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Technical note

Measuring trunk orientation with a CMOS camera: Feasibility and accuracy

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Abstract

The purpose of this study was to develop and validate a new tool to objectively quantify trunk orientation at the bedside, especially dedicated to the measurement of the lateropulsion in acute and subacute stroke patients. We developed software to analyze 2D movement with a CMOS camera (Logitech® Quickcam Pro 4000) and to calculate the orientation of a segment defined by two color markers. First, the accuracy, reproducibility and noise when measuring segment orientations were evaluated with the CMOS camera placed in different positions, and second trunk orientation was measured in static and in dynamic conditions both with a CMOS camera and with a gold standard 3D video system (BTS SMART-e). Results showed that the measurement was accurate (mean error = $0.05 \pm 0.12°$), reproducible (S.D. over five measurements = $0.005°$) and steady (noise signal = $0.02°$). The data obtained with the CMOS camera were highly correlated with those obtained with the 3D video system both in static and in dynamic conditions. However, the CMOS camera must be relatively well centered on the measured segment to avoid error due to image distortion. The parallax error was negligible.

In conclusion, this could be an important step in the postural assessment of acute and subacute stroke patients. The CMOS camera, a simple, portable, compact, low-cost, commercially available apparatus is the first tool to objectively quantify lateropulsion at the bedside. This method could also support the development of a rehabilitation program for trunk orientation based on biofeedback using the real-time signal provided by the device.

Keywords: Stroke; Lateropulsion; Measurement

1. Introduction

The control of trunk orientation is frequently perturbed after stroke, impairing sitting balance and delaying walking recovery [1]. Although lateral tilt of the trunk in sitting and/or in standing (lateropulsion) is a primary postural disorder after brainstem [2] and hemisphere strokes [3,4], its detection and quantification rely only on subjective ordinal scales [5–7]. A more objective and precise assessment tool would be helpful for both medical practice and research. 3D movement analysis systems would provide accurate data of linear and angular displacement, velocity or acceleration but might appear inappropriate in patients who are too fragile to be moved to a movement analysis laboratory at the acute stage. Because there was a need for a more simple and portable system for measuring trunk orientation after stroke, we developed software to analyze 2D movements with a CMOS camera. Such a system also provides real-time information, which may support rehabilitation programs based on feedback. In this paper, we investigated the feasibility and reliability of measuring trunk orientation with a commercial CMOS camera. First, accuracy, reproducibility, and noise of the measurements were evaluated by measuring the orientation of calibrated segments. Second, angular displacements corresponding to trunk rotation in the frontal plane were measured with both the CMOS camera and a gold standard 3D movement analysis system.

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2. Methods

2.1. Recording system and digitizing process

The implemented system was a CMOS camera (Logitech® Quickcam Pro 4000 – 30 images/s – video resolution 640×480 pixels) connected to a PC. Specific image processing algorithms were designed to analyze the image, recognize two color markers and calculate their centroid in order to obtain, in real time, the inclination angle of a segment defined by the two markers. Image processing algorithms were developed using Visual C++® language and consisted in the following sequence: local grey-level histogram analysis, image segmentation using dynamic thresholding, marker extraction using edge detection and color analysis.

In the second part of the study, the motion capture system BTS SMART-e (120 images/s – video resolution 768×576 pixels – measurement accuracy < 0.3mm on a volume of $3\ m \times 2\ m \times 2\ m$) was used as a gold standard (http://www.zflomotion.com/software/bts_smart.php).

2.2. Accuracy, reproducibility and noise

In order to test the validity of the CMOS camera for measuring segment orientations, a frame of reference comprising 10 oriented segments was constructed, and placed 150 cm in front of the CMOS camera. Their lengths (from 40 to 45 cm) and orientations (from -32° to 26.6°) were determined so as to be similar to what could be measured in a patient showing lateropulsion. To measure the orientation of a given segment, two color markers (blue, diameter = 0.8 cm) were placed at its two extremities. Each segment orientation was measured five times. One acquisition lasted 10 s. The accuracy was assessed by the error between the measured and the true orientations. The reproducibility was analyzed using the standard deviation over the five measurements of each segment orientation. The signal noise was analyzed using the standard deviation over the 10-s acquisition time for each segment orientation.

