A Biomechanical Analysis System of Posture

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ABSTRACT

The number of scenarios that may gain benefits from postural analysis performed with sustainable economic costs is virtually limitless. They range from clinical and outpatient studies to sport and dance practicing, from posture learning and replication for humanoid robots to body control techniques. Therefore the authors firmly believe that the Microsoft Kinect, a novel optical markerless, model-free motion/capture commercial system can pave the way towards this direction due to its ease of usage and its low costs. In this paper, a Model-View-Controller based framework for Kinect-based postural analysis is presented in terms of both system architecture and selected test environment. A first prototypal version of the system has been employed to perform a preliminary stabilometric analysis in a real test case, in order to illustrate the adopted natural user interface and the overall system behavior.

Keywords

Posture analysis; biomechanics; stabilometry; Natural User Interface; Microsoft Kinect.

1. INTRODUCTION AND MOTIVATIONS

Classic methods for posture control and evaluation, such as functional reach test or stabilometry, provide important medical hints, but it is not always possible to precisely quantify specific test results, thus needing a subsequent medical examination at hospitals or specialized clinics.

Otherwise, it is clear that, if we want to operate in a timely manner on correcting problems that derive from prolonged assumption of not correct postures (more and more widespread in younger people), and prevent effects on the musculoskeletal system that often could be irreversible, the only winning strategy is a massive and wide range screening, performed over different age groups, in order to prevent the rising of serious pathologies.

In such a framework, we propose a biomechanical posture analysis system which is not invasive and cheap and able to automatically scan subjects in their own normal work or living environment (e.g. students sitting in their classroom, people working out at the gym, players during a football match, and so on). Such system can also automatically detect joint positions of the skeletal system, thus deriving posture mechanics and comparing it with respect to a database of reference patterns, in order to finally produce information on either prospective or actual postural problems.

In these scenarios, recent motion/capture commercial off-the-shelf (COTS) systems and technologies open new and important perspectives that promise to reach amounts of users with minimal costs if compared to the benefit achievable in terms of health and security.

Among these systems, MS Kinect [1], [2] is able to provide real time 3D positions and references to a set of skeletal joints that represent the human body. Moreover, since it is less expensive than many other commercial systems and being also portable and easy to use, it can bridges many of the gaps previously cited.

It is clear that, if the optical detection hardware is made by such device, in order to retrieve intelligible data that should be useful for a clinical diagnosis, we need to build a complex system able to store and elaborate acquired data, to execute comparison with already known derived posture models, and finally to present information in such a way that it can be easily adapted to both user profiles and selected delivery devices.

Although COTS technologies exhibit lesser accuracy than ad-hoc biomedical and kinematic solutions [3], [4], they certainly have the potential to become more pervasive thanks to cost-effectiveness, ease of setup and usage, simple and effortless participation for the subjects, thus disclosing new and innovative contexts of application.

For the posture analysis system proposed in this paper, we envision a profitable use in countless scenarios, in addition to the ones just mentioned above. Not only healthcare studies (e.g., posture, gait, body trajectory, joint stiffness) and sport practicing analysis (e.g., football, volleyball, archery, softball, fencing, golf, tennis) can be performed but also other body-related activities can be studied. Indeed, many other application areas may benefit as well from our system: they range from movement examination in dance and martial arts to sign language; from gait analysis of models on catwalks during fashion shows to body and mental control techniques (e.g., yoga); from pilot training (by simulating movements in the cockpit) to human posture learning and replication for humanoid robots.

According to the application scenarios sketched above, in the framework of the KISS-Health project [5] funded by Italian Ministry for Education, University and Research (MIUR), the authors propose a system to diagnose postural abnormalities. The project aims to develop an inexpensive, practical but effective set of tools capable of screening a group of subjects at the same time, which can be considered as a first massive monitoring approach to identify potential postural diseases.

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2. RELATED WORKS

A considerable quantity of scientific approaches to computer-aided posture and motion reconstruction has been proposed during the last years, thus making necessary a preliminary classification in terms of acquisition methods and body parts they refer to.

As for the acquisition techniques, one can differentiate the methods employing external, body-worn sensors from those based upon real-time optical vision systems (with either single or multiple views, either marker-based or markerless). Hybrid and mutually supporting versions of the two typologies are available as well.

Other techniques such stereoradiography [6] or fluoroscopy [7] will not be considered in this review since they may occasionally expose the subjects to radiations.

