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* Page with Personal Information

The effect of surface geometry on soccer ball trajectories

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Abstract

Two different measurement techniques are used to examine the effect of surface geometry on soccer ball trajectories. Five professional players are observed using high speed video when taking curling free-kicks with four different soccer balls. The input conditions are measured and the average launch velocity and spin are found to be approximately 24 m/s and 106 rad/s. It is found that the players can apply more spin (~50%) on average to one ball, which has a slightly rougher surface than the other balls. The trajectories for the same four balls fired at various velocities and spin rates across a sports hall using a bespoke firing device are captured using high-speed video cameras, and their drag and lift coefficients estimated. Balls with more panels are found to experience a higher lift coefficient. The drag coefficient results show a large amount of scatter and it is difficult to distinguish between the balls. Using the results in a trajectory prediction programme it is found that increasing the number of panels from 14 to 32 can significantly alter the final position of a 20m-curling free-kick, by up to 1 m.

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1. Introduction

The flight of a ball through the air is a key part of many popular sports, and sports balls have been studied aerodynamically since Isaac Newton commented on the deviation of a tennis ball [1]. Soccer is widely regarded as the most popular sport in the world, and the exact speed, swerve or dip of a soccer ball can be match-deciding. Recent developments in soccer ball manufacturing technology have led to the possibility of radical changes in surface geometry and seam configurations. The two key physical interactions in soccer that can be significantly affected by ball design are the impact with the foot and flight through the air. The impact performance of a soccer ball is a stringent criterion for the testing and approval to “International Matchball Standard” by the governing body, FIFA [2]. All balls have to fall within certain limits for size, mass and sphericity as well as passing a standard bounce test. However, neither the surface texture or the panel design are controlled and there are no official tests for aerodynamic behaviour. Therefore different ball designs can behave very differently aerodynamically, which can have a significant impact on the game.

The fundamental aerodynamic phenomena relating specifically to spinning soccer balls have not been studied previously in great detail. This is mainly because they are difficult to mount and fit in wind tunnels and because the combination of topspin and sidespin, which is frequently applied to them, produces swerving and dipping trajectories that are difficult to measure accurately. Recent wind tunnel experiments and CFD studies have revealed some interesting phenomena relating to the unsteady flight of soccer balls launched with low or zero spin [3, 4]. It was found that such trajectories could swerve significantly several times in the air due to the asymmetry of the seam patterns. Although these studies provide useful information, wind tunnel testing is always limited by the fact that the ball has to be held firmly in place to avoid vibrations being set up, usually by a rear-mounted sting, which will affect the aerodynamics. Spinning a ball in a wind tunnel raises further challenges in terms of reducing effects on the air flow. CFD studies, by their very nature, require simplifications and assumptions to be made which limit the usefulness of the findings for real-world applications.

Video analysis has previously been carried out for various types of sports ball. Several estimates were made for baseballs by videoing trajectories from both pitching machines and real pitches [5, 6], and for volleyballs fired from a machine [7] and real serves [8]. Trajectory measurements were only used very early on to estimate the drag coefficient (C_D) and lift coefficient (C_L) for golf [9] and tennis [10]; today, wind tunnel tests for these balls are accurate and well established. High-speed video trajectory measurements have been made of soccer balls fired from a cannon [11, 12, 13, 14], launched from a direct free-kick [15] and thrown [16, 17]. These studies have not directly compared different ball designs.

The work here involves the direct comparison of the trajectories of different soccer ball designs in order to understand their aerodynamic behaviour. The two methods used are player testing and controlled trajectory measurements from a machine.

2. Experimental Methods

2.1 Player Testing

2.1.1 Set-Up

Five youth-team players from an English Premiership club kicked four different balls from approximately 20 m away from goal and 7.3 m to the left of centre, as shown schematically in Figure 1. Each ball was kicked once by each player and the players were not given any opportunity to practise with the balls before testing. The tests took place on the soccer pitch of a Premiership football club during a training session and all players had carried out a standard warm-up. The main difference between the four balls was in the number and shape of the panels (Figure 2). The four balls were all measured for mass and size and their moments of inertia were calculated using the bifilar suspension method. The depth of the seams was also measured using a depth gauge and was found to vary for all the balls. These data are summarised in Table 1, along with the acceptable ranges for "International Matchball Standard" [2]. All the balls were inflated to a pressure of 0.9 bar, which was within the recommended range specified by the manufacturers for each ball.

The players were instructed to curl each ball from the same location every time into a target net that was draped over the front of the far part of the goal. Camera 1, a

Phantom Photosonics camera (1000 fps), measured the initial direction, velocity and spin imparted to the balls, and Camera 2, a Phantom Photosonics camera (500 fps), recorded the position of the balls when they hit the net. The data obtained from Camera 1 was calibrated using the diameter of the ball as a reference, and the initial conditions were calculated from positional data taken from specialist in-house software formed from manual selection of both the centre of the ball and various markers on the ball surface, for each frame. It was initially thought that ball deformation and vibration may be a contributing factor in the aerodynamic performance of footballs. However, in observing the videos it was noted that all the ball returned to its original shape very soon after being kicked and that no deformation or structural vibrations were visible in the ball after the first metre of trajectory. This issue was examined further in some later video testing carried out under more controlled conditions in a laboratory with the same conclusions drawn. Deformation and vibration effects were therefore assumed to be negligible and have no measurable effect on the balls' trajectories in this study.

2.1.2 Error Analysis

The main errors in this method were measurement errors, arising primarily from assuming the ball moved in a plane perpendicular to Camera 1 and from the manual data selection process. These errors were estimated by repeating the manual process five times for one player's data (typical to that measured for all players). This gave approximate errors as displayed in Table 2, where the standard error is given by the standard deviation divided by the square root of the number of samples. The angular velocity was particularly difficult to capture accurately due to the need to track two separate points that remain visible for at least 10 frames.

2.2 Trajectory Measurements

2.2.1 Set-Up

Trajectory measurements were made on the same four balls that were used in the player testing, and. a schematic of the set-up is shown in Figure 3. The tests took place in a sports hall to minimise external effects such as rain and wind. Markers were placed on the floor at 1 m intervals in line with the ball flight, for calibration purposes. A ball firing device was used to launch soccer balls in a trajectory within a vertical plane at various velocities and spin rates. The device, pictured in Figure 4, can be used to fire a soccer ball with top/back and side spin, but for these measurements only topspin was used.

A digital video camera was set up behind the ball firing device to check that the trajectories did not deviate significantly from the vertical plane. The few that did were disregarded and re-tested. Three high-speed video cameras were used to record the trajectory of the balls. Camera 1, a Kodak Motion Corder Analyzer Model 1000, was set up to record the launch conditions at 240 frames per second. Camera 2 and Camera 3, Phantom Photosonics cameras, recorded portions of the trajectory at 1000 frames per second.

Ideally the cameras should have been perpendicular to the ball (in both horizontal and vertical directions) so that planar movement related to a linear scale when projected onto a camera image. This is not possible unless the camera follows the motion of the ball, which was not feasible in this case. The offset from perpendicular is marked as β_1 in Figure 3; a corresponding angle, β_2, existed in the vertical plane. In order to minimise β_1, Camera 2 and Camera 3 were positioned as far away from the trajectory plane as possible; in this case next to the opposite wall of the sports hall. β_1 was minimised by positioning the cameras at heights approximately at the centre of the ball's trajectory.

Each ball was fired six times with launch velocities ranging from approximately 14 to 23 m/s and topspins ranging from 3 to 147 rad/s, and the trajectory details recorded. The initial spin and velocity were obtained from Camera 1 as in the player testing, and the data from Camera 2 and Camera 3 were calibrated using the markers that were placed at 1 m intervals on the floor.

For each launch, the positional data obtained from each camera were combined to produce the complete trajectory by applying a third-order polynomial approximation using the sum of least squares method; examples are shown in Figure 5. C_D and C_L were then estimated by comparison with a mathematical trajectory model, which uses an iterative method to solve the equations of motion and assumes that C_D and C_L vary with the Reynolds Number (Re) and spin ratio (Sp) as found in wind tunnel tests [19].

Note: In this study a scale model of a football was used, but the relationships between the aerodynamic parameters are assumed to be similar. The spin ratio is given as shown in Equation 1:

$$Sp = \frac{r\omega}{v} \tag{1}$$

where r is the ball radius (m), ω the rotational velocity (rad/s) and v the ball's velocity (m/s). The sum of the squares of the differences between the simulated and measured x and y co-ordinates was calculated, and the sum of these two values minimised by altering C_D and C_L iteratively until a converged solution was reached. It was not possible to repeat this process for every time step and therefore C_D and C_L were assumed to be constant throughout the flight.

2.2.2 Error Analysis

Measurement errors arose from assuming the ball moved in a vertical plane with only one axis of spin, from parallax from the cameras and from human error from the manual selection process. These errors were estimated by repeating the manual process five times for one case, as can be seen in Figure 6, giving errors as shown in Table 3.