2.3. Parallax errors due to 2D data acquisition

First, the accuracy of measurement was tested with the CMOS camera placed at different distances (85, 100, 150 and 200 cm) from the frame of reference. Second, the influence of the CMOS camera translation and/or rotation on measurement accuracy was tested. The CMOS camera was placed in five positions with respect to the frame of reference: centered (see above), translated 35 cm rightward (RT35) or leftward (LT35), i.e. to the extremities of the camera vision field, translated outside the vision field at 60 cm rightward (RT60) or leftward (LT60) with a 15° compensatory rotation. One-way ANOVA was performed to compare the CMOS camera positions. Third, segment orientations were measured with out-of-plane positions in order to test the effect of torso rotation or flexion on measurement accuracy. The frame of reference was inclined either 20° forward or 25° backward and then rotated either 30° rightward or leftward.

2.4. Measurement of trunk orientations

Trunk orientations were measured in static and dynamic conditions simultaneously with the CMOS camera (sample rate: 10 Hz) and the SMART-e movement analysis system (sample rate: 120 Hz) in one subject who gave his informed consent to participate in this study approved by the local ethical committee. Two specific markers were designed to be recognized by both the CMOS camera and the SMART-e system. They were positioned on the spine axis, at TH5 and L3. The CMOS camera was positioned 100 cm behind. Three SMART-e 3D cameras were used and calibrated in order to define a $3\ m \times 2\ m \times 2\ m$ space including the subject seated on a chair without a backrest.

Regarding the static condition, the subject was instructed to incline the trunk laterally to a given position determined by the experimenter and to hold this position for 15 s. Seven trunk orientations corresponding to one vertical posture, one mild, one moderate and one pronounced tilt (left and right sides) were measured three times. Regarding the dynamic condition, the subject was instructed to make cyclic trunk movements in the frontal plane ranging from -30° to 30° of inclination, at different angular velocities: low (a posteriori $5^\circ\ s^{-1}$), moderate (a posteriori $13^\circ\ s^{-1}$) and fast (a posteriori $18^\circ\ s^{-1}$) with an adjusted period of time to obtain more than four cycles for each trial. Three trials at each speed were recorded.

Regarding the static condition, data for each orientation were averaged and the error was calculated as the difference between the mean SMART-e angle and the mean CMOS camera angle. In addition, the correlation between measurements obtained by the two systems was calculated.

Regarding the dynamic condition, a cross-correlation between the data acquired by the two video systems was performed in order to analyze the coefficient of correlation and the possible time lag between the two signals. Due to different sample rates for the CMOS camera (10 Hz) and the SMART-e system (120 Hz), the acquired data were synchronized at 10 Hz.

3. Results

3.1. Accuracy, reproducibility and noise

The measurement of segment orientations with the CMOS camera placed 150 cm from the frame of reference was very accurate (mean error ± S.D.: $0.05 \pm 0.12^\circ$, mean absolute error: 0.11°). The reproducibility of the CMOS camera was high since the standard deviation over four measurements of the segment orientations was on average 0.005°. The noise signal was low since the standard

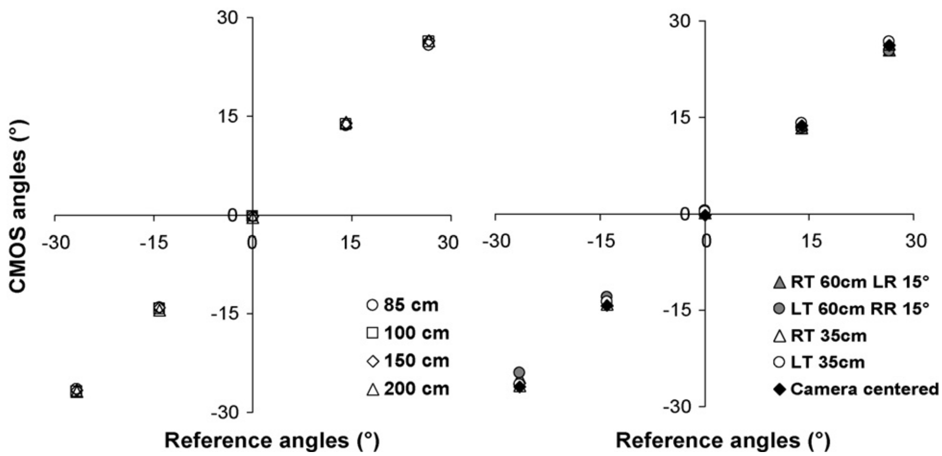

Fig. 1. Parallax errors. (Left part) Five segment orientations measured with the CMOS camera placed at different distances from the frame of reference. (Right part) Five segment orientations measured with the CMOS camera translated or/and rotated from the frame of reference. The camera positions were abbreviated—RT: right translation, LT: left translation, RR: right rotation, and LR: left rotation.

deviation over the 10-s acquisition time was on average 0.02° for all acquired data in static conditions.

