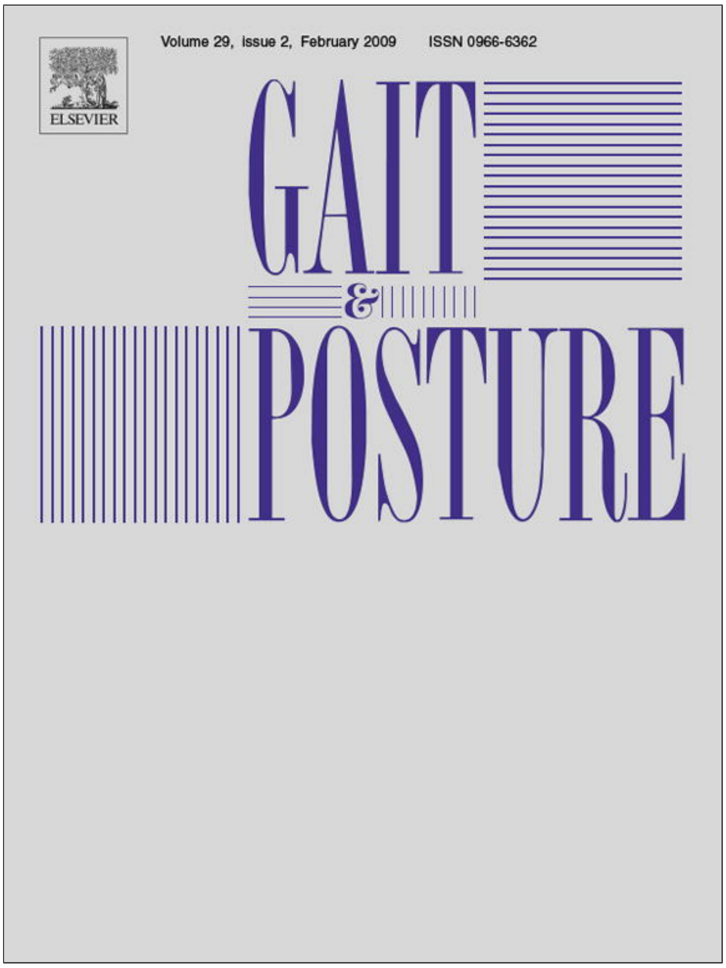
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Technical note

Pendulum-based method for determining the temporal accuracy of digital video-based motion capture systems

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ABSTRACT

Objective: To develop a simple method to determine the temporal accuracy of motion analysis systems incorporating commercial digital video cameras.
Methods: A planar column pendulum with a natural frequency of 0.872 Hz was used to analyse five systems incorporating commercially available cameras and a single codec.
Finding: The frame rate for each camera was measured to be within 3% of the US National Television Systems Committee (NTSC) broadcasting digital video standard of 29.97 fps; however some cameras produced a frame duplication artefact. Least squares curve-fitting using a sinusoidal function revealed RMS differences between 3–5% for angular position and 5–15% for angular speed compared to the captured motion data.
Conclusion: A simple method of evaluating temporal accuracy of a digital-based motion capturing system is demonstrated and it is shown that some digital-video cameras and computer playback software contain data compression technology that may produce substantial temporal frame inaccuracies in recovered video sequences. The results indicate that temporal accuracy should be evaluated in digital-based human motion analysis systems prior to their use in experimentation.

1. Introduction

A need exists to evaluate motion during high-demand activities of daily living in natural environments [1–3]. However, there are practicalities associated with cost, portability, and multiple camera use when capturing biomechanical data in field studies using three-dimensional based laboratory systems [4–7]. As such, digital video-based motion capturing systems are attractive for use in some clinical, industrial, academic, and sports applications. Ideally, these devices should be formatted to provide accurate reproduction of image data. However, the reality of handling video file formats for use in playback software requires compression technology to code information while still reproducing visually acceptable images.

A goal of motion capture systems used in biomechanical assessment is to minimize error and to accurately represent motion [8]. The utility of these systems relies on spatial and temporal techniques both of which affect image fidelity and motion capturing quality [9]. Image-based methods and spatial reconstruction techniques have been extensively studied [1,4,9–18]. In contrast, relatively few methods have been developed to test overall system performance with respect to time.