As for the targeted body parts, such systems are usually capable of reconstructing the posture of either the whole body or its most relevant components (e.g., head, hands, limbs, joints), depending on the purposes of the reconstruction activity.

It is a matter of fact that some methods have proven to be more effective than others in capturing specific body parts kinematics and dynamics, as it will be pointed out in the following.

2.1 Wearable, Sensor-Based Posture Reconstruction Systems

One of the very first acquisition techniques employed non-optical external sensors placed at key body points [8]. Nowadays, inertial systems are used to take care of body motion (accelerometers) and rotation (gyroscopes), whilst magnetic systems (transmitters and magnetometers) can reconstruct body position and orientation by sensing magnetic fields within a specific working volume [9].

These systems have progressively become lighter due to the advances in sensor miniaturization (e.g. MEMS [10]), more cost-effective [11] and wireless-based. They are now capable of real-time posture and motion tracking, even in unconstrained environments [12], like the solutions provided by Xsens [13] and Ascension [14].

However, many issues still affect these techniques and the presence of body-worn objects is undoubtedly the most relevant. Indeed, on the one hand, wearing such devices on small body parts [10] to monitor specific phenomena (e.g., flexion/extension of limbs, abduction/adduction angles and internal/external rotation of joints) still represents a feasible solution, especially for ambulatory purposes [15]. But, on the other hand, placing sensors on the whole body may disturb the subject [16]. Moreover, wiring may severely limit movements and gestures as well.

Additional relevant usage restrictions refer to: a) limited number of joints that can be examined at the same time [10], b) low resolutions achievable by miniaturized, wireless sensors [17], c) high costs and power consumption, d) presence of ferromagnetic materials in the environment disturbing magnetic field sensors [18].

In order to overcome some of these drawbacks, hybridized solutions employing complementary optical motion analysis systems have been proposed, but they typically exhibit increased costs and complexity [19].

Alternatively, special suits wrapping a set of wireless inertial sensors can be used, such as the Xsens MVN [20]. Despite the ability of such suits to work without markers or external cameras and to capture a great variety of movements and postures, they usually have high adoption costs, additional weight for the subject (up to some kilograms) and cannot be easily used on children.

Although not directly capable of measuring motion, force sensors can be used, since they provide data about center of pressure, shear forces and pressure patterns for the test subjects, provided that they are located on specific sensor pads [21]. The absence of depth horizontal information and the necessity of using those force platforms, such as the Nintendo Wii Balance Board [22] limit the range of their applications.

2.2 Optical Posture Reconstruction Systems

Even if the most recent non-optical wearable sensors allow posture reconstruction with lower costs than vision systems, they may suffer from potential ambiguity and incompleteness of retrieved information [16] and require considerable efforts in data post-processing.

Therefore, optical acquisition methods still represents a very efficient and reliable solution. Amongst them, one can distinguish marker-based and markerless approaches.

Marker-based optical systems surely have the largest distribution in motion capturing (MoCap) scenarios, being employed in a great variety of situations. They range from healthcare (e.g., gait analysis, rehabilitation, biofeedback) [23] to dance [24], from cinema and videogame animation [25] to robotics [26].

In such systems, kinematic data are reconstructed thanks to infrared optical cameras and high-speed video cameras acquiring data from either transmitting (active) or reflecting (passive) markers attached all around the subject body or placed onto wearable, thin suits.

Single-camera systems are capable of recording just 2D kinematic data (height and width) thus proving to be less effective. In order to record depth information, at least a second camera is needed but, actually, no less than six cameras are needed to reconstruct high-quality data (stereophotogrammetry). In general, the larger is the scene to be observed or the number of subjects to be "mocapped", the greater is the number of required cameras.

Many commercial marker-based solutions are nowadays employed to perform professional MoCaps, such as those from Optitrak [4], Vicon [27], NAC [28] and MotionAnalysis [29]. Some of them are specifically designed for the healthcare sector, such as the integrated biomedical and kinematic solutions provided by BTS Bioengineering [3]. Despite their popularity and their extreme accuracy, they show some important issues severely hindering their applicability to the test cases we sketched in Section II.

Firstly, such systems exhibit high costs (very rarely below 30k€) and usually demand special training for their operators [30]. Complex preliminary setup and calibration phases are often needed, as well controlled environment to profitably acquire data and avoid unwanted side-effects such as the so-called skin artifact [31]. Depending of the needed resolution, a considerable quantity of markers (up to a few dozens) has to be employed on each subject, thus limiting its movements and requiring excessive placement times [23]. Proprietary and quite expensive image processing software are also needed for data elaboration.