3.2. Parallax errors due to 2D data acquisition

As shown in Fig. 1 (left part), the distance of the CMOS camera from the frame of reference (from 85 to 200 cm) did not significantly change the measurement accuracy. In contrast, there was an influence of the camera translation and/or rotation on measurement accuracy ($F = 18.04$, $p < 0.001$) (Fig. 1, right part). Post hoc analysis showed lower accuracy in the positions RT60 (mean absolute error: 0.76°) and LT60 (mean absolute error: 1.04°) as compared to the other positions, with no differences between positions RT35 and LT35 compared to the centered position. For large out-of-plane motions, measurement errors increased all the more so the measured angle was high, although the errors remained negligible for segment orientations under 10° (Fig. 2).

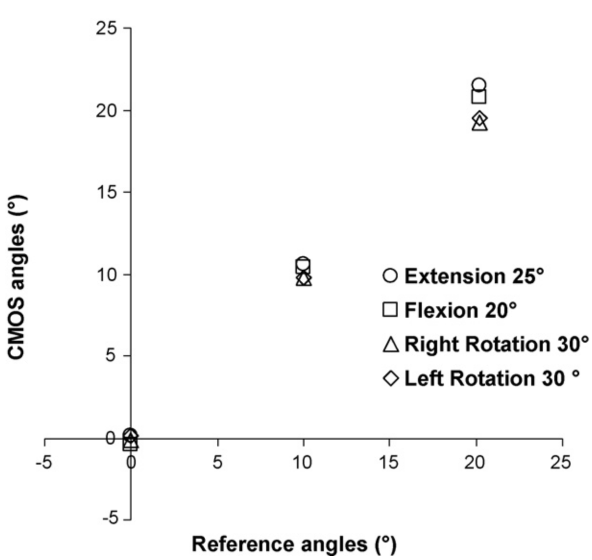

Fig. 2. Three segment orientations measured with the CMOS camera placed at 150 cm from the frame of reference which was inclined either 20° forward (flexion 20°) or 25° backward (extension 25°) or rotated either 30° rightward (right rotation 30°) or leftward (left rotation 30°).

3.3. Measurement of trunk orientations

Regarding the static condition, the difference between the trunk orientations measured by the CMOS camera and the SMART-e system was small (mean ± S.D.: −0.56 ± 0.75°). Moreover, the CMOS camera measurements were highly correlated to static trunk inclinations measured with SMART ($r = 1$, $p < 0.001$). Regarding dynamic conditions, Fig. 3 shows typical traces obtained when the subject moved his trunk at three angular velocities. The CMOS camera data were almost superimposed on the SMART-e data. The correlation coefficient was always 1 with no time lag (0 ms). In addition, the subject torso rotation/flexion motions during static or dynamic tasks were analyzed from the 3D data set obtained with the SMART system. They were negligible.

4. Discussion

This study showed that a simple, low-cost, commercial CMOS camera could be used for the measurement of trunk orientation in 2D. For this application, the device appeared to be valid, accurate and comparable to a gold standard 3D movement analysis system, and it provided reproducible angular data. This system very well suits the measurement of lateropulsion in acute, subacute and chronic stroke patients since it is compact and mobile and it does not require any calibration. The camera can be translated laterally over a distance of 70 cm and lengthways up to 200 cm from the subject without modifying the accuracy provided that the camera axis is sagittal. Even if there is a theoretical possibility of a parallax error due to measurement in 2D with a single camera, our results showed that this error is negligible for physiological out-of-plane motions of the trunk like torso rotation or flexion. Therefore, the interpretation error is very limited for analyzing lateropulsion. Regarding movement velocity, this system may analyze mean trunk orientations even with trunk oscillations up to 20° s^{-1}, which is sufficient to quantify lateropulsion in sitting and in standing.

