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Technical note

# A markerless sub-pixel motion estimation technique to reconstruct kinematics and estimate the centre of mass in posturography

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**Abstract**

A novel method to evaluate postural sway is presented: balance strategies are identified by applying a markerless image processing algorithm to video sequences obtained from commercially available systems.

The motion estimation technique for the analysis of video sequences is a coarse to fine procedure based on the block matching algorithm (BMA). The method makes it possible to estimate the movement of selected elements on the scene with a sub-pixel precision. It has been done by applying a bicubic spline interpolation to the coarse results obtained by the BMA.

Results achieved through the analysis of synthetic video tests make it possible to determine the accuracy of the proposed sub-pixel algorithm. Figures show how the proposed method can be confidently applied to evaluate postural sway.

The proposed method has been applied to videos recorded during orthostatic posture trials in different conditions, and to combined tests where signals from a balance plate have been acquired simultaneously to the video sequence. The results show the usefulness of the proposed approach in order to evaluate balance strategies in posturography.


*Keywords:* Human motion analysis; Markerless systems; Sub-pixel motion estimation; Posturography

## 1. Introduction

Upright stance is a not trivial task that deals with keeping several joints and muscle groups in a geometric relationship with the environment [1]. In biomechanics the human body is generally considered as a multi-segmental system, composed of body segments interconnected through hinges. Even when required to stand still, the human body cannot be considered as a motionless structure, and continuous action of the central nervous system (CNS) is necessary to maintain balance. In the literature, it has been suggested that in order to counteract gravity and control balance the CNS performs by using essentially the so-called ankle and hip strategies [2]. The ankle strategy controls the body's barycentre, the centre of mass (COM), by generating a torque at the ankle level, which counteracts torques due to gravity or other disturbances, thus moving the whole body as a simple inverse pendulum. In the hip strategy, the body is controlled by minimizing the COM trajectory, through the generation of active torques both at the hip and at the ankle level. Regardless of the specific strategies adopted by the CNS, tiny body oscillations are always present, both in anterior/posterior and in medium/lateral directions.

To gain information on these body oscillations, force plates [3,4] and marker-based systems [5] are generally used in order to achieve both the dynamics and kinematics [5,6].

Force plate allows to measure the instantaneous position of the ground reaction force application point, the so-called centre of pressure (COP) [7], while stereophotogrammetric systems make it possible to capture the coordinates of a set of markers, either active or passive, which are fixed on the anatomical landmarks whose spatial trajectories are to be measured [8–12]. Marker systems show high levels of accuracy: tests made by Ehara et al. [12,13] yield root mean square errors between 2 and 5 mm for passive systems and less than 1 mm for active ones. Despite their accuracy, stereophotogrammetric systems are not disseminated in reha-

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bilitation contexts, as they are costly and so time consuming in setting up that could cause patients to feel uneasy.

More recently, some authors tried to come up to the requirements in terms of time and cost-effectiveness, by applying techniques derived from computer vision to track relevant elements without using markers, i.e. markerless. Thus, markerless motion analysis performs the activity of studying and estimating human motion by applying image processing techniques [14].

Literature shows several techniques that can be classified on the basis of the presence of a priori body models, for tracking and pose estimation processes [15,16]. The topic is widely studied and is still up to date, as it is demonstrated by recent works. Aggarwal and Cai [15] review existing motion estimation techniques and compares the performance of model-based and model-free approaches and more recently, a survey by Gavrila [14] has provided a general introduction to the topic with a special focus on different applications.

Model-based approaches use the information about human body shape in order to reconstruct the entire gesture kinematics [17]. Some of them represent the body with a probabilistic region model [18] or a stick figure [19]. More advanced algorithms assemble a kinematic skeleton by means of simple shape primitives, such as cylinders [20], ellipsoids [21–23] or superquadrics [24].

Model-free approaches analyse video sequences in order to estimate the movement of regions of interest, usually enclosing relevant anatomical points, without any preliminary information about object shape [25]. They can be roughly grouped into four categories [26]: gradient [27], pixel recursive [28], transformed domain [29], and block matching [30].

The choice of the approach should be deeply influenced by the application. In fact, it does not exist a golden-standard technique and the single performance varies with respect to the problem under exam.

In this work, by proposing a model-free approach to track and estimate the pose of points on human body, the authors aim at assessing the performance of proposed technique when dealing with the tiny oscillations of the body during orthostatic posture tests.

The markerless method proposed in this work analyses video sequences from a commercial camera by applying a "coarse to fine procedure" which allows estimating the trajectories of specific anatomical points, with a sub-pixel precision. The video sequences have been recorded during the execution of orthostatic posture trials and the position of the camera has been chosen to analyse postural sway in the sagittal plane. In order to estimate the position of body segments through time, trajectories of relevant junctions have been evaluated. Data obtained from the proposed method allow the extraction of thigh flexion-extension, and foot plantar-dorsiflexion among others, and therefore the identification of the postural strategy used to maintain balance. Results obtained on tracked elements, supplemented by anthropometric data [31,32], make it possible to estimate the COM projection on the sagittal plane through time.

The presence of a balance plate could make it possible to verify the reliability of the obtained results on kinematics, and to add information on the dynamics of postural trials. As a corollary, a human body model has been used in order to reconstruct and represent joint kinematics of postural movements during the trials.

## 2. Materials and methods

In this section, the proposed approach is described by detailing the theoretical background, and its application to synthetic and experimental video sequences.

### 2.1. The proposed technique

The proposed technique aims at tracking and reconstructing body segment movements in the sagittal plane, by analysing consecutive frames from video sequences recorded during the execution of orthostatic posture trials. The procedure consists of the following consecutive steps:

- tracking of relevant points on the human silhouette [33,34] (*Tracking*);
- evaluation of the rotations of the principal body segments [35] (*Body Pose*) and then estimation of COM trajectories (*COM estimation*).

#### 2.1.1. Tracking

The technique exploits information on the correlation between consecutive frames [33] and relies on a two-phase procedure: a block matching technique, followed by a fine interpolation.

In posturographic tests the body oscillations are typically not greater than a few centimetres. Thus every point of the silhouette was assumed as moving according to a sum of rigid translations. In this case, each pixel $\underline{r}$ of the moving silhouette undergoes the same movement, and thus the movement of $\underline{r}$ in $[t, t+\Delta t]$ can be expressed as

$$\underline{I}(\underline{r}, t+\Delta t) = \underline{I}(\underline{r}-\underline{d}, t) + e(\underline{r})$$

where $\underline{r}=x+jy$ represents the coordinates of the selected pixel, $I(\underline{r}, t)$ and $I(\underline{r}, t+\Delta t)$ are the frames recorded respectively in $t$ and $t+\Delta t$, and $e(\underline{r})$ accounts for the model error and for the noise; $\underline{d}$ represents the motion vector of the selected element in the frame plane.

The objective of the technique is to estimate the motion vector by a coarse to fine procedure. The coarse estimation of the motion vector, with a standard block matching algorithm, minimizes an integral cost function $\mathrm{CF}(\underline{d}, t)$ over the block of dimension $W$ centred in $\underline{r}$:

$$\underline{d}_{\underline{r}}^{\mathrm{INT}}(t) = \arg\min_{\underline{d}\in A} \mathrm{CF}(\underline{d}, t)$$