The main source of error was thought to be in the assumption of constant C_D and C_L and the resulting sum of the squares of the differences approximation method. An example that demonstrates this procedure is shown in Figure 7, which compares a fitted trajectory based on measurement data to a simulated trajectory based on constant C_D and C_L. All the other predictions showed similar deviations from the measured data. For this case, the average of the differences in x was 0.03 m (0.18% of the maximum x) and the average of the differences in y was 0.09 m (3.54% of the maximum y). The sensitivity of the trajectory to the estimated constant C_D and C_L values assigned to a ball was tested by altering C_D and C_L in turn and observing their effect on the trajectory. For the example trajectory given in Figure 7, C_D and C_L were altered ± 10%, and the resulting trajectories are shown in Figure 8. The x-position at the end of the trajectory varied from the original trajectory by an average of 1.9%.

3. Results and Discussion

3.1 Player Testing Results

Wind tunnel results presented in a previous study [4] show that there is a certain ball velocity, above which the drag coefficient suddenly decreases from approximately 0.5 to 0.2 due to laminar-to-turbulent boundary layer transition. The measured launch conditions for each of the five players tested show comparatively low average velocities. This means that the ball may well spend some of its flight in the transition or laminar regime and may suddenly slow down or drop in the air as the C_D rises suddenly. This behaviour is simulated in a parallel study in which the effects of changing C_D on the trajectory were investigated [4].

Due to the fact that each player kicked the balls slightly differently and consequently there was a variation in the velocity and orientation of the foot for each kick, the overall effectiveness of each kick was compared by calculating the total Kinetic Energy (K.E.) imparted to each ball, using Equation 2:

$$\text{K.E.} = 1/2\,mv_b^2 + 1/2\,I\omega^2 \tag{2}$$

where m = mass of ball (kg), v_b = launch velocity of ball (m/s), I = moment inertia of ball (kg/m^2) and ω = angular launch velocity of ball (rad/s).

It was not possible to come up with an estimate of the K.E. of the foot before impact, due to difficulties in estimating the effective mass of the foot and the error due to variation between the players. Therefore the total K.E. imparted to the ball was plotted against foot velocity squared (v_f^2) (Figure 9), showing that in general K.E. increased linearly with v_f^2.

The error bars were calculated as follows, where the error in the mass measurement was given by ± 0.23% (calculated by weighing all the balls used during testing with scales that were accurate to 0.001 kg), the error in the calculation of I was estimated as ± 5% using repeat measurements for various different balls, the errors in v_b and ω

were taken from Table 2, and the final % error was calculated using worst-case (i.e. lowest) values of $1/2mv_b^2$ and $1/2I\omega^2$. The equations are given in Kirkup [18].

All the balls showed a similar trend of increasing K.E. with foot velocity squared, but it was difficult to distinguish between the balls. This is probably due to the combined effects of varying ball mass (up to 20 g) and imparted spin. In order to distinguish between the balls better, Figure 10 shows a bar chart of the average spin rate imparted to the balls during the testing. The error bars used were those of the standard % error calculated for ω (Table 2).

The range of average angular velocity imparted to the balls was 94.7-146.0 rad/s. It can be seen that, on average, significantly more spin (~50% more) was imparted to Ball 2 than to the other balls, which all have similar average spin rates (within about 5%). The reasons for this could be due to differences in surface finish, in the coefficient of restitution of the ball at high velocity or in its moment of inertia. Each ball had passed the same FIFA bounce test [2], suggesting that the normal impact behaviour of the balls was similar. However, Ball 2 was noted to have a different, rougher surface to the other balls, which would explain why more spin could be imparted by the foot. Further studies regarding surface finish would be instructive in understanding this phenomenon in more detail. Ball 2 was also found to have a slightly higher moment of inertia than the other balls, but it is thought that this difference was not significant, compared to the surface finish.

3.2 Trajectory Results

3.2.1 Drag results

The C_D values that were extracted from the testing are shown in Figure 11, together with the corresponding wind tunnel measurements [4] and CFD simulations [3]. The results showed a large amount of scatter and it was difficult to distinguish between the balls, and therefore for clarity not all the results are displayed. It can be seen that Re varied from 2.15×10^5 to 3.18×10^5 ($2.67\times10^5 \pm 19\%$), compared to the average measured Re of 3.56×10^5 in the player testing.

The C_D values were of the expected order of magnitude, but increase sharply with Re, contrary to results from the other studies [3, 4] and the expected trend. Previous wind tunnel tests on a spinning scale-model soccer ball [19] showed a drop in C_D in this Reynolds number regime. A plot of C_D vs. Sp shows no convincing trend, which is expected from previous wind tunnel tests on a spinning scale-model soccer ball [19]. It is difficult to draw any further conclusions due to the high scatter, which was probably mainly caused by the assumption of constant C_D, where in reality the flow could be in transition and therefore C_D would vary. This confirmed that wind tunnel testing is a preferred method for gaining accurate C_D values for non-spinning balls, where the effect of transition can be measured.

3.3.2 Lift results

The results for C_L magnitude at various Sp values are shown in Figure 12, with approximate fits, compared to wind tunnel results for a spinning scale model soccer ball (which had exaggerated seams) [19]. Sp varied from 0.044 to 0.804 (0.424 ± 90%), compared to the average measured values for curling kicks in the player testing of Sp = 0.49. The C_L values were of the expected order of magnitude, and they increased with Sp from zero at Sp = 0 to a maximum as the Magnus Effect became larger. C_L flattened off to a maximum because there was a limit to both the latest and earliest separation points on the ball, and therefore to the asymmetry of the wake. The curves for each ball show that more panels resulted in higher C_L, probably because the greater number of seams encouraged later separation and caused the wake to be deflected more. This has an upper limit, where an increase in panel number results in no change in C_L. These results confirmed that trajectory testing can be a powerful method for assessing differences in spinning ball behaviour.

3.3.3 Effects on trajectory

For a high-spin curling kick, the aerodynamic behaviour of each ball type was compared by entering the results into a trajectory prediction model [19] and keeping the initial conditions otherwise the same, which corresponded to a typical curving kick, with a ball launch velocity of 21.1 m/s, an initial angle of elevation 26.2^{o} and a launch spin rate of 100 rad/s.

The three-dimensional trajectory simulation model calculates the forces experienced by the ball at discrete time intervals during its flight using the following Equations 3 and 4 (using a time step of 2.5 ms). The coefficients C_D and C_L are calculated at each time interval based on the mathematical fits of the wind tunnel data, as the velocity, Re and Sp of the ball changes. The spin is assumed to remain in the horizontal plane throughout the flight with no significant degradation.

$$F_D = \frac{1}{2} C_D \rho A v^2 \tag{3}$$

$$F_S = \frac{1}{2} C_L \rho A v^2 \tag{4}$$

The measured C_L values were entered in as C_S values, corresponding to sidespin rather than topspin, in order to simulate a kick that bent to the side. The variation of C_D with Re was taken as that of Ball 1 from previous wind tunnel results [4]. The resulting trajectories are shown in Figure 13.

The comparison of these trajectories to the non-spinning trajectory highlights the large effect of spin on the flight, and it can be seen that the more panels the ball had, the more swerve it achieved. The difference in the final horizontal position between Ball 1 and Ball 4 was 1.04 m. The choice of ball from the current selection could therefore be the difference between whether a goal is scored or missed.

For each of these trajectories, the change in C_D and C_S with time is shown in Figure 14. It can be seen that, for this type of kick, each ball slowed down enough to enter the critical region, and therefore C_D increased with time. C_D began to drop off again towards the end of flight as the velocity actually increased slightly due to gravitational acceleration. C_S increased with time as the ball slowed down and Sp correspondingly increased, and C_S was significantly higher for Ball 1 than for the other balls.

4. Conclusions

Four different balls were curled into the corner of the goal by five Premiership youth-team players, and the launch conditions of the kicks were successfully measured using a high-speed video camera. It was found that the players could apply more spin

(~50%) on average to Ball 2, which had a slightly rougher surface than the other balls. The balls were launched at an average of 23.7 m/s, and with an average spin of 106 rad/s, which gave an average spin ratio, Sp, of 0.49. It was therefore thought that the balls probably spent some of their flight in the transition or laminar regime and therefore may have suddenly slowed down or dropped in the air.

The trajectories for four different balls fired at various velocities and spin rates across a sports hall were captured using high-speed video cameras, and their C_D and C_L values estimated. For each ball, C_L increased to a maximum and compared well to previous experimental results. Balls with more panels experienced a higher C_L, and increasing the number of panels from 14 to 32 could alter the final position of a curling free-kick significantly, by up to 1 m.

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References

[1] Newton I (1672) New theory of light and colours. Phil Trans 80**:** 3075-3087

[2] FIFA (2006) Testing and certification of footballs – International Matchball Standard. http://www.fifa.com/mm/document/afdeveloping/pitchequip/ims_sales_doc_05_2006_13411.pdf. Accessed 5 April 2010.

