A virtual system for postural stability assessment based on a TOF camera and a mirror

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ABSTRACT

Postural stability is often compromised in many pathological states and decreases with age. In clinical practice, an objective tool for balance is fundamental. Recently, virtual tools, based on the use of depth cameras, have been presented. In this paper, a new virtual system for postural stability assessment was presented, involving the use of a Time of Flight camera (TOF) and of a mirror for the reduction of the occlusions errors by allowing the camera to see the hidden body surface. The validity of the tool was assessed through some experimental results. Data were also compared with those measured by a physical force platform and those calculated with another virtual stability assessment system, in order to highlight the error reduction while maintaining simplicity and low-cost.

CCS Concepts

•Computing Methodologies → Artificial Intelligence → Computer Vision → Image and video acquisition → 3D imaging; •Computer Applications → Life and medical sciences → Health informatics.

Keywords

Balance Control; Postural Sway; COP; COG; Force Platform; TOF Camera; Mirror.

1. INTRODUCTION

Balance control is the ability to maintaining the body Center Of Mass (COM) within its limits of stability. This capability, fundamental for controlling body movement, decreases with age [1] and could be compromised by many pathologies [2-4]. Both for diagnostic purposes and for assessing therapeutic progresses an objective and quantitative postural balance measure is needed. Recently, the effectiveness of a new generation of virtual instruments, exercises and practices for rehabilitation, have been studied and developed [5-9].

The assessment of the postural sway can be defined statically, if measurements are made while the subject tries to remain still standing, or dynamically, if the measurements are made under the effects of balance perturbations (these are important to assess the recovery from a loss of balance) [10]. Obviously, systems allowing dynamic measurements are also usable for static studies. Postural sway could be estimated starting from kinetic or kinematics parameters. Kinetic information include the excursion of the Center of Pressure (COP), applied to a support surface, and measured by means of clinical force platforms [11] or low-cost commercial instruments, like for example the Wii Balance Board [12]. Kinematic data could be used to estimate the spatial position of the Center of Mass and, consequently, its vertical projection on the ground, the Center of Gravity (COG). It could be measured by using wearable inertial sensors [13] or optical motion analysis, like that described in [14]. In particular, in [14] a low-cost tool for COM/COG assessment, based on a TOF camera was illustrated. During a virtual balance task, the COG excursions were recorded and compared with the movements done by COP, acquired by means of a force platform. Results showed that this tool was able to assess the sway of the human body also in dynamic conditions. The system had a lower dynamic range than a physical force platform, mainly due to the difference between COG and COP [15]. However, those differences were more evident in the Medio-Lateral (ML) direction of the subject movements than in the Antero-Posterior (AP) direction. This systematic error was produced because the Field Of View (FOV) of the camera was partial. Moreover, to ensure a real-time response, the model of the human body was approximated by a reduced set of spheres over the depth map. To overcome these issues, in this paper a refined version of the assessment method was presented. The method taken advantage from the presence of a mirror in the scene, whose orientation allowed the focusing of occluded portions of the body. The use of a mirror, instead of other TOF cameras, was twofold: it maintained low-cost; it avoided multiple-camera synchronization and high-frequency acquisition.

The proposed method was validated by comparing the measured COM/COG movements with the COP excursions, observed by

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means of a force platform [16], and with data calculated with the method proposed in [14], during the execution of a virtual balance task, in dynamic conditions.

The rest of the paper is organized as follows: Section 2 illustrates the proposed method, Section 3 shows and discusses some experimental results, Section 3 reports conclusions.

2. THE PROPOSED METHOD

In the proposed method, the room was equipped with a single TOF-RGB camera and a plane mirror for collecting information about occluded portions of the subject body (the position of the mirror was studied in order to occupy a part of the scene usually not occupied by the subject, as clarified below). This information, merged with those obtained by the direct point of view, allowed the refinement of the COG assessment.