Recorded digital video is a sequence of captured images, which are processed at a constant time interval. This rate can be manually selected; however, the accuracy of the recovered data is determined by internal pre-programmed digital processing systems specific to each camera. For example, typical consumer cameras with a nominal frame rate of 30 fps adhere to the frame rate standard set by the US National Television Systems Committee (NTSC) of 29.97 fps. In addition, algorithms termed *codecs* are used in digital-video cameras and computer playback software to increase image storage capacity that result in the loss of essential information and may sacrifice the accuracy of motion data recovery. This does not preclude their use, as long as the inherent shortcomings of these systems are appreciated and appropriate controls are used to reduce inaccuracies. As such, the objective of this study was to develop a simple pendulum-based method to determine the temporal performance characteristics of motion analysis systems incorporating commercial digital video cameras.

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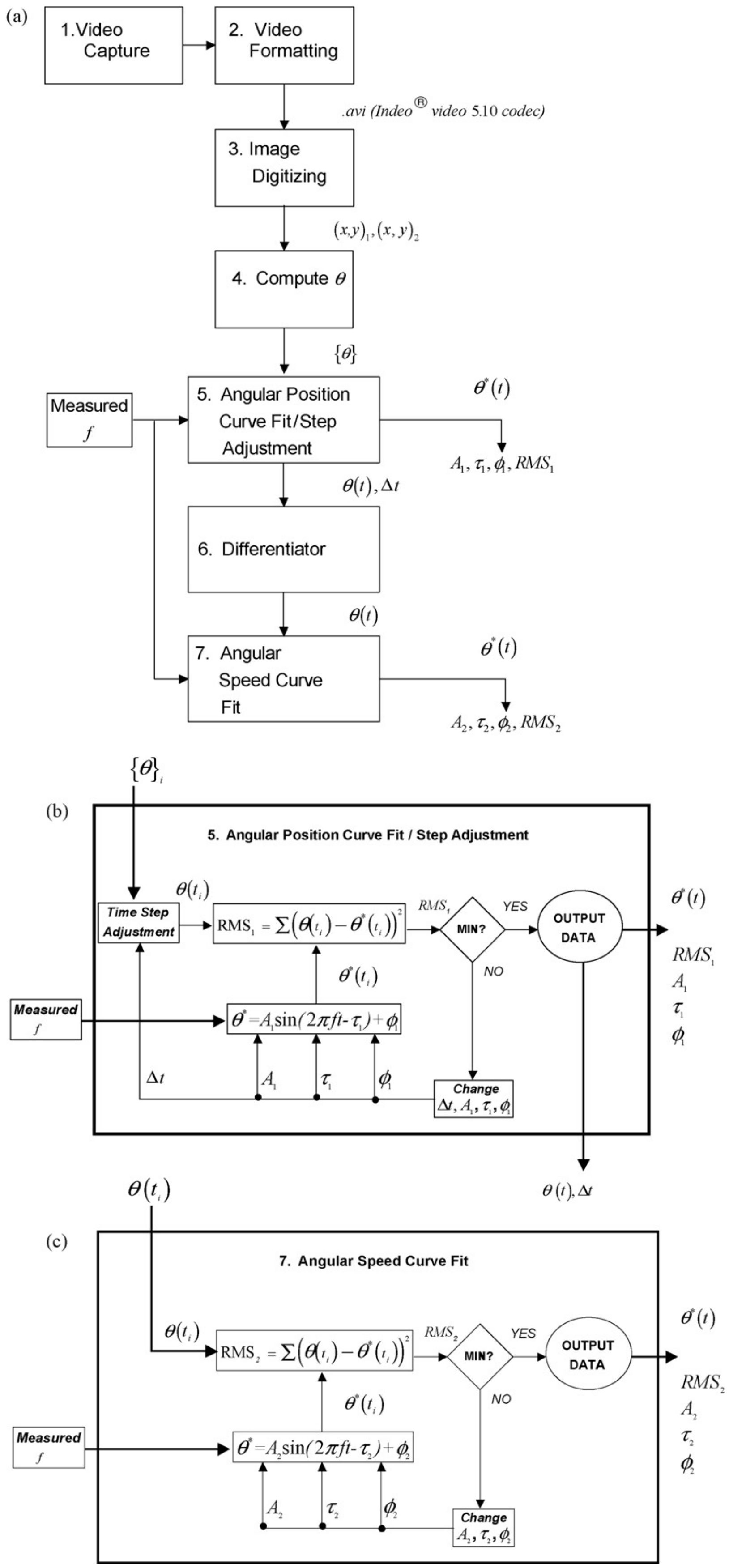