[3] Barber, S., Chin, S. B. & Carré, M.J. (2009) Sports ball aerodynamics: a numerical study of the erratic motion of soccer balls. J. Computers and Fluids, **38**, 1091-1100

[4] Barber S, Seo K, Asai T, Carré MJ (2007) Experimental investigation of the effects of surface geometry on the flight of non-spinning soccer balls. In: Fuss FK, Subic A, Ujihashi S (eds) The impact of technology on sport II, Taylor & Francis / Balkema, The Netherlands, pp 397-402

[5] Alaways LW, Hubbard M (2001) Experimental determination of baseball spin and lift. J Sports Sci 19**:** 349-358

[6] Taniguchi T, Miyakazi T, Shimizu T, Himeno R(2005) Measurement of aerodynamic forces exerted on baseballs using a high-speed video camera. In: Subic A, Ujihashi S (eds) The Impact of Technology on Sport, Australasian Sports Technology Alliance, pp 23-26

[7] Cairns, TW (2004) Modelling lift and drag forces on a volleyball. In: Hubbard M, Mehta RD, Pallis JM (eds) The Engineering of Sport 5: Proceedings of the 5th International Conference on the Engineering of Sport, ISEA, UK, pp. 97-102

[8] Deprá P, Brenzikofer R, Goes M (1998) Fluid mechanics analysis in volleyball services. In: Riehle HJ, Vieten M (eds) 16 International Symposium on Biomechanics in Sports, ISB, pp. 101-106

[9] Chikaraishi T, Alaki Y, Maehara K, Shimosaka H, Fukazawa F (1990) A new method on measurement of trajectories of a golf ball. In: Cochran AJ (ed) Science and Golf: Proceedings of the World Scientific Congress of Golf, SPON product, pp. 193-198

[10] Zayas JM (1985) Experimental determination of Cd of a tennis ball. Amer J Phys**:** 622-625

[11] Asai T, Carré MJ, Akatsuka T, Haake SJ (2002) The curve kick of a football I: impact with the foot. Sports Eng 5**:** 183-192

[12] Carré MJ, Asai T, Akatsuka T, Haake SJ (2002) The curve kick of a football II: flight through the air. Sports Eng 5**:** 193-200

[13] Goff, E.J., Carré, M.J. (2009) Trajectory analysis of a soccer ball. Am J Phys 77 (11): 1021-1027

[14] Goff, E.J. & Carré, M.J. (2010) Soccer ball lift coefficients via trajectory analysis. Eur J Phys 31: 775–784

[15] Bray K, Kerwin DG (2003) Modelling the flight of a soccer ball in a direct free kick. J Sports Sci 21**:** 75-85

[16] Bray K, Kerwin DG (2004) Modelling the long throw in soccer using aerodynamic drag and lift. In: Hubbard M, Mehta RD, Pallis JM (eds) The Engineering of Sport 5, ISEA, UK**,** pp. 56-61

[17] Kerwin DG, Bray K (2004) Quantifying the trajectory of the long soccer throw. In: Hubbard M, Mehta RD, Pallis JM (eds) The Engineering of Sport 5, International Sports Engineering Association**,** pp. 63-68

[18] Kirkup L (1994) Experimental methods. John Wiley and Sons, Brisbane

[19] Carré MJ, Goodwill SR, Haake SJ (2005) Understanding the effect of seams on the aerodynamics of an association football. J Mech Eng Sci 219 (7)**:** 657-666

Table 1 Balls used throughout testing, along with the range of characteristics for a FIFA approved size 5 according to “International Matchball Standard” [2]

Table 2 Ball data measured from player testing

Table 3 Ball data measured from trajectory testing

Fig. 1 Apparatus used for player testing

Fig. 2 Ball used throughout testing

Fig. 3 Apparatus used for trajectory testing

Fig. 4 Machine used to launch balls for trajectory testing

Fig. 5 Example of trajectory fitting to camera data

Fig. 6 Repetition of trajectory fitting, used to estimate errors

Fig. 7 Comparison of a fitted trajectory based on measurement data to a simulated trajectory based on constant C_D and C_L

Fig. 8 Comparison of trajectories to evaluate the sensitivity of the trajectory to the constant C_D and C_L values assigned

Fig. 9 Kinetic energy analysis of player testing

Fig. 10 Spin imparted during player testing

Fig. 11 Drag coefficient data obtained from trajectory testing, compared to previous studies

Fig. 12 Lift coefficient data obtained from trajectory testing, compared to previous studies

Fig. 13 Free-kick simulations for the four ball types

table

Table 1 Balls used throughout testing, along with the range of characteristics for a FIFA approved size 5 according to "International Matchball Standard" [2]

	Ball 1	Ball 2	Ball 3	Ball 4	IMS range
Construction	32 panels, stitched	26 panels, stitched	20 panels, stitched	14 panels, bonded	Not specified
Mass (g)	417	434	425	440	410 to 450
Diameter (mm)	219	220	219	220	216 to 223
Moment of Inertia (kgm^2)	3.00×10^{-3}	3.29×10^{-3}	3.15×10^{-3}	3.23×10^{-3}	Not specified
Seam depth (mm)	1.0 to 1.6	1.0 to 1.6	1.0 to 1.6	1.4 to 1.7	Not specified

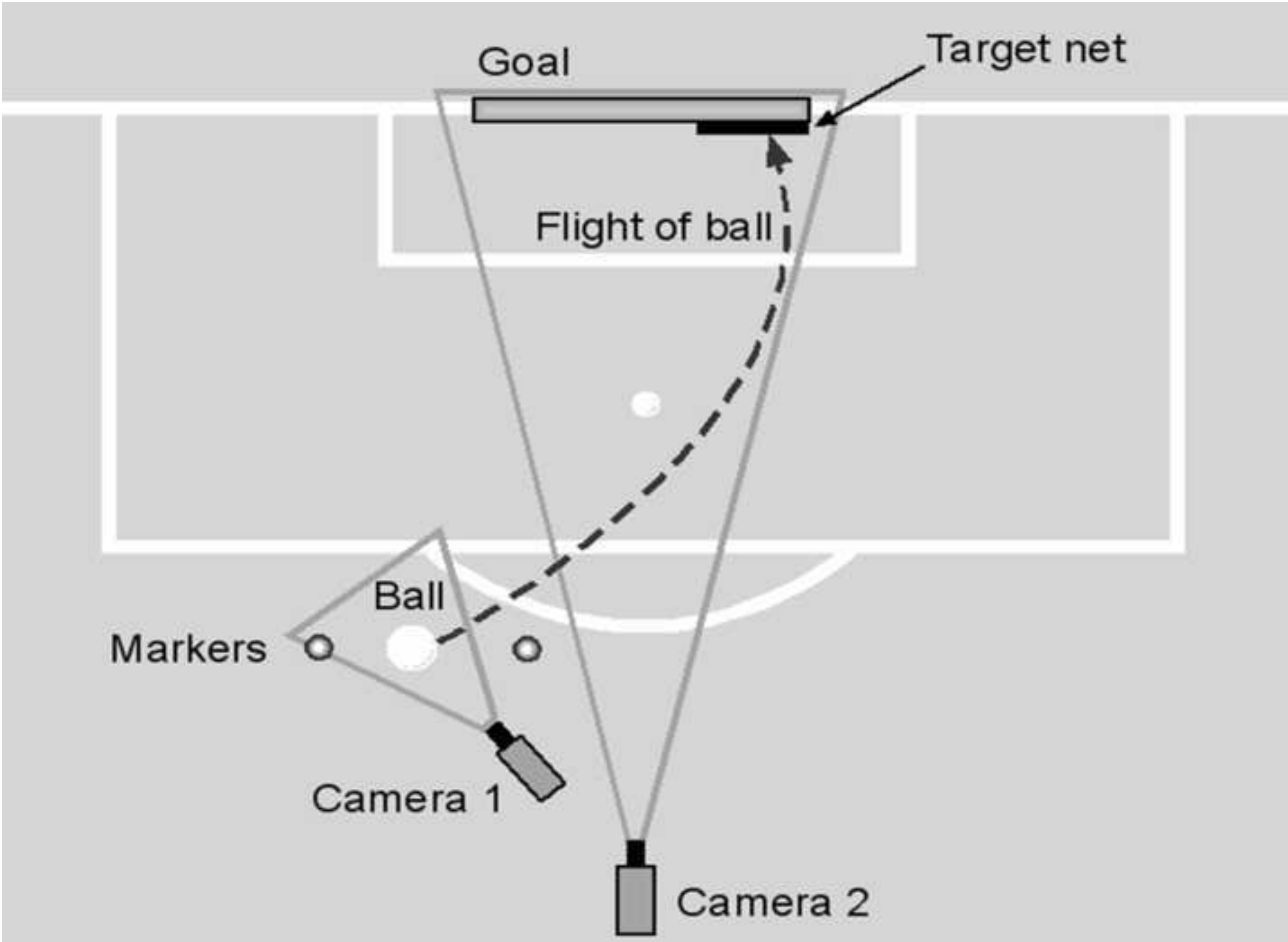
table

Repeat	Ball launch velocity (m/s)	Ball initial elevation (°)	Ball initial angular velocity (rad/s)
1	27.88	14.44	72.11
2	27.09	14.27	94.82
3	24.90	14.61	79.67
4	24.68	15.02	87.77
5	24.28	14.80	96.84
Mean	**25.77**	**14.63**	**86.24**
Standard deviation	**1.61**	**0.29**	**10.38**
Standard error	**0.72**	**0.13**	**4.64**
Standard % error	**2.80%**	**0.90%**	**5.38%**

table

Repeat	Ball launch velocity (m/s)	Ball initial elevation (°)	Maximum distance travelled (m)	Time of flight (s)
1	22.17	15.65	17.79	1.04
2	21.15	15.10	18.02	1.05
3	21.08	16.65	18.27	1.06
4	21.00	16.61	18.30	1.06
5	21.26	15.34	18.15	1.06
Mean	**21.33**	**15.87**	**18.11**	**1.05**
Standard deviation	**0.49**	**0.72**	**0.21**	**0.01**
Standard error	**0.21**	**0.32**	**0.09**	**0.00**
Standard % error	**1.00%**	**2.03%**	**0.51%**	**0.38%**