Markerless systems originate from Computer Vision and Artificial Intelligence scientific domains. They address many of the issues affecting marker-based solutions. However, they also exhibit troublesome features such as lower accuracy in 3D kinematics acquisition due to the absence of markers. In order to tackle this aspect, two categories of markerless methods have been proposed: model-based and model-free approach.

The model-based approach is based upon a priori human models against which the available visual observations of the subjects are evaluated, by performing optimization processes.

Such methods are fast and represent a suitable solution for ambiguities and incorrect poses identification [32]. They do not require complex training procedures since both kinematics and dynamics data are usually store within the model itself [33].

However, model-based approaches lack in subject and body parts correct identification and statistical calibration or model-fitting algorithms are usually needed in preparatory MoCap stages [34].

The model-free approach maps sensed observations directly onto posture large databases. Despite some difficulties in finding silhouette ambiguities and potential database incompleteness [32], these systems have proven to be the most cost-effective ones, thus disclosing a wide range of user-appealing application scenarios.

The widely-known Microsoft Kinect can be used to profitably extract and infer human posture. Indeed, instead of using color images, it allows to acquire 3D data by constructing depth images from a projected pattern captured by an IR sensor [35].

Many algorithms have been proposed to perform MoCap from the default single depth image provided by Kinect [36], however, the achieved postures are usually noisy, especially when the subject body is not fully visible. But if motion databases [37] and ad hoc smoothing algorithms are employed to fill missing data and remove noise, MoCap results can be compared with those from commercial marker-based optical systems [38].

As for multi-Kinect MoCap, at our knowledge, just a few of them are in a development stage at the moment, such as the iPi's single or double Kinect solution [39], limited to 3D animation renderings. On such bases, we believe that the proposed approach represents a considerable improvement in the markerless, model-free MoCap arena.

3. PROPOSED SOLUTION

Even if the advantages previously reported are undoubtedly several, the problems to cope with are of different rank. Such issues are briefly listed in the following:

- physical connection to the system of more than one Kinect sensor at a time, and their correct detection by the OS;
- overall system calibration;
- data-fusion of real-time data;
- display of results through computer-vision techniques.

The system prototype, designed to overcome these issues, was developed using well-established design patterns and architectural styles. In particular, the system has been designed following the widely-accepted "Model View Controller" (MVC) design pattern, since it naturally allows to decouple system functional levels, thus making them interchangeable and easy to manage. The MVC pattern also allows to maintain task separation between software components which interpret the following three main roles.

- **Classes related to the model** provide methods to access data relevant to the application, such as: remarkable repositories of postural models, data acquisition history, master data for the system use sessions, data warehouse for statistical investigations.
- **Classes related to the view** display data stored in the model and manage the interaction with users and agents, adapting the data presentation to the context of use, (intended as the couple of user profile - used device).
- **Classes related to the controller** receive user commands (usually through the view) or from capture devices (e.g. the Kinect sensors) and implement them by changing the status of the other two components.

Figure 1 schematically represents the proposed system software architecture in the large.

3.1 Data Layer

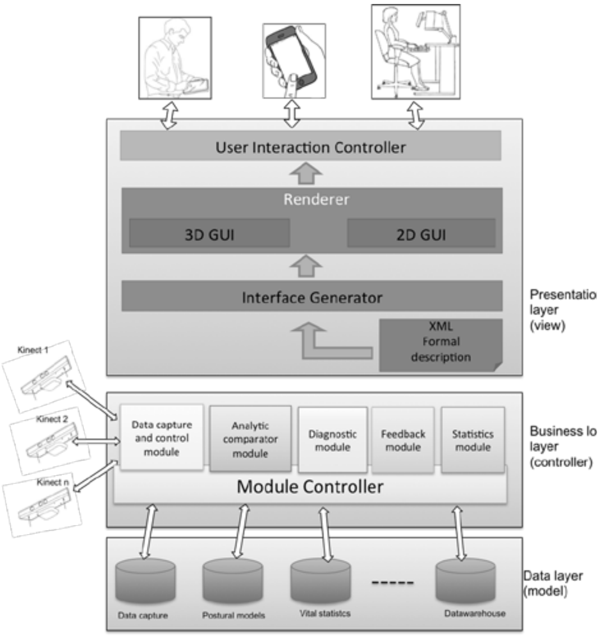


Figure 1. Software architecture in the large.