In order to obtain the depth map, a TOF camera enlightens the scene with an incoherent light signal, in the non-visible near infrared range of the spectrum, modulated in amplitude by a sine of frequency f_{mod}. The light signal travels with constant speed in the air and is reflected by the surface of objects. By measuring the phase-shift φ_{shift} between the emitted and the reflected light signal (by means of an infrared sensor), the distance d_k of the object k from the camera plane, is:

$$d_k = \frac{c}{2f_{mod}} \frac{\varphi_{shift}}{2\pi} \qquad (1)$$

where c denotes the speed of light, f_{mod} represents the modulation frequency, φ_{shift} the phase shift. The value of d_k is proportional to the phase-shift value φ_{shift}. When the phase-shift overcomes 2π, the calculated distance loses in distinctiveness: for this reason, the maximum distance of the object from the camera depends on the modulation frequency f_{mod}. By knowing the horizontal and the vertical fields of view of the TOF camera, it is possible to compute the spatial coordinates of a point $k = (x_k, y_k, z_k)$, referred to a three-dimensional Cartesian coordinates system with its origin corresponding to the center of the camera sensor, X and Y forming the camera plane and Z orthogonal to the X-Y plane.

The placement of a mirror in the scene (Figure 1) allows the indirect observation of an object, through its reflection: the modulated signal is reflected by the mirror, hits the object and, following the same path, goes back to the sensor. A virtual space behind the mirror plane contains the reflection of the object and of the sensor. The reflected object is like the real object, seen by a virtual sensor, after a horizontal image inversion.

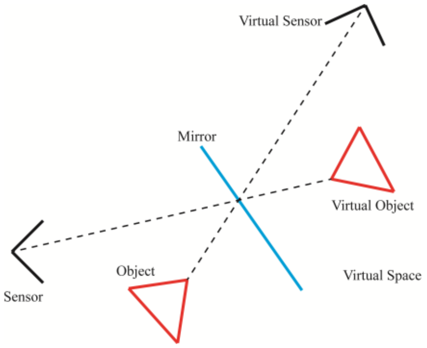

Figure 1 – A mirror placed in the scene creates another point of view.

If the equation of the plane m containing the mirror surface with respect to the coordinate system is known, it is possible to estimate the position of the real object using information from the reflected one. In fact, let $ax + by + cz + d = 0$ be the equation of m, it's possible to derive the point $p = (x_p, y_p, z_p)$ from its reflection $q = (x_p, y_p, z_p)$, by using the equalities of the straight line l for p and orthogonal to the plane and of the distance from a point $t = (x_t, y_t, z_t)$ on the plane of the mirror. By solving the system below we obtain the solutions representing the coordinates of the point p from its reflection q:

$$\begin{cases} \dfrac{x_q - x_p}{a} = \dfrac{y_q - y_p}{b} = \dfrac{z_q - z_p}{c} \\ \sqrt{(x_q - x_t)^2 + (y_q - y_t)^2 + (z_q - z_t)^2} = \\ = \sqrt{(x_p - x_t)^2 + (y_p - y_t)^2 + (z_p - z_t)^2} \end{cases} \qquad (2)$$

Figure 2 shows a schematic representation of the environment that we used for our system assembly, containing a mirror placed in the higher portion of the scene never occupied by the subject. This placement ensured both that the mirror was not occluded by the subject and allowed to reserve a specific region of the scene for the pixels to be marked (see below). Two foreground images are visible to the camera: the direct image and the one seen through the mirror (they can be extracted from the depth map by means of a background removal operation).

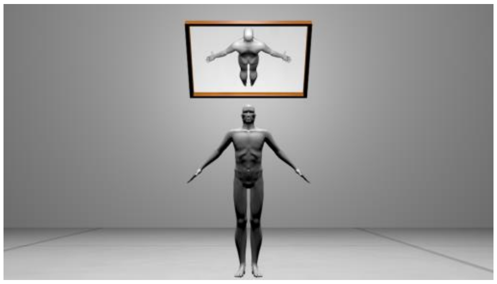

Figure 2 – Example of an environment containing a mirror, from the camera point of view.

The proposed approach consisted of three phases: calibration, 3D positioning and COG assessment.