Fig. 1. (a) A flow chart depicting the steps in the temporal accuracy analysis procedure. Video recordings were converted to *.avi* file format using WinMPG™ video conversion software and Indeo® video 5.10 codec (Steps 1 and 2). Ehuman™ motion analysis software (HMA Technology, Inc., Toronto) was used to digitize the pivot point and centre of

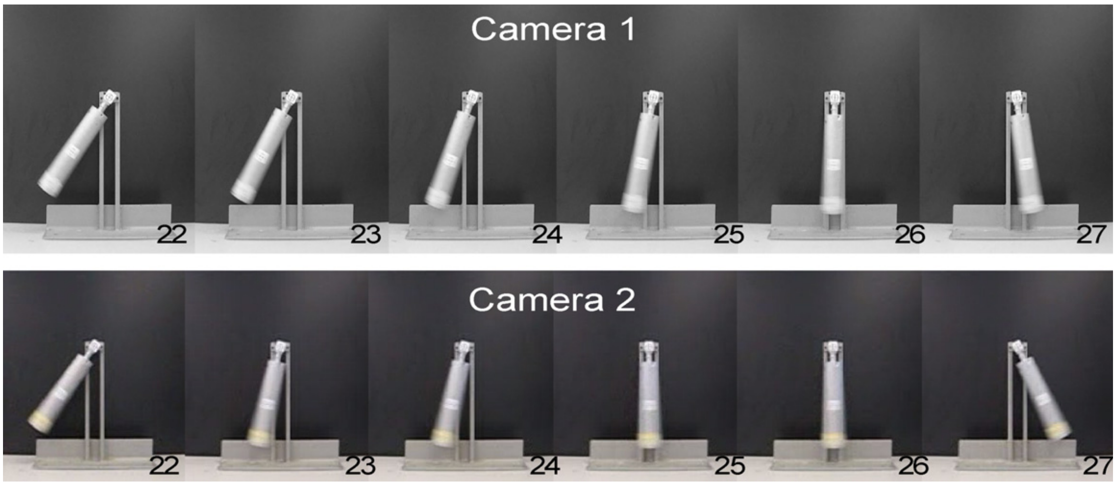

Fig. 2. Angular displacements of the pendulum captured using Camera 1 and Camera 2.

2. Method

2.1. Apparatus

A freely moving pendulum was used as a reference device [7] and was comprised of an aluminum column with a mass of 4.3 kg and length of 0.36 m mounted on a cantilevered bearing. Circular, 27 mm diameter markers were attached to the centre of rotation and the centre of mass located 0.246 m from the bearing. The timing of 10 trials of 100 cycles each gave a mean natural frequency of 0.872 Hz with a standard error of 0.0006 Hz.

2.2. Video capture instrumentation

Five different digital video cameras were chosen. Cameras 1 through 4 were representative within the class of consumer devices; Camera 5 was designed specifically for scientific motion capture. The NTSC setting of 30 fps was selected for all five cameras.

Each camera was placed 1.5 m from the pendulum base and oriented perpendicular to the plane of motion using the laboratory reference frame. The pendulum was released from approximately 90° from the vertical and motion recorded at a nominal frame rate of 30 (29.97) fps for 6 s starting on the 12th cycle.

A flow chart of the analysis procedure is shown in Fig. 1a. After video capture (Step 1), video recordings were converted to *.avi* file format using WinMPG™ video conversion software (Direct-Soft Inc.) and the Indeo® video 5.10 codec (Step 2). A right-handed coordinated system was defined in which the y-axis was vertical and the x-axis was horizontal to the right. Pendulum motion was digitized in a two-point model defined by the pivot point (x_1, y_1) and CoM (x_2, y_2) using eHuman™ motion analysis software (HMA Technology Inc., Toronto); coordinates for each point were collected for three sequential pendulum cycles (Step 3).

In Step 4, angular position was defined for each frame, i, such that

$$\theta_i = \tan^{-1}\left(\frac{x_2 - x_1}{y_1 - y_2}\right)_i. \quad (1)$$

In Step 5, the measured pendulum natural frequency, f, was used to adjust the time step, Δt, between each frame. As detailed in Fig. 1b, the time step was first assumed to be the nominal value of 1/29.97 = 0.03737 s to allow the measured angular position to be expressed as a function of time, $\theta(t)$. Next, the pendulum was modelled as simple harmonic motion such that the angular position, was given by:

$$\theta^*(t) = A_1 \sin(2\pi ft - \tau_1) + \phi_1, \quad (2)$$

where $\theta^*(t)$ is the modelled value for position, A_1 is the amplitude, τ_1 is the phase shift, and ϕ_1 is the offset. The latter two parameters arise because the starting point for recording is arbitrary; however, the amplitude and frequency directly relate to the physical system.