In this layer, all the data sources that the system must be able to acquire and manipulate (relational databases, XML files, binary files, data streams, images, etc.) are made available to upper layers. Access to information is allowed through calls that the controller module can perform directly to the specific repository of interest, or through an intermediate data structure like DAO (Data Access Object), capable of guaranteeing the separation between logical queries to data and database physical structure.

The available system repositories could be extremely various as for both their typology and their quantity. However, there will be at least the following structures:

- **Database of postural models**: it gathers the "templates" of all the correct postures each current acquisition has to be compared with (e.g., standing posture, sitting posture, walking posture, running posture, etc.).
- **Database of subject data capture**: this database contains detected postures for different patients under observation.
- **Database of reference data**: it stores patient data (master data), information about system users, system configurations, etc.
- **Data warehouse**: it is the repository that stores transactional data extracted from archives and it is accessible in read-only mode.

3.2 Business Logic Layer

This layer manages system application logic. It is divided into modules tailored to a set of specific functions detailed below.

The proposed system, according to the variety of data collected by different data capture stations, (also geographically distributed), gets a glimpse of new usage possibilities. Indeed, it allows to discover clinical trends indicating specific pathologies or correlations between pathology and patient lifestyle that would be otherwise extremely difficult to be found.

3.2.1 Data Capture and Control Module

It communicates with data sources (i.e., capture devices), sets system operating modes and "acquires" raw information from the sensors performing a run-time normalization of multiple readings of the same subject when the mode acquisition is multi-sensor.

3.2.2 Analytical Comparator Module

This module will refer to the "pattern matching" feature: in other words, it will perform a comparison between postures acquired through input sensors and the correct ones included within the database of postural patterns.

3.2.3 Diagnostic Module

It is able to process the "differences" (i.e., non-compliance) between two compared postures, highlighting their "criticalities" and supporting the user during the diagnostic or auto-diagnostic process.

3.2.4 Feedback Module

This module behaves as an expert system that "learns" from the various detections during time. Users have the opportunity to indicate any "corrections" in the surveys and comparisons thus instructing the system to provide each time more precise and calibrated data and diagnosis outcomes.

3.2.5 Statistics Module

It allows making synoptic data extraction through data warehousing techniques on all the surveys and providing textual and graphical statistics.

3.3 Presentation Layer

The presentation layer of the entire architecture is extremely important because, to be a truly effective tool for communication and control, it should be tailored to user needs (i.e., it should comply with a user-centered design), in order to maximize product usability.

The design and implementation of the presentation layer was started by searching for possible ergonomic, innovative interfaces that would be really effective in real-time interactions. The solution that we propose here is a multimodal and multi-channel user interface.

Multimodality allows the system to present information according to the user that is currently interacting with the device and with respect to his/her specific contextual needs. Indeed, after the registration phase, depending on the user that has logged in, the system dynamically generates a different interface. The user role determines which kind of elements the system should present to him/her. For instance, specialists are presented with a complete user interface, rich of medical indications, tailored to their area of expertise, in order to help them determining the proper diagnosis. In the same way, users desiring a self-diagnosis and exhibiting less medical know-how, are presented with a much more aggregated, essential and high-level interface.

The multi-channel paradigm has been developed according to the information on available channels and devices, as well as to their capabilities and the format data should have, in order to use the pair channel / device more proficiently. We provide the following potential types of devices to fruition, whose actual implementation will be agreed with the medical research team on the basis of requirements elicitation.

Workstation: it will behave as a classical standalone application.

Tablet: application developed as "apps" for multi-touch devices.

Smartphone: apps similar to the previous ones but exploiting devices with smaller screen, thus having less presentation and interaction modes.

Web: the system can be used as SaaS (Software as a Service) that will allow users (including non-specialized ones) to connect to the server through a local station (such as a notebook) equipped with the Kinect sensor(s) in order to use the system at full capacity.

In particular, the knowledge base contains the classification and detailed description of node profiles (user, channel, device) belonging to the considered system. The various elements making up the knowledge base are linked together by appropriate reasoning systems. The macro areas that the knowledge base should contain describe and classify the following aspects:

- users;
- channels;
- devices;
- data formats.