The calibration phase aimed at computing the position of the mirror with respect to the camera sensor (i.e. the equation of the plane in the space that contained its surface). This operation had to be performed just once, when the system was installed. In order to find the plane equation, the coordinates of the same point both in the real and in the virtual space had to be known. Theoretically, it would have been possible to observe the same point directly and by its reflection with the TOF sensor and to compute its spatial coordinates through the depth map, but the low resolution of the IR sensor could leads to significant numerical errors that could heavily affect the calibration phase, and, consequently, the reflection of the points. However, TOF cameras are normally equipped with an RGB sensor that has a good resolution. The proposed calibration strategy was based on camera stereo calibrations (performed by means of the Camera Calibration Toolbox for Matlab [17]). First, the position of RGB sensor with respect to the IR sensors was found, by using a set of images of a special chessboard formed by alternating opaque and reflective squares, visible from both sensors. Then, a set of images of the same chessboard, seen both directly and through its reflection, was used to discover the reciprocal positions of the two RGB sensors (the real and the virtual one). Knowing the position of the virtual RGB sensor with respect to the real one and the position of the latter with respect to the IR sensor, allowed to evaluate the position of a point (real RGB) and its reflection (virtual RGB) with respect to the system coordinates centered in the IR sensor and, consequently, the mirror plane equation. In this phase, the coordinates of a pixel in the depth map, belonging to the ground, were calculated, in order to store the height H of the camera from the floor. The 3D positioning phase aimed at computing, for each frame, the spatial coordinates of the subject surface points, using the pixels allowing both to the direct foreground and to the reflected one. This phase consisted of three steps, as shown in Figure 3 for a lateral point of view. First, each point of the foreground was determined in the 3D coordinates system (direct and reflected images were managed in the same way). Then it was marked as “real”, if belonging to the same half-space of the system origin, or as “virtual” elsewhere (respectively red or green in Figure 3b).

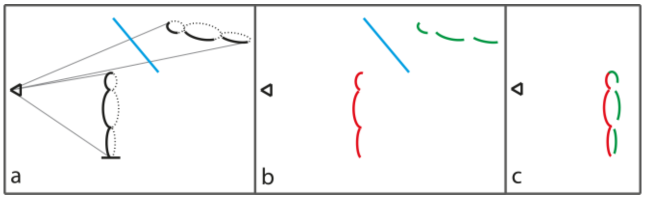

Figure 3 –3D positioning phase main steps: foreground 3D determination (a), real/virtual pixels marking (b), virtual pixels reflection (c).

This operation was simplified by reserving a region of scene to the mirror. Finally, the reflection with respect to the mirror plane was applied to each virtual pixel, by using Equation 2. In this phase, the original distances from the camera of the foreground pixels were stored in memory (they are needed to compute pixel weights in the next phase, as clarified below). The COG assessment of the proposed approach differed from that described in [14], since in the present method no sampling algorithms was used (each foreground pixel was considered). A weight-based approach was used in order to normalize the pixel contribution to the COG evaluation, proportionally to the body surface covered by it (a near pixel would have a lower contribution with respect to a farther one). In fact, given a frame, for each pixel i belonging to the foreground F, the weight to be considered was:

$$w_i = \frac{d_i^2}{\sum_{j \in F} d_j^2} \tag{3}$$

where d_i was the pixel distance from the camera from Equation 1. The COM coordinates were computed as follows:

$$COM = \left(\sum\nolimits_{j \in F} w_j x_j \, , \sum\nolimits_{j \in F} w_j y_j \, , \sum\nolimits_{j \in F} w_j z_j \right) \tag{4}$$

while the COG coordinates, corresponding to the vertical projection of the COM on the ground, were the following:

$$COG = \left(\sum\nolimits_{j \in F} w_j x_j \, , -H, \sum\nolimits_{j \in F} w_j z_j \right) \tag{5}$$

3. TOOL VALIDATION

In order to validate the proposed system, a comparison between data obtained from it (M2) and those obtained by a force platform [16], and a comparison between data obtained from the method proposed in [14] (M1) and those obtained by a force platform were performed. The datasets, representing the COG (obtained with both the virtual methods) and the COP (obtained by a physical platform) excursions, were recorded during the execution of 2-minutes sessions of the virtual task described in [14] and implemented with the framework described in [7]. The subject had to recover the equilibrium, standing barefoot, with the arms along the body, on a virtual circular board, that could oscillate as though it was fixed to an invisible cable secured to an invisible point 2.5 m above. The board was affected to randomized perturbations.

The virtual stability assessment system was composed of a TOF camera [18], located at 3.5 m from the expected subject location and 1.45 m from the floor, and a squared mirror (1.5 m sided), positioned with its center at 4.5 m from the camera and 2.35 m from the floor. The mirror was inclined by 50° with respect to the vertical position.