This could be an important step in the clinical assessment of stroke patients. The CMOS camera is the first tool to objectively quantify trunk lateropulsion at the patient's bedside. Patients would be asked to sit steadily on their bed for a few seconds, eyes closed, legs freely hanging and hands crossed on the thighs. Our objective, now, is to analyze the prevalence of lateropulsion after stroke.

Another perspective is to develop a rehabilitation program of trunk orientation based on biofeedback using the real-time signal provided by the device. The patient would be seated on a chair in front of a screen and would perceive his trunk movement through a virtual personage (Fig. 4). It implies measuring relatively fast trunk movements. The current system lost the marker(s) above 20° s^{-1} because of its low sample rate. An embedded system dedicated to real-time image processing and movement analysis could enhance time resolution and marker extraction [8–10]. We are designing a new system using a fast CMOS sensor (250 images per second) connected to an embedded programmable device (FPGA) able to perform marker extraction in a very short time (less than 10 ms).

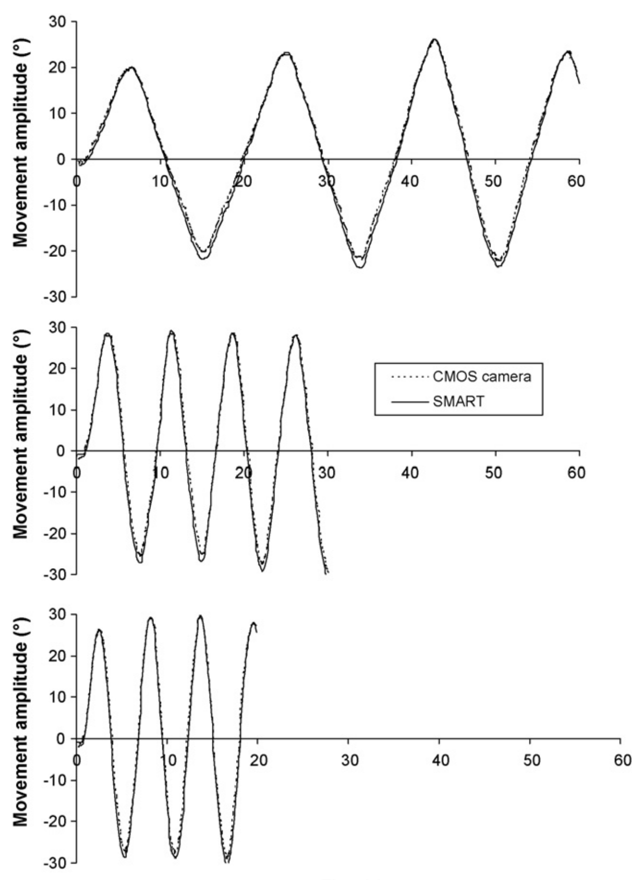

Fig. 3. Data obtained during cyclic trunk movements at three different angular velocities (upper traces: 5° s^{-1}, middle traces: 13° s^{-1}, lower traces: 18° s^{-1}) with a mean amplitude of about 50–60°. Dotted line: CMOS camera. Plain line: SMART-e.

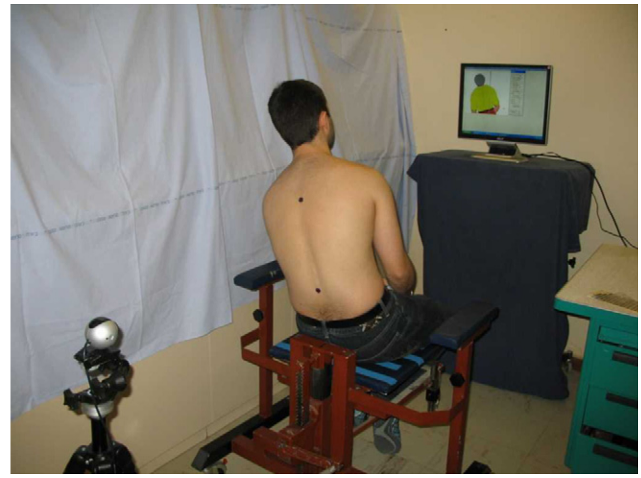

Fig. 4. Exercises of trunk positioning based on feedback obtained from the real-time measurements of trunk orientation with the CMOS camera.

Acknowledgement

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