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*Full Length Research Paper*

# A study on the calibration of stereo photogrammetric systems used in motion analysis

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**Scientific recording of motion and providing feedback based on the evaluation of the recorded data is an essential element of sport science. Today, motion analysis in sports can only be performed in a laboratory environment. In that case, fine differences specific to sports are lost and limited information can be achieved regarding the factors that bring success. The idea of performing motion analysis in sports by recording motions using digital video cameras and evaluating the recorded images through photogrammetric methods is a current issue in sport science. The aim of the present study was to describe a new photogrammetric method used in the analysis of sport movements. For this purpose, images were obtained using two 200 FPS+VGA+1394B Dragonfly Express video cameras. A calibration cage was used while recording the images. Afterwards, the recorded images were evaluated using Pictran, which is a software package for the photogrammetric evaluation of digital images.**

**Key words:** Motion analysis, digital photogrammetry, biomechanics, calibration.

## INTRODUCTION

Motion analysis systems are commonly used today for measuring human movements. The use of camera systems is the most convenient method in defining physical quantities (parameters) such as distance, speed, acceleration, power, energy and momentum. Motion analysis systems with cameras are usually preferred in the quantitative analysis of sport-specific movements, which include particularly complex motions (Bahamonde, 2005; Shan and Westerhoff, 2005). Measurements in camera systems are performed in two ways, as with and without using markers. Since the desired accuracy and precision has not yet been achieved in the studies conducted without using markers (Remondino, 2006), studies in which markers are used are more common in the literature (Graham-Smith and Lees, 2005; Jaitner et al., 2001). In a previously conducted study, the DLT (Direct Linear Transformation) method was used for the evaluation of static objects. Accuracy values regarding camera parameters were obtained in the mentioned study (Göktepe, 2005). Synchronous evaluation of motion images is a demanding task. The data regarding the time of recording can only be obtained through software applications characterized by a strong mathematical model. The Pictran software, which was used in this study, is an application that fits for this purpose.

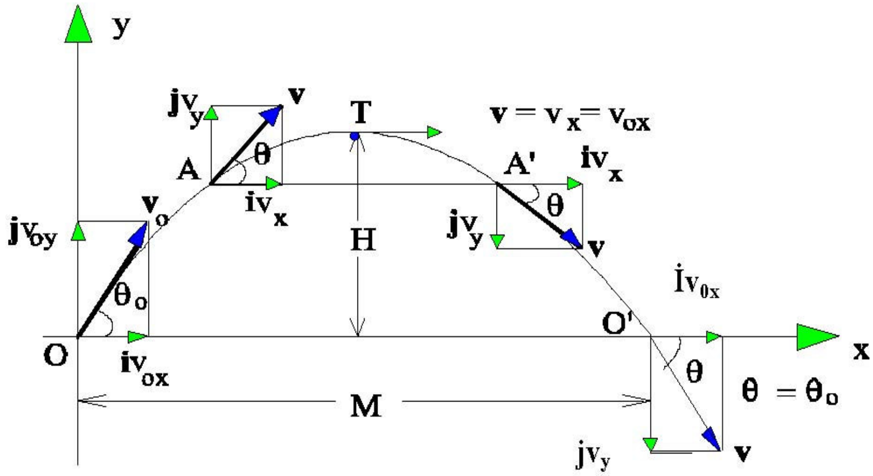
## MATERIALS AND METHODS

### Projectile motion of a tennis ball and parabolic trajectory

Projectile motion is the most distinctive example of curved motion with constant acceleration. The displacement of a ping-pong ball, a tennis ball or a football along with a curvilinear trajectory is an example of projectile motion. Here, the effect of air resistance is neglected, since the displacement of the particle will be examined. The acceleration due to gravity 'g' is vertical to the Earth and directed downward, and this acceleration does not have a horizontal component. Let us choose a two-dimensional vertical coordinate system with a positive direction on the Earth. In this system, the acceleration components of the particle are $a_x = 0$ and $a_y = -g$. Let us take the starting point of the projectile motion as the starting point of the coordinate system and consider that a particle is thrown from here at time t = 0 with an initial velocity $\mathbf{v}_0$ at an angle $\theta_0$ with the x axis (Figure 1). The horizontal and vertical components of the initial velocity vector are calculated as:

$$v_{0x} = v_0.\cos\theta_0 \text{ ve } v_{0y} = v_0.\sin\theta_0$$

The motion equations of the planar curvilinear motion on the x(horizontal) and y (vertical) axes are as follows:




| | x-axis motion equations | | y- axis motion equations | | |
|---|---|---|---|---|---|
| initial velocity | $v_{0x} = v_0 \cos\theta_0$ | (a) | $v_{0y} = v_0 \sin\theta_0$ | (a') | (1) |
| acceleration | $a_x = 0$ | (b) | $a_y = -g$ | (b') | (2) |
| velocity | $v_x = v_0 \cos\theta_0$ | (c) | $v_y = v_0 \sin\theta_0 - gt$ | (c') | (3) |
| displacement | $x = v_0 t \cos\theta_0$ | (d) | A study on the calibration of stereo photogrammetric systems used in motion analysis | | |