line figure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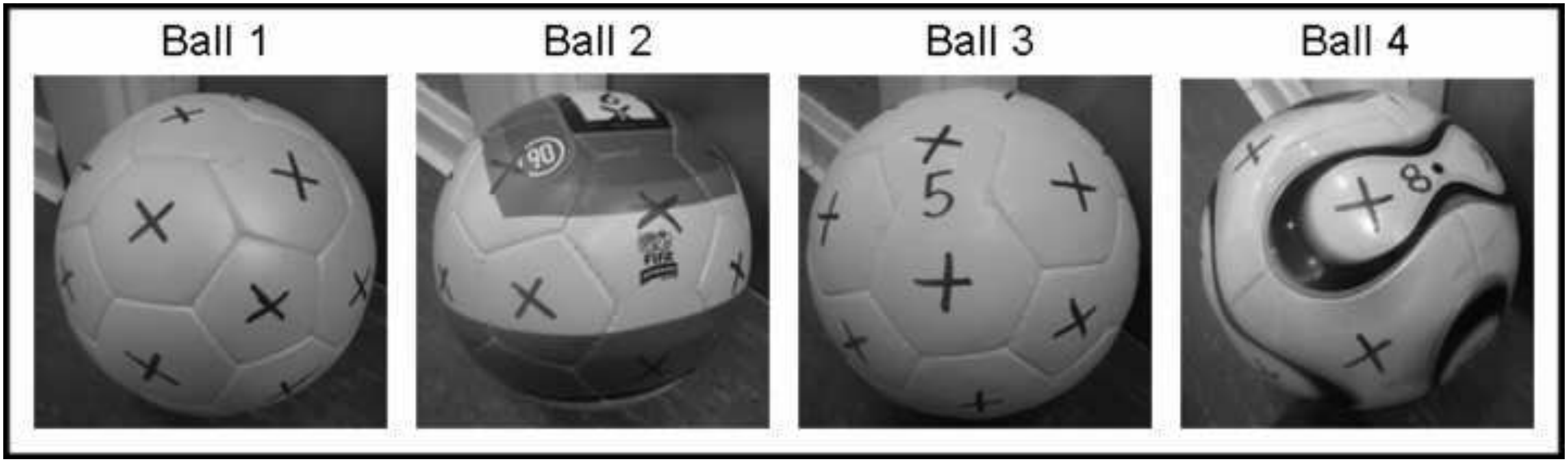
Target net
Flight of ball
Ball
Markers
Camera 1
Camera 2

line figure



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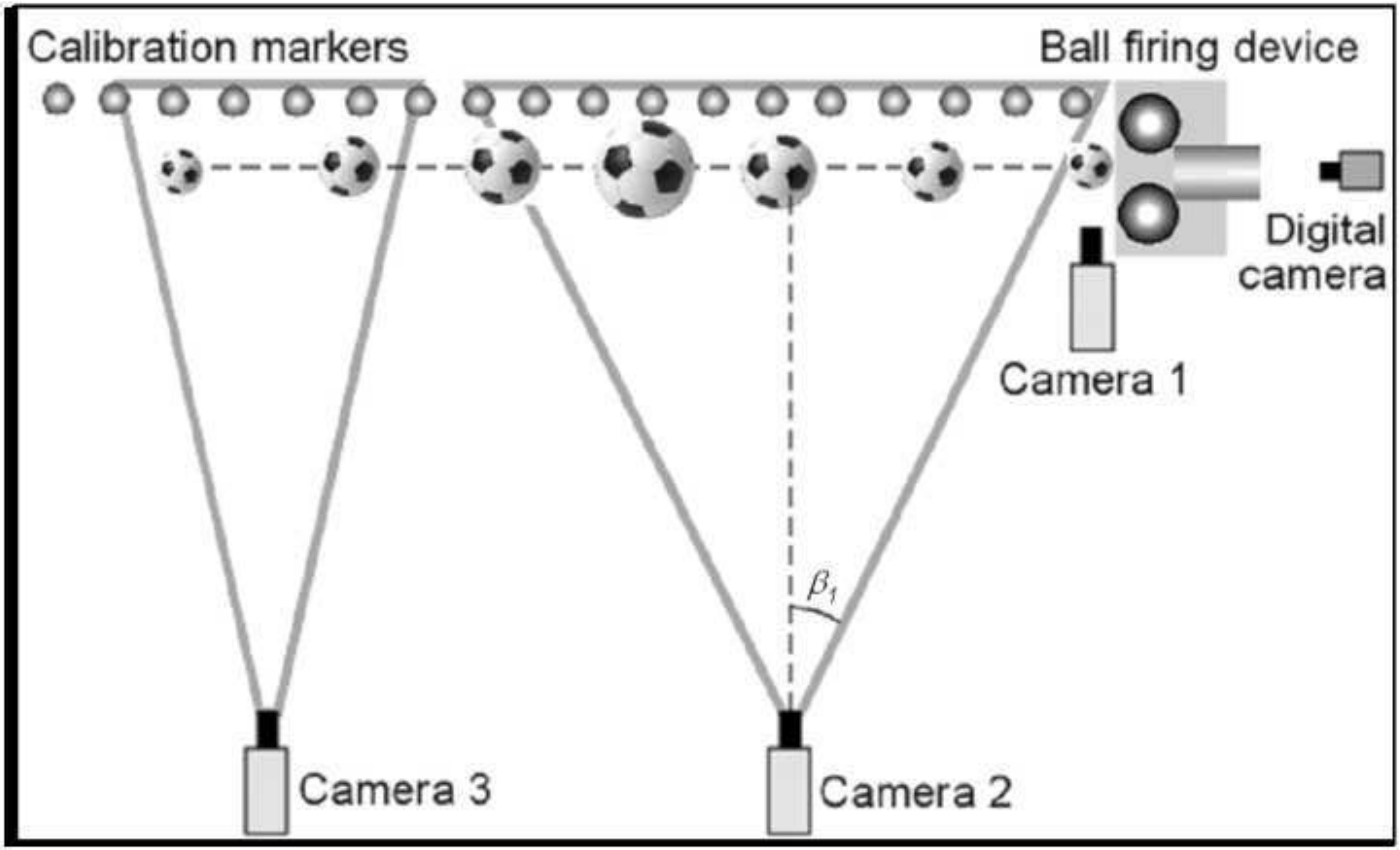
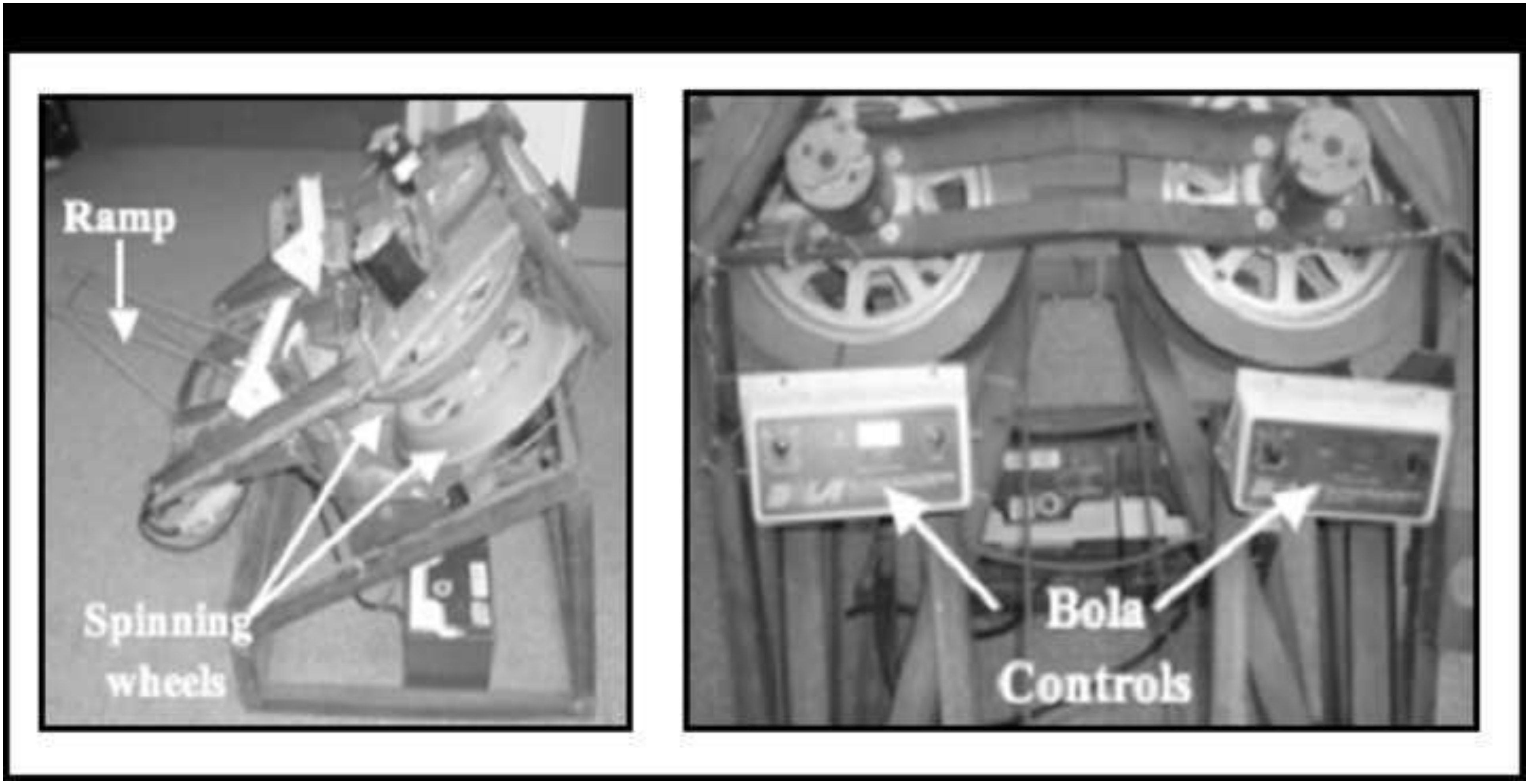