The reasoning system will be able to:

- classify information formats according to channels and devices;
- decide the best format suitable to convey the information, on the basis of both the pair channel - device and the data format.

Since the flexibility of representation is one of the keys to success in this kind of activity, we consider it essential to base the video-graphical interface on a formal XML description of its structure.

This choice has a two-fold advantage: firstly, it will allow to represent both the traditional 2D interface rendering and the most recent (at least in the medical field) semi-immersive 3D interfaces through which it is possible to show postural capture sessions. By doing so, clinicians may better analyze patients' issues.

Secondly, even the patient himself/herself will be allowed to perform preliminary self-diagnostic tests and to access those additional data complementing the information range in order to check analysis outcomes and diagnosis sessions.

4. TEST ENVIRONMENT

Since the described system is still under development, we could not perform a full test of all the features presented in the previous section. However, we succeeded to implement one of the most used medical protocol for posture analysis: the Stabilometric test.

4.1 Test Case Description

Stabilometry, which means "measurement of stability", deals with the characterization of patient sways when he/she is in an erect conditioned position under quiet, disturbance-free conditions (spontaneous sway). Indeed, the standing still position requires an effort to control small bodily fluctuations within specific limits, measured with this test.

A typical stabilometric session is performed both OE (open eyes) and CE (closed eyes), to enhance significantly the stabilizing effect of the visual system. This test also allows to assess cervical interferences on a back-warded-head posture (by calculating the Cervical Interference Index) and also to evaluate postural changes, in OE condition, while using correcting eyeglasses or corrective lenses (by calculating the Chieti Index).

In order to ascertain whether the balance in orthostatic conditioned position is maintained, the postural control system integrates the pertinent information input from the vestibular, visual and somatosensory systems. If one of these systems is impaired, the postural control system must handle the information provided by the various sensorial inputs so as to continue to perform its motorial task with an acceptable degree of reliability.

The analysis of the Center of Mass (CoM) position over a period of time is performed using an ad-hoc, internationally standardized graphical representation, named Stabilogram. This Stabilometric Test provides qualitative numerical indicators based on the detected parameters during each test. The results concerning this test are described in the following section.

4.2 Test Results

This sub-section illustrates the achieved results in terms of the interactions amongst the sensing system (i.e., MS Kinect), the Subject Under Observation (SUO) and the current version of the system GUI.

Figure 2 represents the adopted setup for the test case: the SUO is initially placed in front of the Kinect device. The Kinect is connected to a notebook where the system is running. The system GUI shows the relevant parameters of the Stabilometric test in a very straightforward and intuitive way, allowing the user (either clinicians or even the patients themselves) to have a rapid access to all the principal Stabilometric parameters.

At this point, it is important to recall both the Kinect Cartesian coordinate system and the Kinect skeletal acquisition mode [40] before starting to examine the system GUI.

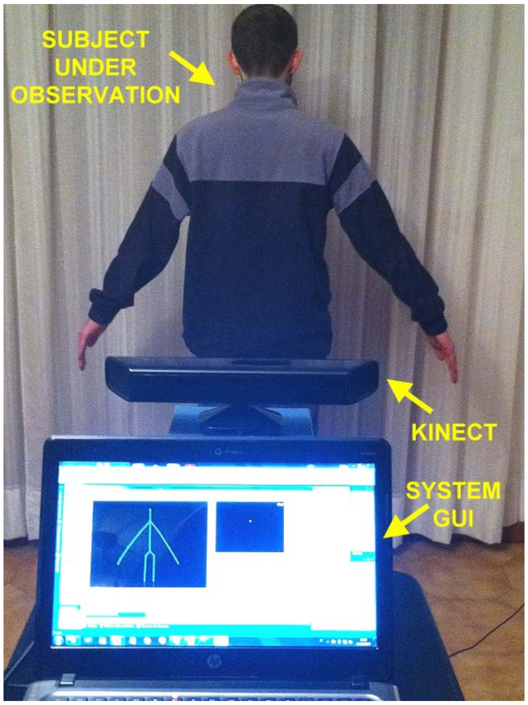


Figure 2. Initial setup for the Stabilometric test case.

As for the first aspect, the Kinect adopts a right-handed reference system where the device is at the origin, the positive X-axis extends leftward, the positive Y-axis points upward and the positive Z-axis extends in the direction along which the Kinect is pointed.