**Figure 1.** Projectile motion, parabolic trajectory.

These are known as the parametric equations of the trajectory of a projectile. Here, the motion of the particle is a harmonic motion. The motions of the particle that presents planar curvilinear motion are thus explained.

***Trajectory of motion (parabolic trajectory)***

The trajectory equation of the particle is obtained when t is eliminated within the Equations (4) where the displacements are given.

$$y = x \tan\theta_0 - \frac{gx^2}{2v_0^2 \cos^2 \theta_0} \quad (5)$$

$$y = Ax - Bx^2 \quad (5^1)$$

Equation 5 mathematically describes a parabola. For this reason, the trajectory of such a motion is defined as ‘parabolic trajectory’.

***Peak point***

The highest point that the particle reaches along the x-axis is called the *peak point*. This is the point where the trajectory is maximum ($dy/dx = 0$, and $v_y = dy/dt = 0$). In Equation (3c') when $v_y = 0$, the equation for the time that takes for the particle to get to the highest point is given as:

$$t_t = \frac{v_0}{g} \sin\theta_0 \quad (6)$$

When this value is transferred to Equation (4d'), then the equation which gives the height of the peak point is found as:

$$H = \frac{v_0^2}{2g} \sin^2 \theta \quad (7)$$

***Throwing distance (range)***

Since in Equation (5) y = 0 at the point where the particle falls, by giving y = 0, the equation for the throwing distance is obtained as follows:

$$M = \frac{v_0^2}{g} \sin 2\theta \quad (8)$$

In the present study, projectile motion was demonstrated by throwing the tennis ball within the test area. The demonstration was recorded synchronously by using two cameras. The 25th, 30th, 35th, 40th, 43rd, 48th, 53rd, 58th and 63rd pictures (Figure 2) were selected from among the recorded images and subjected to

