors can come from three primary sources: human error in the process of sensor/marker placement, the measurement system, and the subject under evaluation [19]. Variability is defined by the sum of variances from each independent source [20]. Sensor placement variation among technicians is the largest source of unwanted variability [6]. Inaccurate sensor placement causes measurement variability, which is a key impediment to the wider adoption of home-based assistive rehabilitation. Particular care should be taken to ensure that sweating, rapid movements and the placement of markers on the subject's body during different trials and sessions do not affect sensor/marker positioning specified by the

Given the clinical relevance of variability in motion capture measurements, it is critical that we summarize and compare motion data in a way that reflects the true nature of motion variability [21]. To measure variability among gait curves, some distance based measures have been used in literature, including the mean distance from all curves to the mean curve in raw 3-dimensional spatial data [6], the point-by-point intercurve ranges averaged across the gait cycle, and the norm of the difference between coordinate vectors representing upper and lower standard deviation curves in a vector space spanned by a polynomial basis [6].

### *5.2. Energy efficiency*

The importance of body sensing systems to monitor patients over a prolonged period of time has increased with an advance of home healthcare applications. Wearable medical devices could eliminate patients' dependence on clinical environments and allow monitoring at home. Body sensing platforms for monitoring of various biological and physiological signals face the challenge of how to achieve low power consumption as well as mentioned sensor placement challenge. The overall size of the electronic part of wearable systems is generally dominated by the size of the batteries. Hence to have less bulky systems, sensors need to operate with low power consumption.

When considering the hardware platform, we can distinguish three major constituents consuming significant energy: computation units, communication units, and storage units. In body sensing systems the computation unit is usually centralized and far from the human body and signals can be sent via the communication units to the computation unit. Biological and physiological signals are usually saved in the centralized unit which can be connected to sources of power with fewer power restrictions in comparison to the sensors' batteries. Energy efficiency of the communication units depends on the hardware and the protocols which are used to capture the biological signals and send them to the central computing units [22].

## 6. Conclusion

In this paper after introducing human body modelling for motion capture, we reviewed sensor technologies for motion capture, and techniques to derive motion data. Motion capture systems are sensitive to exact positioning of sensors, or alternatively need a calibration procedure which is time consuming and requires training. For ambulatory motion capture and especially home-based rehabilitation, systems should be portable. Two important requirements of portable motion capture systems are tolerance to changes in the position of sensors and extended system life. Therefore, we reviewed causes and effects of variability in motion pattern, and energy efficiency of on-body sensing systems for the purpose of motion capture.

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