To determine model parameters, the root mean square difference for position, RMS_1 was defined over n data points such that:

$$RMS_1 = \sqrt{1/n \sum (\theta(t) - \theta^*(t))^2}. \quad (3)$$

RMS_1 was minimized by adjusting A_1, τ_1, ϕ_1 and the time step, Δt, using the *SOLVER* function in EXCEL™ (Microsoft Office 2000 Professional, Microsoft Inc.).

Using the adjusted value for Δt, angular position data were differentiated in Step 6. The angular speed $\dot{\theta}(t_i)$ was defined for time, t_i, such that

$$\dot{\theta}(t_i) = \frac{\theta(t_{i+1}) - \theta(t_{i-1})}{2\,\Delta t}. \quad (4)$$

In Step 7, the angular speed was modelled using the assumption of simple harmonic motion such that:

$$\dot{\theta}^*(t) = A_2 \sin(2\pi ft - \tau_2) + \phi_2, \quad (5)$$

where $\dot{\theta}^*(t)$ is the modelled speed, A_2 is the amplitude, f is the frequency, τ_2 is the phase shift, and ϕ_2 is the offset. Using a procedure similar to that described for angular position, model parameters for angular speed were determined using a least squares method as detailed in Fig. 1c. Note that the time step, Δt, was the value determined in Step 5 and that it was not a parameter within the minimization to obtain the modelled angular speed. The root mean square difference for angular speed RMS_2 over n data points was defined by:

$$RMS_2 = \sqrt{1/n \sum (\dot{\theta}(t) - \dot{\theta}^*(t))^2}. \quad (6)$$

3. Results and discussion

System temporal performance characteristics were evaluated by determining the image quality, frame rate, and the degree of fit of the position and speed models to the measured values, expressed as RMS_1 and RMS_2. The term *RMS difference* is used recognizing that these values include system errors from all phases of the data acquisition process, not only those associated with the camera; a gold standard is not used in this analysis.

3.1. Image quality

Temporal errors were evident in recovered image sequences and were specific to each camera. A sequence of six pendulum images from Camera 1 and Camera 2, are shown in Fig. 2. For

mass locations (Step 3). A two-point model defined by the pivot point and CoM locations were used to collect 2D data in the plane of motion. The *XY* coordinates for each point were collected for three pendulum cycles and exported into Microsoft® Excel and angular position as shown in Step 4, was computed for each frame, i, and used for subsequent analysis. (b) The measured angular position was compared to the classical analytical solution for pendulum motion. Least squares minimization of RMS_1 was used to determine A_1, τ_1, ϕ_1, and $\Delta(t)$. (c) The angular speed determined from differentiating the angular position data compared to the classical analytical solution for pendulum motion. Least squares minimization of RMS_2 was used to determine A_2, τ_2, andϕ_2.

Table 1
Performance measures for five cameras using a single *codec (Indeo 5.10)*.

Camera	Camera video file format	Frame duplication	Computed frame rate (fps) [error*]	RMS_1 (position, °)	RMS_2 (speed, °/s)
1	.mov (30 fps)	N	29.79 [−0.6%]	0.62	13.8
2	.avi (14 fps)	Y	29.91 [−0.2%]	4.64	73.9
3	.avi (15 fps)	Y	29.13 [−2.8%]	2.70	21.0
4	.avi (15 fps)	Y	28.94 [−3.4%]	3.66	51.9
5	.avi (30 fps)	N	29.02 [−3.2%]	0.43	6.57

Error compared to 29.97 fps NTSC standard.

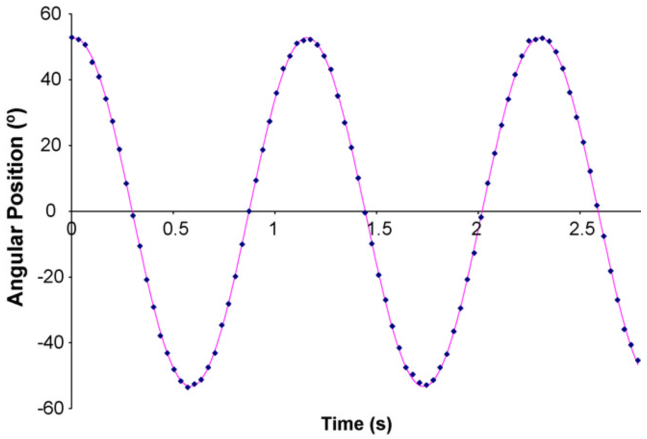

Fig. 3. Pendulum angular position as a function of time using Camera 1.