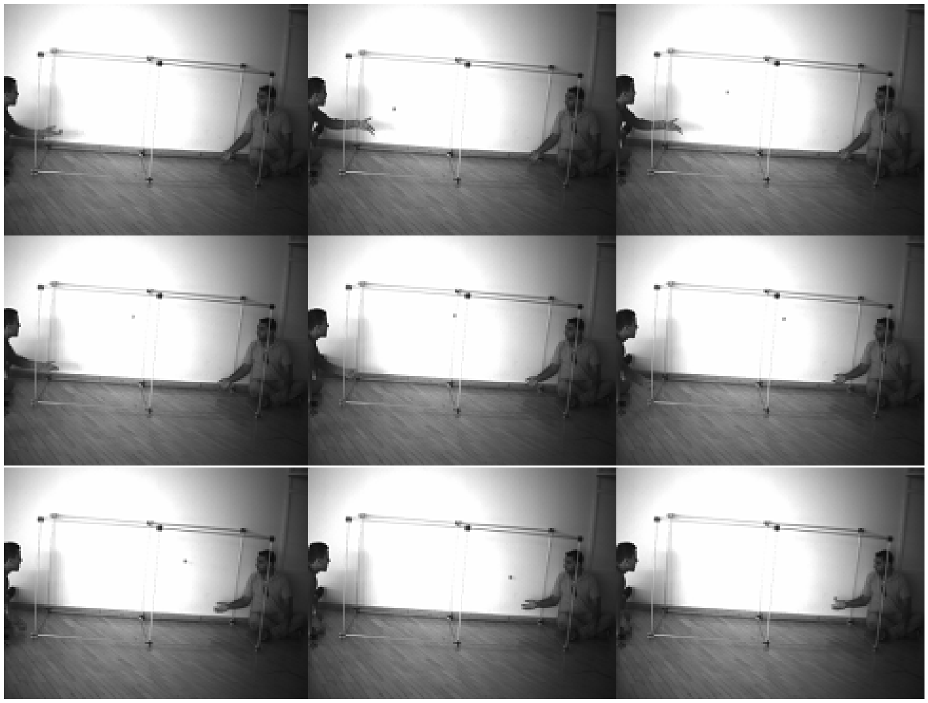


**Figure 2.** Tennis ball experiment, selected Images.

**Table 1.** Test area coordinates.

| NN | X | Y | Z |
|---|---|---|---|
| 1 | 503.489 | 989.602 | 201.01 |
| 2 | 504.543 | 989.569 | 201.011 |
| 3 | 505.612 | 989.489 | 200.997 |
| 4 | 505.583 | 989.531 | 199.972 |
| 5 | 504.556 | 989.561 | 199.970 |
| 6 | 503.504 | 989.608 | 199.973 |
| 7 | 503.474 | 988.572 | 201.001 |
| 8 | 504.513 | 988.532 | 201.003 |
| 9 | 505.544 | 988.499 | 201.011 |
| 10 | 505.540 | 988.506 | 199.986 |
| 11 | 504.507 | 988.526 | 199.980 |
| 12 | 503.490 | 988.563 | 199.990 |

photogrammetric evaluation. The evaluation process was carried out by using Pictran, which is a photogrammetric software package developed by Berlin Technical University. The three dimensional coordinates of the test area were repetitively acquired by using the Topcon 3007 electronic distance measurement device (Table 1).

The coordinate values along the path travelled by the ball, which are required for calculating gravity following the photogrammetric evaluation, are given in Table 2.

Again, the values for the path travelled by the ball from the starting point (s) and the height from the ground (h) are given in Table 3. The θ angle values of the tennis ball on the horizontal axis, initial velocity V0 and the gravity values (g) (Figure 1) calculated based on these values are given in Table 4. The average acceleration of gravity for the area where the images were taken was calculated as 9.807571.

**Table 2.** Three dimensional coordinates of the tennis ball.

| Image No | y | z | x |
|---|---|---|---|
| 25 | 503.693 | 200.322 | 989.382 |
| 30 | 503.904 | 200.548 | 989.303 |
| 35 | 504.119 | 200.705 | 989.213 |
| 40 | 504.336 | 200.794 | 989.121 |
| 43 | 504.467 | 200.814 | 989.066 |
| 48 | 504.679 | 200.789 | 988.969 |
| 53 | 504.893 | 200.697 | 988.857 |
| 58 | 505.102 | 200.54 | 988.777 |
| 63 | 505.31 | 200.312 | 988.666 |

**Table 3.** Distance and height of the tennis ball.

| Number of images | Distance (s) | Height (h) |
|---|---|---|
| 25 | 0 | 0.32 |
| 30 | 0.21 | 0.55 |
| 35 | 0.42 | 0.71 |
| 40 | 0.64 | 0.79 |
| 43 | 0.77 | 0.81 |
| 48 | 0.98 | 0.78 |
| 53 | 1.2 | 0.7 |
| 58 | 1.41 | 0.54 |
| 63 | 1.62 | 0.31 |

**Table 4.** Horizontal angle, velocity and acceleration values.

| Number of Images | θ (degrees) (horizontal angle) | Vo(m/Sn) (initial velocity) | g (acceleration of gravity) |
|---|---|---|---|
| 25 | 0 | - | |
| 30 | 47.32 | 1.44 | 9.842 |
| 35 | 42.3 | 2.03 | 9.768 |
| 40 | 36.63 | 2.56 | 9.801 |
| 43 | 32.78 | 2.88 | 9.806 |
| 48 | 25.68 | 3.51 | 9.819 |
| 53 | 17.7 | 4.51 | 9.819 |
| 58 | 9.13 | 6.64 | 9.798 |
| 63 | 0 | - | |