Calibration markers
Ball firing device
Digital camera
Camera 1
β_1
Camera 3
Camera 2

line figure



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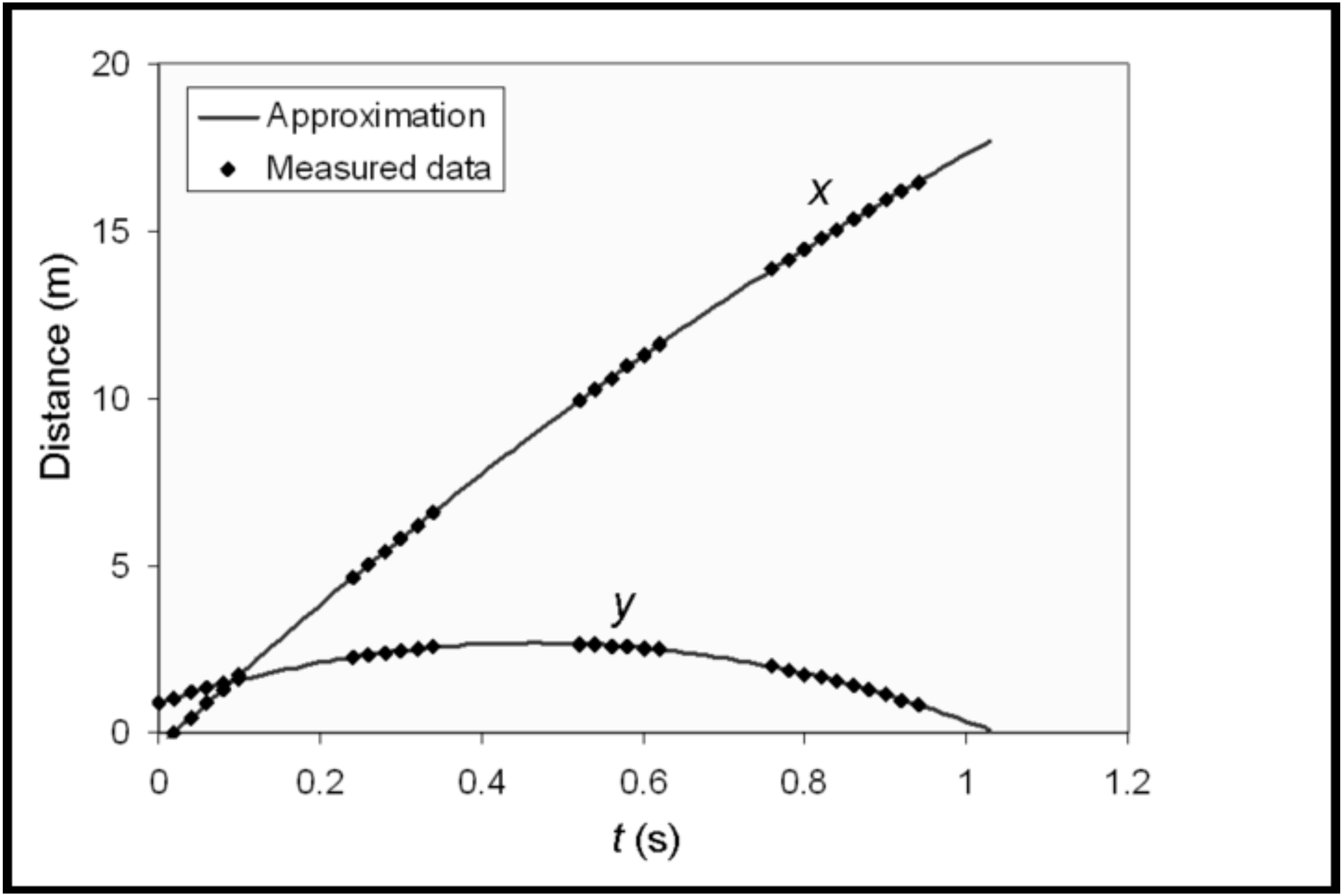

Approximation
Measured data
x
y
Distance (m)
t (s)
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15
20
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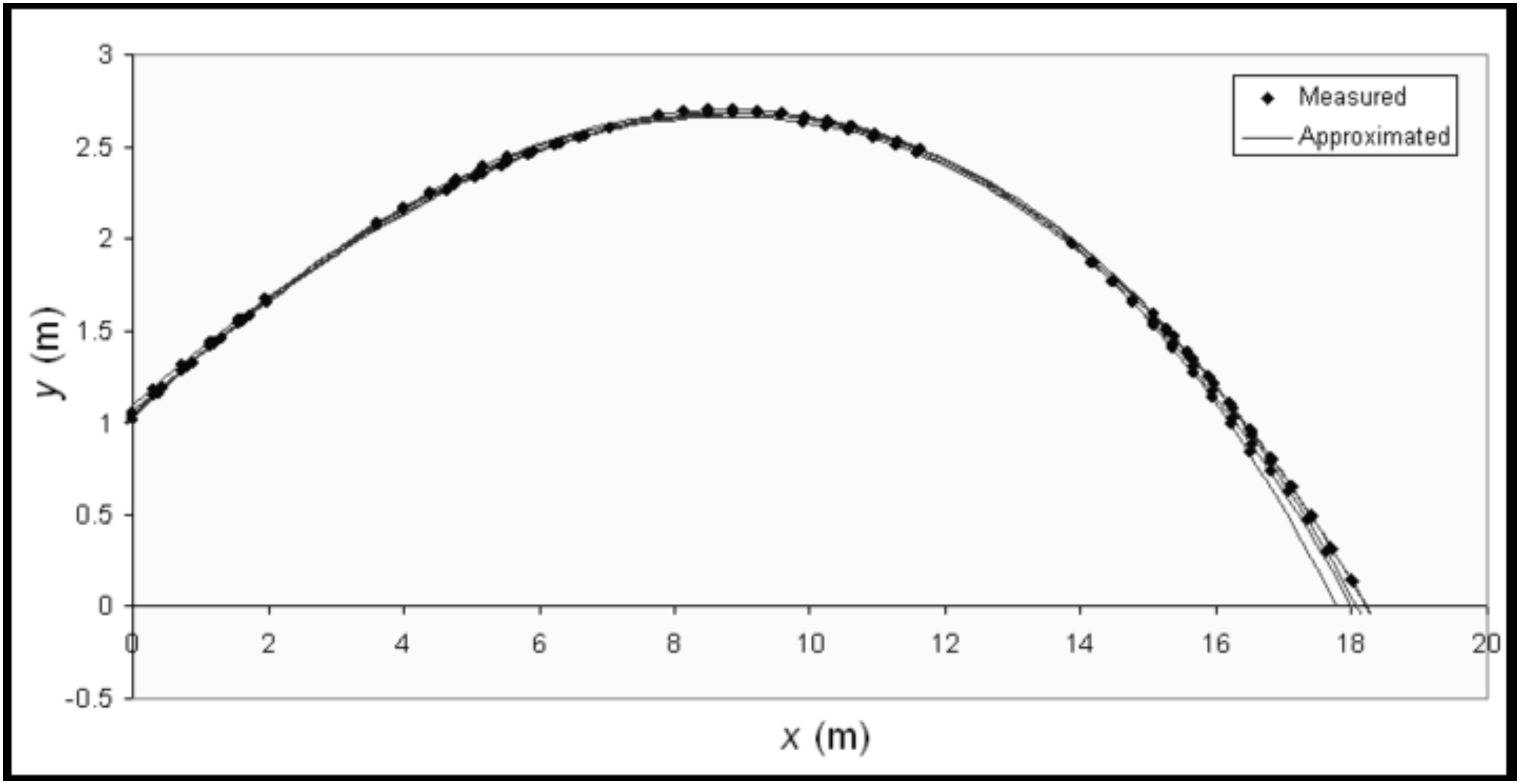
0.4
0.6
0.8
1
1.2