As for the skeletal representation offered by the Kinect, it can track two whole SUO skeletons both in standing still (full skeleton mode) and seated position (seated mode). In our system, only the full skeleton mode was considered, since the seated mode cannot be profitably used for acquiring complete observation of a SUO. Data streams coming from the Kinect represent skeletons as a collection of 20 joints connected by edges and fully described in terms of their spatial position. Kinect joints refer to specific body parts: ankles, elbows, feet, hands, head, hip, knees, shoulders, spine and wrists.

Our system complements the Kinect skeleton tracking capabilities with additional elements and views according to our research purposes, as detailed below.

Figure 3 depicts the GUI in details. The image on the right side of the GUI represents the skeleton of the SUO, tracked by the Kinect in full skeleton mode, according to the specifications provided above and generated thanks to the Kinect SDK. It serves as a simple visual reference for monitoring in real time the SUO position.

Both the joints (as green dots) and the bones connecting those joints (green lines) are shown for the tracked SUO. This view refers to the vertical plane of the Kinect coordinate system (XY plane), therefore it stands for the frontal-coronal plane of the SUO.

The central section of the GUI hosts two graphs for Stabilometric analysis. They are realized by our system, taking advantage of Kinect data streams. They refer to the Center of Mass (CoM) joint. Since the Kinect SDK does not provide such joint, we calculate it at run-time by considering the relative positions of the Kinect joints.

On the upper part, the actual CoM position is represented as an orange dot. A dotted orange oval shape represents the adopted Stabilometry Confidence Ellipse.

On the lower part, consecutive CoM positions are trailed and depicted as discrete orange dots placed on a reference polar plot in the background. By doing so, the sways occurring along both X-axis and Z-axis can be accurately examined. Both these views refer to the vertical plane of the Kinect coordinate system (XZ plane), that is the transverse plane of the SUO, therefore body oscillations in the sagittal-frontal planes, or anterior-posterior and lateral-lateral can be observed. Indeed, as the skeleton on the left image moves, both the actual CoM in the upper part and its trailing in the lower one moves accordingly. The system also shows the actual number of consecutive trailed CoM positions

The rightmost section of the GUI hosts additional Stabilometry indicators. Two progress bars quantify positional biases occurring between two consecutive CoM positions, along the X-axis and the Z-axis respectively. The measurements are expressed in [mm] and their numerical quantification is presented to the examiner as well. Moreover, the platform provides, at each moment in time, the CoM coordinates referred to the Kinect spatial reference system.

The GUI was delivered by the system in this way since the addressed clinician has user role exhibiting expertise in stabilometry.

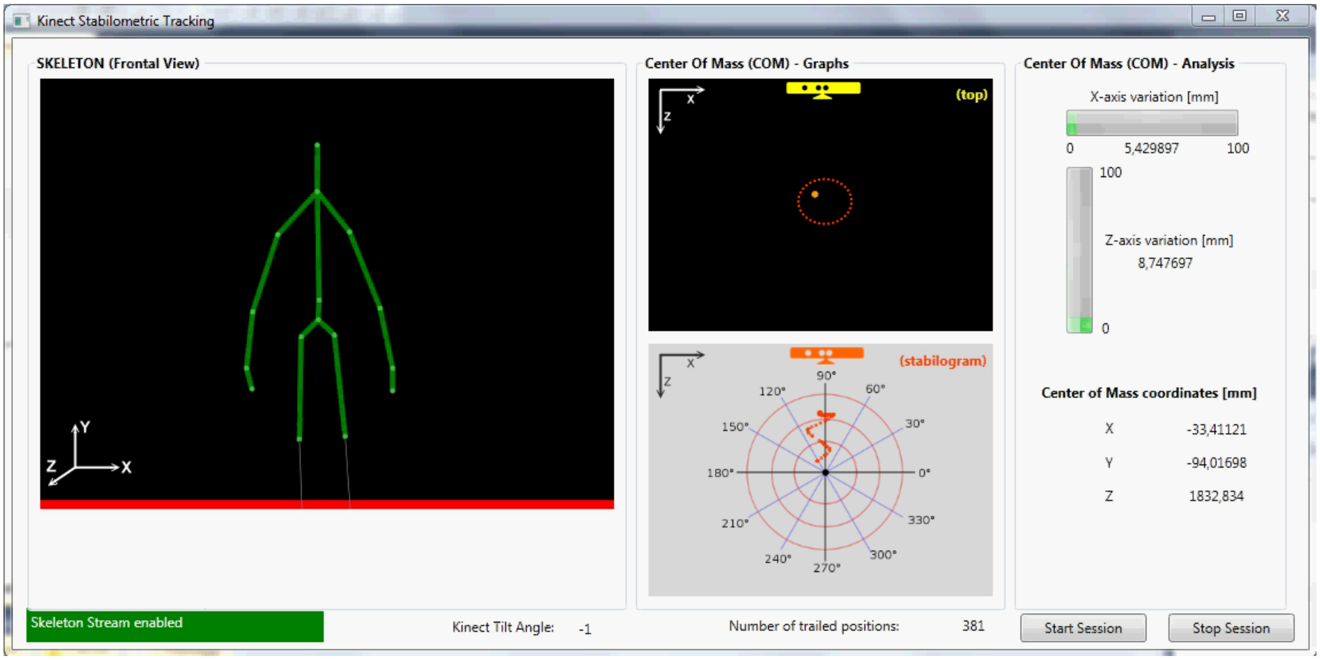
In the same way, the system calculates a set of useful data to monitor postural behavior of the SUO. The stabilometric analysis involves, amongst the other, the computation of following values, referred to an entire session of monitoring referred to the CoM:

- max rightward movement w.r.t observer, in [mm];
- max leftward movement w.r.t. observer, in [mm];
- max anterior movement w.r.t. observer, in [mm];
- max posterior movement w.r.t. observer, in [mm];
- max lateral-lateral movement w.r.t. observer, in [mm] (this value describes the maximum sway of the SUO's CoM occurred during the monitoring session along X axis);
- max anterior-posterior movement w.r.t. observer, in [mm] (this value describes the maximum sway of the SUO's CoM occurred during the monitoring session along Z axis);
- average speed of lateral-lateral movement, in [mm/s] (this value quantifies how quickly the SUO's CoM moves along X axis);
- average speed of anterior-posterior movement, in [mm/s] (this value quantifies how quickly the SUO's CoM moves along Z axis).

Since the system is at its initial, although very promising, development stage, many additional elements for Stabilometric analysis are currently under implementation, such as: estimation of the energy consumed by the patient to maintain the erect position, frequency analysis of body oscillations (Fourier analysis and Power Spectral Density) and Stabilometry specific indexes (B.P.I). In the same way, a detailed comparison between our system results and commercial stabilometric systems is under way.

5. CONCLUSIONS

According to the mission of the KISS-Health idea, the researchers are implementing new protocols to prevent postural injuries, needing at the same time a technique for human body kinematic estimation that does not require markers or fixtures on the body. The Kinect sensor has opened the path for developing many applications in several different areas. Medical and health applications are benefitting from the Kinect as it allows non-invasive body motion capture analysis that can be used for example in motor rehabilitation or phobia treatment. Anyway, in



X-axis variation [mm] 5,429897

Z-axis variation [mm] 8,747697

Center of Mass coordinates [mm]

X	-33,41121
Y	-94,01698
Z	1832,834

Kinect Tilt Angle: -1

Number of trailed positions: 381

Figure 3. Output of Stabilometric analysis performed on a SUO. The system GUI shows the SUO tracked skeleton (on the left), the actual COM position (on the center, top), the trail of previous COM positions (the so-called "Stabilogram", placed on the center, bottom of the GUI), the dimensional biases along X and Z axes between the actual COM position and the previous one (on the right, top) and the actual COM coordinates (on the right, bottom).

recent times, newer and more accurate sensors are already available on the market, such as leap 3D by Leapmotion [41] which claims to offer 200x the accuracy of anything else on the market, that equates to an accuracy of 0.01mm. Moreover, Microsoft itself has released a new motion controller, the Kinect 2, along with its new console: the Xbox ONE, which is provided by a full HD sensor showing an increased detail (1920 x 1080 x 16 bpp 16:9 YUY2 @ 30 fps) and depth data (512 x 424 x 16 bpp, 13-bit depth).

This new generation devices let the authors envisage a new set of more accurate medical related applications, that would be a real and effective counterpart of medical equipment devoted to image analysis performed in specialized diagnostic laboratories. According to this, a postural monitoring system based upon a well-established software architecture and exploiting data streams provided by capturing devices (i.e., MS Kinect) has been proposed, showing its effectives in a concrete use case scenario for stabilometric tests. Early results, even if not yet compared with professional systems, are very promising in terms of system responsiveness and level of details.

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