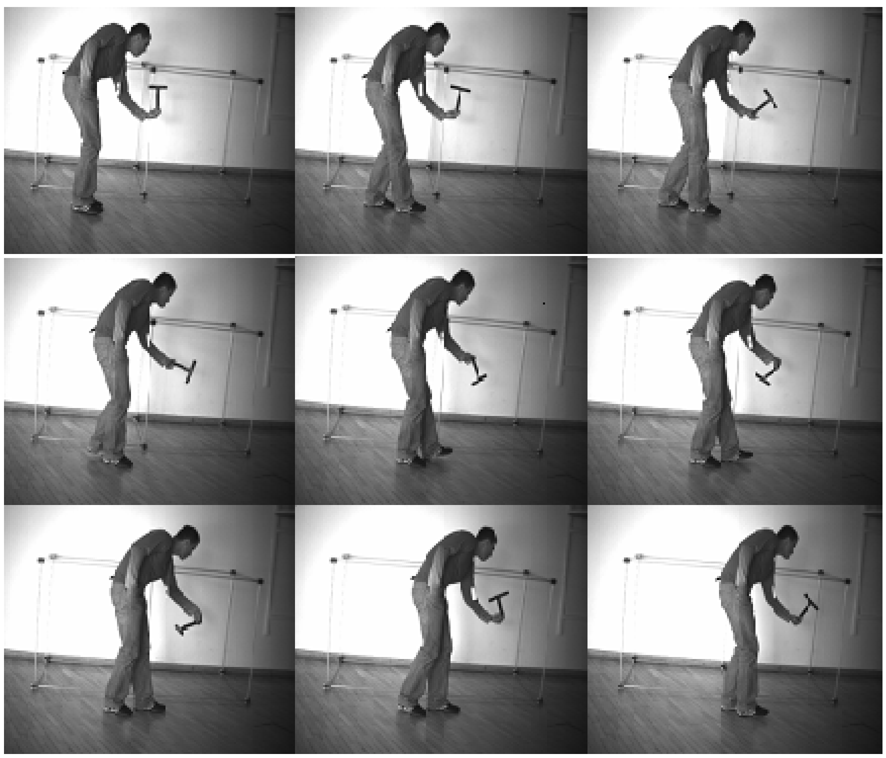


**Figure 3.** T experiment images.

**T- experiment implementation**

During the implementation of the experiment, a T-shaped object of 184 mm in length was moved to different positions inside the test area. The time of moving the object was recorded in a synchronized manner by using two cameras for 5 s (Figure 3). These images were recorded on a computer and the 25th, 30th, 35th, 40th, 43rd, 48th, 53rd, 58th and 63rd pictures were selected from among the recorded images and subjected to photogrammetric evaluation.

The coordinates of the two tips of the T bar (T1-T2) were obtained as the result of the photogrammetric evaluation. The compatibility of the coordinate system at the time of recording and the coordinate system used in the evaluation was maintained by changing the axis. The length of the T bar was calculated for each time of capture based on these coordinates (Table 5). The average of the new length values was found as 0.187272 mm. Since the measured value of the T bar was accepted as the actual value, the calculated value was not subjected to a statistical analysis.

## DISCUSSION AND CONCLUSION

There are a number of studies in the literature on the accuracy and precision of systems used for movement analysis (Nicholls et al 2003; Kejonen et al 2004). States and Pappas (2006) used a repeated measures design study to evaluate the precision and repeatability of the Optotrak 3020, which is an optoelectronic measurement

**Table 5.** T bar coordinate and length values.

| Point No | Image No | Y | X | Length (m) |
|---|---|---|---|---|
| T1<br>T 2 | 20 | 504.688<br>504.498 | 200.882<br>200.872 | 0.190263 |
| T 1<br>T 2 | 40 | 504.788<br>504.598 | 200.856<br>200.887 | 0.192512 |
| T 1<br>T 2 | 60 | 504.889<br>504.764 | 200.744<br>200.883 | 0.186938 |
| T 1<br>T 2 | 80 | 504.942<br>504.887 | 200.742<br>200.563 | 0.187259 |
| T 1<br>T 2 | 210 | 505.096<br>504.928 | 200.893<br>200.813 | 0.186075 |
| T 1<br>T 2 | 250 | 505.175<br>505.318 | 200.863<br>200.74 | 0.188621 |
| T 1<br>T 2 | 290 | 505.531<br>505.357 | 200.814<br>200.771 | 0.179234 |

system, and found that the precision of the Optotrak system was better than other movement analysis systems. Furthermore, the measurement error of this system was smaller when compared to other movement analysis systems (Haggard and Wing, 1989; Scholz, 1989; Richards, 1999; Vander Linden et al., 1992). However, the Optotrak system is based on optical sensors. For this reason, it is normal that the measurement error of this system was found to be smaller when compared to other camera systems. Since the area covered by the sensors is limited in case of movements on a wide area, such a system has a high possibility of failure in sport movements (Meriç and Aydin, 2008).

In the study, the acceleration due to gravity for the studied area was calculated as 9.807571 as a result of the examination of the projectile motion of a tennis ball (Table 3). In the T bar experiment, while the accepted actual value of the bar was 0.184 m, it was found as 0.187272 m based on the calculations (Table 5). This value obtained as a result of the calculations, is considerably close to the actual value.

In conclusion, it can be seen that the system used in the present study gives pretty good results in the analysis of sport movements. The biomechanical analysis of the service toss in tennis was performed in a study conducted by using the system introduced in the present study (Göktepe et al., 2009). The usability of the system is possible through precisely obtaining the three dimensional coordinates of the calibration cage which is used while taking the images. It is important that the light falls at the correct angle for facilitating the recognition of the objects during the evaluation process. The intensity of operating procedures during the evaluation of the images seems to be the disadvantage of the system. The development of the system can be achieved through the automatic evaluation of the images by the software used in the system instead of manual evaluation.

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