The implementation of the virtual task required a projection screen (1 m x 1.2 m), used to show the virtual scene to the subject, positioned at 1.5 m from the subject area, along the direction orthogonal with respect to the axis subject-camera. In this way the subject could see the virtual environment on the screen. The subject had to stay on a physical force platform and his COP was registered during the exercise, for comparison. It is important to note that the projection screen and the force platform [16] were not part of the virtual stability system. The subject model, for the real time representation, was reconstructed by the framework, while the depth map (recorded at 25 fps to ensure synchronization between virtual methods and the physical platform) was stored and analyzed in off-line, to obtain COG information.

Experimental data were collected by 5 young healthy subjects (3 women and 2 men, average age 26.6y, σ=2.7y, average height 1.72 m, σ=0.08 m, average weight 68 kg, σ=12.4 kg). Each subject executed a 2-minutes session. The resulting data were analyzed with Matlab [19] and the following parameters for each movement axis (ML and AP) were computed: maximum error (platform COP data were used as gold standard), average error with the relative standard deviation. The results are summarized in Table 1.

The results show two main points: 1) M2, like M1, had a lower dynamic range with respect to the force platform, due to the discrepancy between COP and COG; 2) as compared to M1, M2 exhibited a lower discrepancy (both in terms of maximum and average errors), confirming that part of the differences of M1 with the force platform were due to the the lack of information from the hidden parts of the subject body and to the model approximation.

Table 1 – Personal data (grey) and error analysis, for all the tested subjects, for both the virtual methods, each compared with the physical platform.

Subject #	**1**	**2**	**3**	**4**	**5**
Age (years)	25	30	23	28	27
Gender	F	F	F	M	M
Height (m)	1.65	1.62	1.75	1.82	1.74
Weight (kg)	55	61	63	86	75
M1 Max ML err. (mm)	11.0	5.2	13.3	10.9	14.2
M1 Max AP err. (mm)	18.4	20.7	21.0	16.5	19.5
M1 Avg. ML err. (mm)	0.6±2.0	0.3±2.2	0.6±3.8	0.6±2.3	0.4±2.9
M1 Avg. AP err. (mm)	0.6±4.3	0.8±3.7	0.7±4.4	0.5±5.1	0.6±4.0
M2 Max ML err. (mm)	4.3	6.9	8.8	7.4	6.7
M2 Max AP err. (mm)	6.6	11.4	12.7	13.0	9.1
M2 Avg. ML err. (mm)	0.2±1.5	0.3±1.8	0.4±2.6	0.3±1.5	0.1±2.0
M2 Avg. AP err. (mm)	0.3±2.7	0.1±1.4	0.2±1.1	0.2±2.4	0.4±1.8

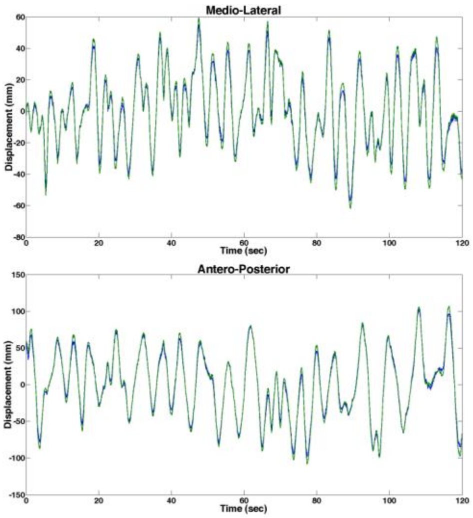

Figure 4 – COG (blue) and COP (green), computed, respectively, with the proposed tool and the force platform. ML and AP components are shown separately.

Figure 4 reports, as an example, the ML and AP trajectories for subject #3 both for M2 (COG, blue line) and for the physical platform (COP, green line) during the exercise. These data confirmed that the followed trajectories were very similar to those of the physical platform and that the relative errors were really low.

4. CONCLUSIONS

The proposed method demonstrated a better accuracy than a previous method [14], while maintaining the cheapness of the old method. The new approach required the positioning of a mirror in the scene, but in a region (the highest part of the room) where it did not represent an obstacle for the movements of the analyzed subject. The calibration operations were simple and done just once. With this tool, the balance control ability cold be assessed as frequently as needed both with monitoring aims or, coupled with a framework like that in [7], as part of the training activities. In the current version, the proposed method could be used just in an off-line mode (we preferred precision to real-time): though this is not a real limitation for balance assessment, work is in progress in order to optimize it and to regain real-time without reducing precision (in this case, also the presence of more than one mirror can be considered).

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