line figure



Measured
Approximated
y (m)
x (m)
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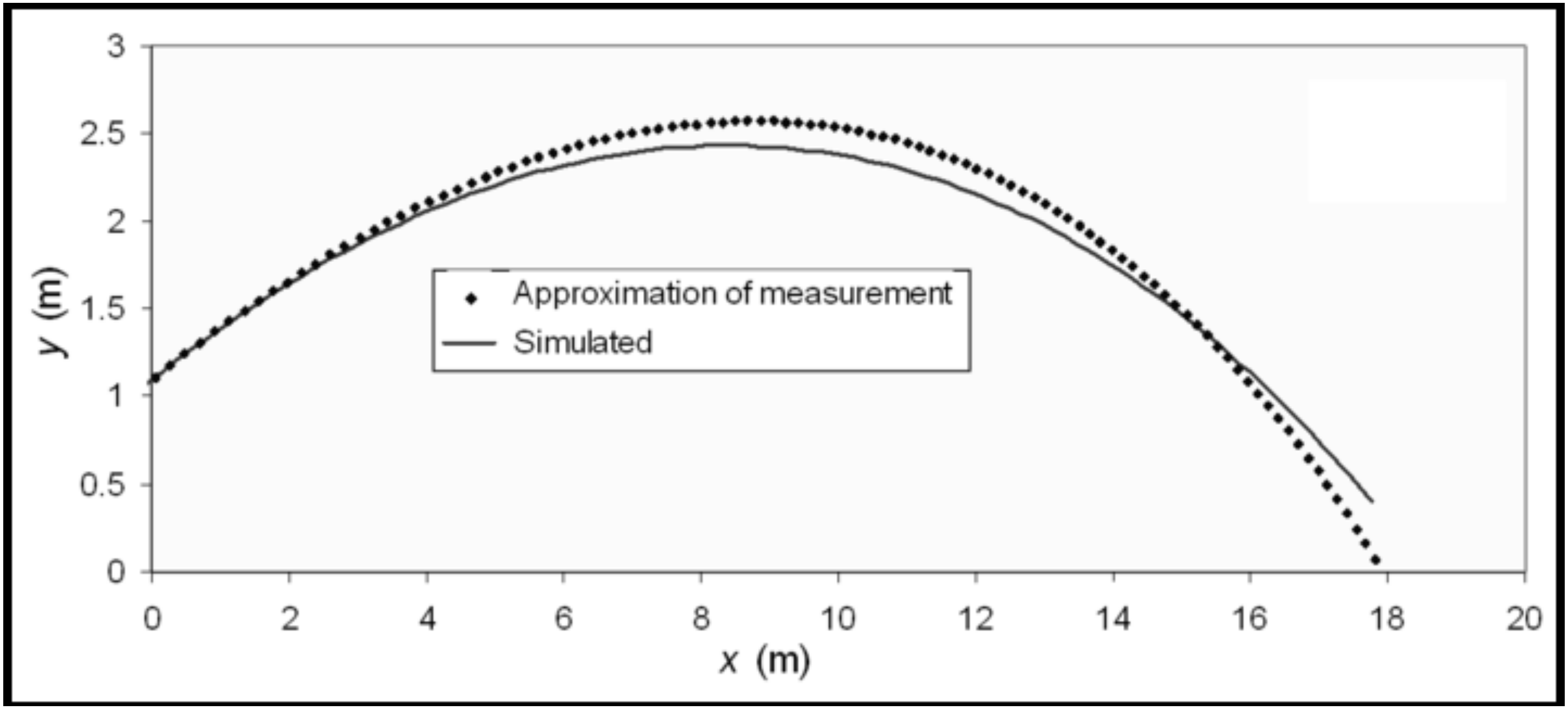
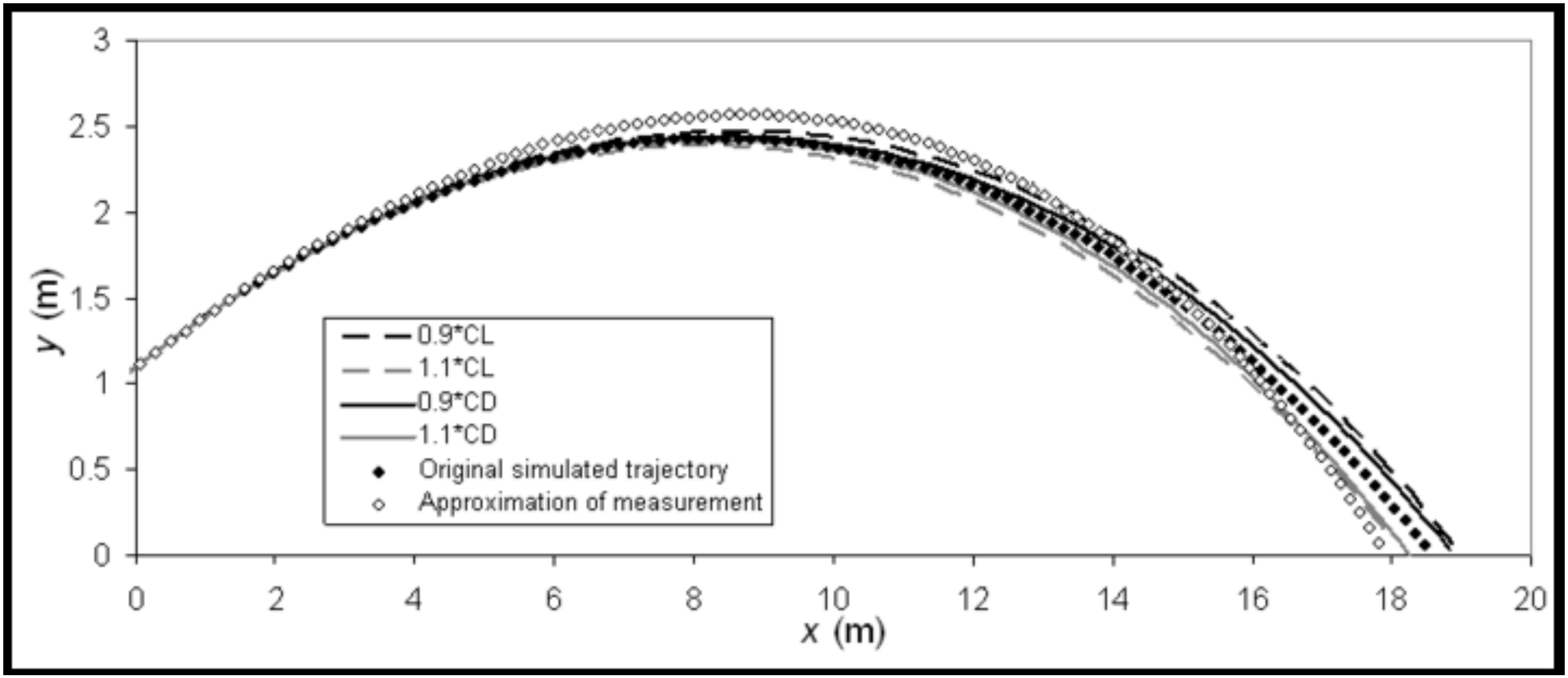
2.5
2
1.5
1
0.5
0
-0.5
0
2
4
6
8
10
12
14
16
18
20

line figure



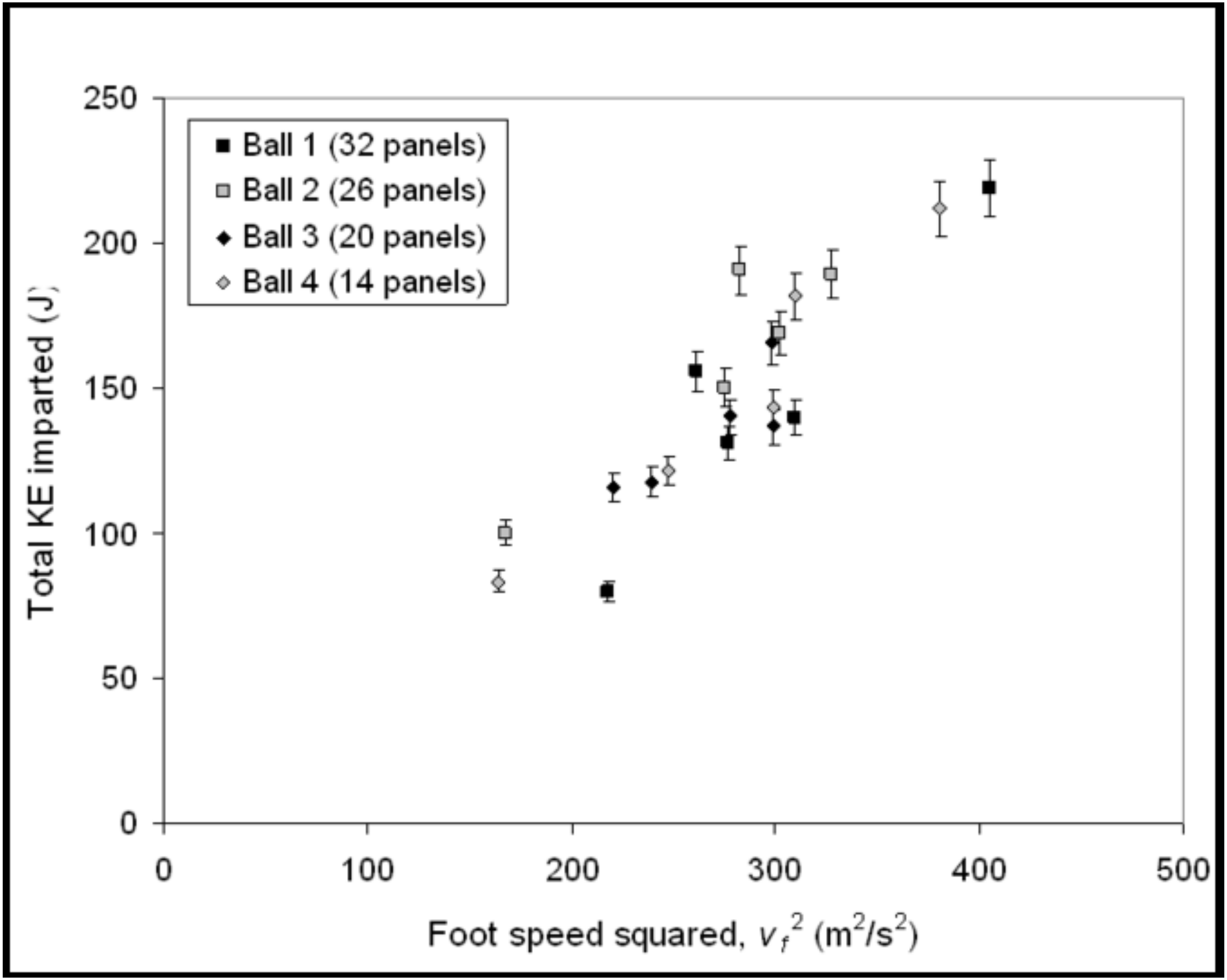
3
2.5
2
1.5
1
0.5
0
y (m)
Approximation of measurement
Simulated
0
2
4
6
8
10
12
14
16
18
20
x (m)