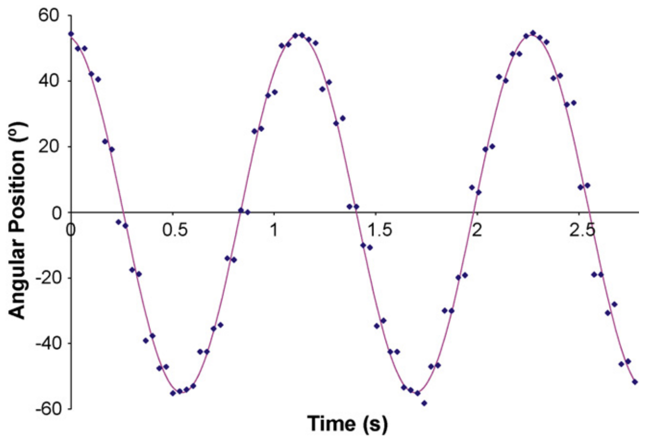

Fig. 4. Pendulum angular position as a function of time using Camera 2.

Camera 1, frames 22–27 show sequential advancement of the pendulum angular position. Camera 2 recordings between frames 23–24 and 25–26 show duplicated frames. This is predictable from the output file format of Camera 2; when this device is set to the NTSC standard to produce 30 fps, frame duplication is used so that only 15 frames are unique in each 30-frame sequence.[1] Similar frame duplication trends were observed for Cameras 3 and 4 as shown in Table 1; Camera 5 (designed for scientific motion capture) did not show frame duplication.

[1] Prior to using the codec, the recorded video files were examined under the "properties" command and Cameras 2, 3, 4 indicated a frame rate between 14 fps and 15 fps. (Cameras 1 and 5 indicated 30 fps.)

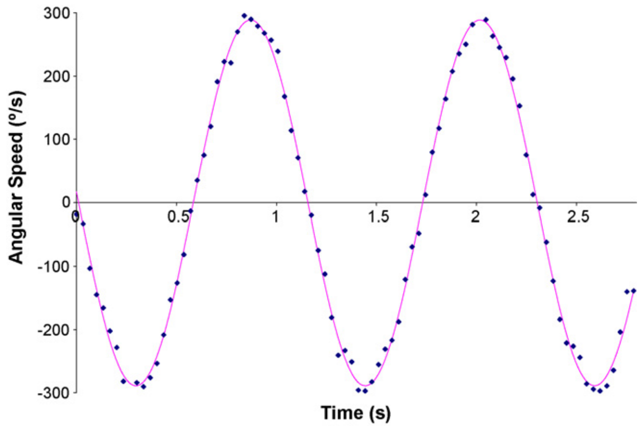

Fig. 5. Angular speed of the pendulum as a function of time using Camera 1.

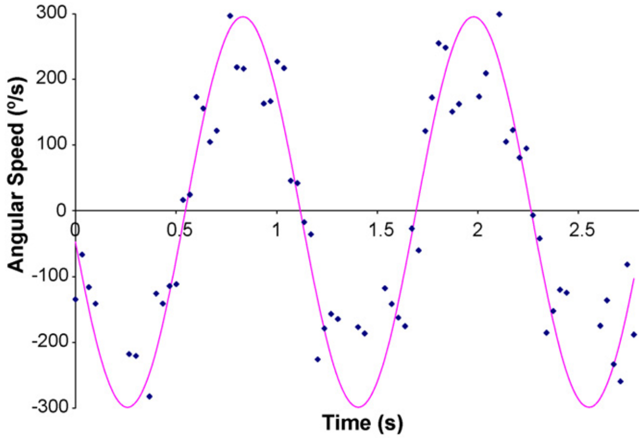

Fig. 6. Angular speed of the pendulum as a function of time using Camera 2.

3.2. Frame rate

The computed frame rate was compared to the NTSC standard of 29.97 fps for each camera as shown in Table 1. Note that while all cameras were within 3% accuracy compared to this standard, some contained a frame duplication artefact on playback.