line figure



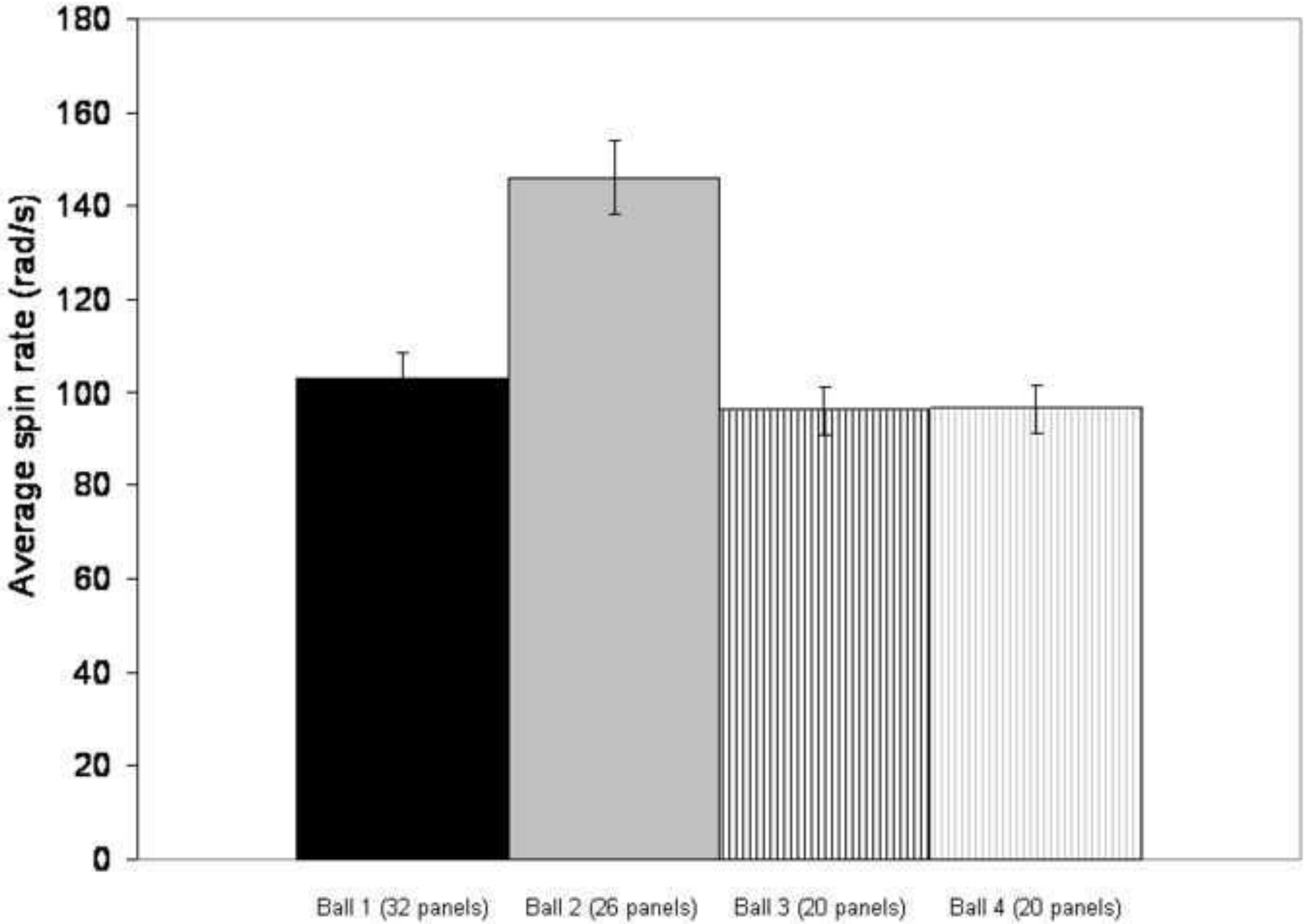
3
2.5
2
1.5
1
0.5
0
y (m)
0
2
4
6
8
10
12
14
16
18
20
x (m)
0.9*CL
1.1*CL
0.9*CD
1.1*CD
Original simulated trajectory
Approximation of measurement

line figure



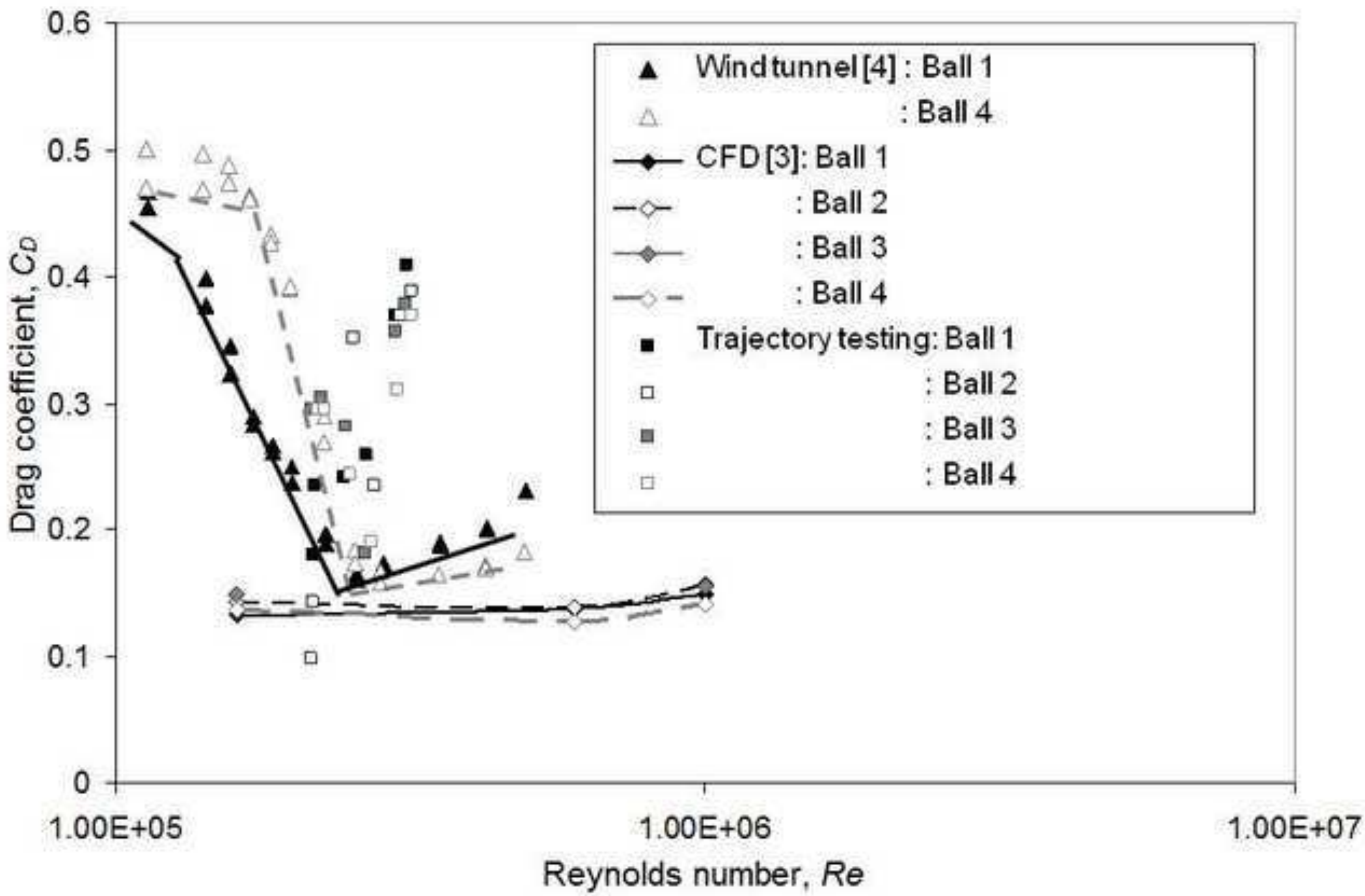
Ball 1 (32 panels)
Ball 2 (26 panels)
Ball 3 (20 panels)
Ball 4 (14 panels)
Total KE imparted (J)
Foot speed squared, v_f^2 (m^2/s^2)
0
50
100
150
200
250
0
100
200
300
400
500

line figure

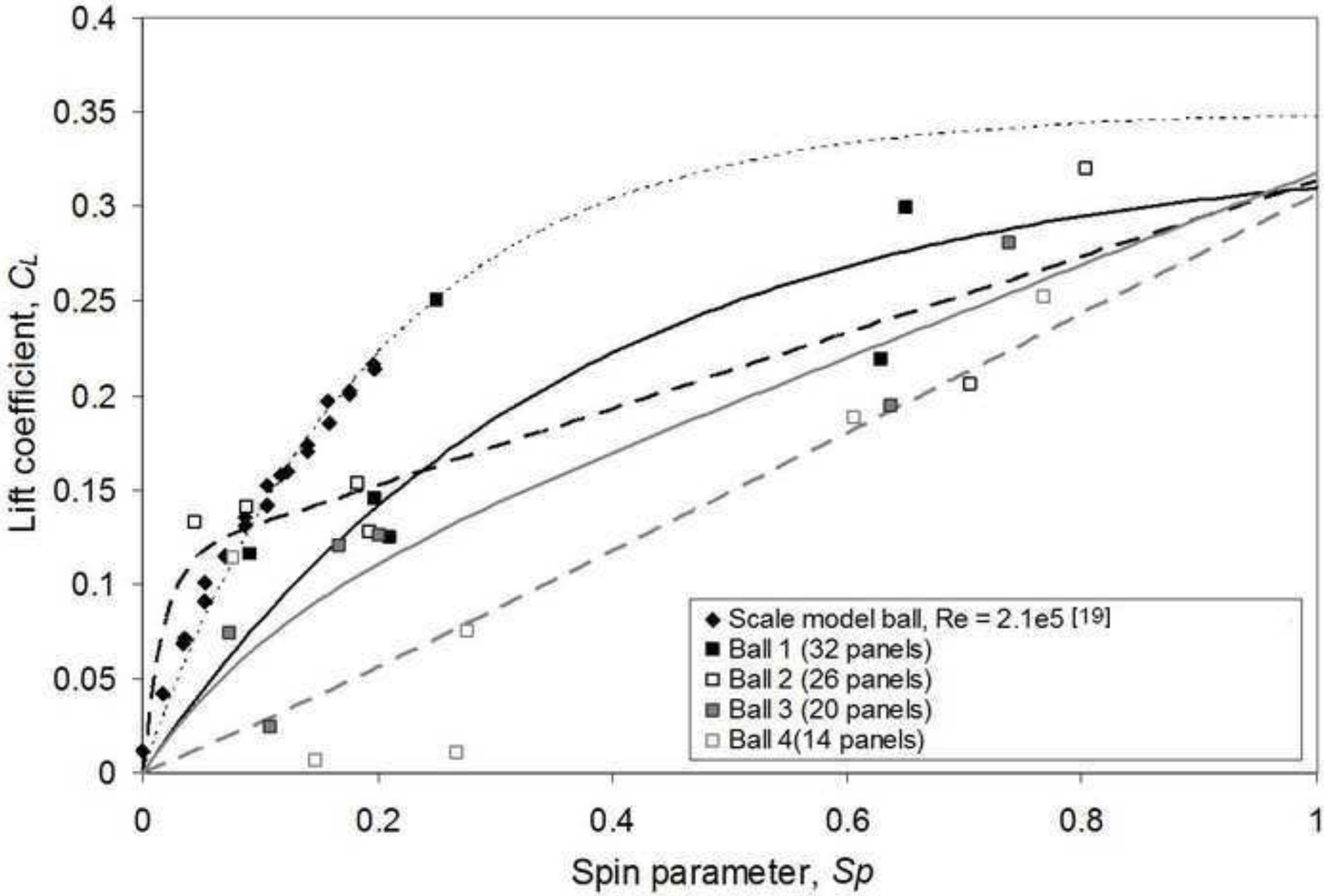


Average spin rate (rad/s)
180
160
140
120
100
80
60
40
20
0
Ball 1 (32 panels)
Ball 2 (26 panels)
Ball 3 (20 panels)
Ball 4 (20 panels)

line figure

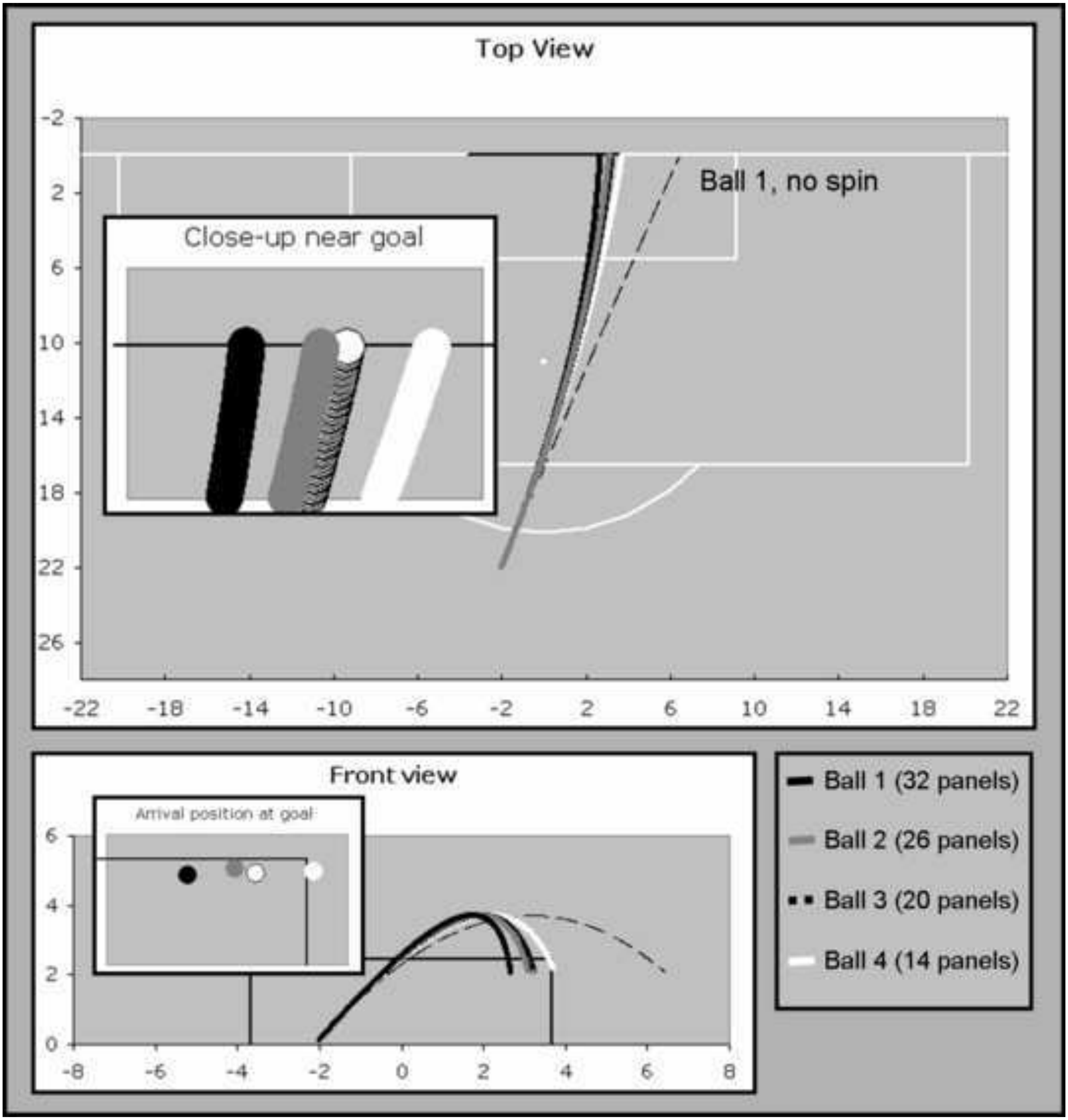

Wind tunnel [4] : Ball 1
: Ball 4
CFD [3]: Ball 1
: Ball 2
: Ball 3
: Ball 4
Trajectory testing: Ball 1
: Ball 2
: Ball 3
: Ball 4
Drag coefficient, C_D
0.6
0.5
0.4
0.3
0.2
0.1
0
1.00E+05
1.00E+06
1.00E+07
Reynolds number, *Re*

line figure



Lift coefficient, C_L
Spin parameter, Sp
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
Scale model ball, Re = 2.1e5 [19]
Ball 1 (32 panels)
Ball 2 (26 panels)
Ball 3 (20 panels)
Ball 4(14 panels)

line figure



Top View
Ball 1, no spin
Close-up near goal
-2
2
6
10
14
18
22
26
-22
-18
-14
-10
-6
-2
2
6
10
14
18
22
Front view
Arrival position at goal
6
4
2
0
-8
-6
-4
-2
0
2
4
6
8
Ball 1 (32 panels)
Ball 2 (26 panels)
Ball 3 (20 panels)
Ball 4 (14 panels)