3.3. Degree of fit of position and speed models

Angular position as functions of time for Camera 1 and Camera 2 are shown in Figs. 3 and 4, respectively. The data for Camera 1 show continuous changes in position while the presence of frame duplication for Camera 2 is evident. As a result, the sinusoidal curve fits had RMS_1 differences of 0.62° and 4.64° as shown in Table 1. This effect of frame duplication on precision was also evident in the other cameras studied. Cameras 3 and 4, with frame duplication, had RMS_1 differences of 2.70° and 3.66°; Camera 5, without frame duplication, had an RMS_1 difference of 0.43°.

The differentiation of position data to obtain speed is known to amplify measurement errors. This was evident for Cameras 1 and 2 as shown in the angular speed vs. time waveforms of Figs. 5 and 6, respectively. The RMS_2 differences were 13.79°/s when frame duplication was not present (Camera 1) and 73.89°/s when duplication was present (Camera 2). This pattern was also consistent for Cameras 3, 4, and 5 as shown in Table 1.

4. Conclusion

A simple method of evaluating temporal accuracy of a digital-based motion capturing system has been demonstrated. The results of five cameras studied using the *Indeo 5.10 codec* indicated a frame rate within 3% of the NTSC standard; however, frame duplication was observed in some systems due to the compression/decompression methods used in the camera. This resulted in a decrease in precision in angular position and angular speed measurements by factors of three to four compared to cameras in which frame duplication was not present. It is recommended that temporal accuracy be evaluated in digital-based human motion analysis systems prior to their use in experimentation.

Conflict of interest statement

None.

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References

[1] Lu C, Ferrier NJ. A digital video system for the automated measurement of repetitive joint motion. IEEE Trans Inf Technol Biomed 2004;8:399–404.

[2] Lugne PC, Alizon J, Collange F, Van Praagh E. Motion analysis of an articulated locomotion model by video and telemetric data. J Biomech 1999;32:977–81.

[3] Sutherland CA, Albert WJ, Wrigley AT, Callaghan JP. The effect of camera viewing angle on posture assessment repeatability and cumulative spinal loading. Ergonomics 2007;50:877–89.

[4] D'Apuzzo N. Human body motion capture from multi-image video sequences. Videometrics VIII, vol. 5013. 2003. p. 54–61.

[5] Everaert DG, Spaepen AJ, Wouters MJ, Stappaerts KH, Oostendorp RA. Measuring small linear displacements with a three-dimensional video motion analysis system: determining its accuracy and precision. Arch Phys Med Rehabil 1999;80:1082–9.

[6] States RA, Pappas E. Precision and repeatability of the Optotrak 3020 motion measurement system. J Med Eng Technol 2006;30:11–6.

[7] Deluzio KJ, Wyss UP, Li J, Costigan PA. A procedure to validate three-dimensional motion assessment systems. J Biomech 1993;26:753–9.

[8] Holden JP, Selbie WS, Stanhope SJ. A proposed test to support the clinical movement analysis laboratory accreditation process. Gait Posture 2003;17:205–13.

[9] Borghese NA, Cerveri P, Rigiroli P. A fast method for calibrating video-based motion analysers using only a rigid bar. Med Biol Eng Comput 2001;39:76–81.

[10] Ambrosio J, Lopes G, Costa J, Abrantes J. Spatial reconstruction of the human motion based on images of a single camera. J Biomech 2001;34:1217–21.

[11] Ambrosio J, Abrantes J, Lopes G. Spatial reconstruction of human motion by means of a single camera and a biomechanical model. Hum Mov Sci 2001;20:829–51.

[12] Castro JL, Medina-Carnicer R, Galisteo AM. Design and evaluation of a new three-dimensional motion capture system based on video. Gait Posture 2006;24:126–9.

[13] Cerveri P, Borghese NA, Pedotti A. Complete calibration of a stereo photogrammetric system through control points of unknown coordinates. J Biomech 1998;31:935–40.

[14] Eian J, Poppele RE. A single-camera method for three-dimensional video imaging. J Neurosci Methods 2002;120:65–83.

[15] Yang F, Ding L, Yang C, Yuan X. Spatial reconstruction of human motion utilizing two dimension images and a biomechanical model. J Biomed Eng 2005;22:307–11.

[16] Schmid OA. A new calibration method for 3-D position measurement in biomedical applications. Biomed Technik 2001;46:50–4.

[17] Schmid OA. Dynamic accuracy survey of the new "single plane–single frame 3-D calibration" technique for use in biomedical applications. Biomed Technik 2005;50:38–44.

[18] Unal G, Yezzi A, Soatto S, Slabaugh G. A variational approach to problems in calibration of multiple cameras. IEEE Trans Patt Anal Mach Intell 2007;29:1322–38.