Sports Engineering (2022) 25:24
https://doi.org/10.1007/s12283-022-00389-y

TECHNICAL NOTE

Repeatability of a piezoelectric force platform to measure impact metrics for a single model of football

Katie L. Mills[1] · Johsan Billingham[2] · Simon Choppin[1] · Marcus Dunn[1] · Terry Senior[1] · Simon Goodwill[1]

Accepted: 3 October 2022 / Published online: 3 November 2022

Abstract

The visco-elastic properties of a football influence how it bounces and therefore its performance in a game. Previously, high-speed camera footage has been used to quantify deformation, coefficient of restitution and contact time for an impact between a football and a rigid surface but these systems do not provide any information on the forces acting on the football during the impact. The aim of this study was to determine the repeatability of measuring the peak impact force, impulse, rise time and loading rate for four samples of the same model of football using a commercial force platform (Kistler 9281EA). A football impacted the floor-mounted piezoelectric-type force platform at 6.04 and 19.4 m s^{-1}. High absolute (coefficient of variation (CV) ≤ 10%) and relative (intraclass correlation coefficient (ICC) ≥ 0.94) repeatability was observed for repeated impacts at both velocities. The minimal detectable differences were calculated to evaluate the ability for the force platform to be used to make meaningful comparisons between footballs. For all metrics, the minimum detectable difference accounted for less than 5% of the mean value. Therefore, it can be concluded that provided the difference in impact metrics between football models exceeds the minimal detectable difference, the commercial force platform can be used to measure and detect differences in physical impact metrics between models of footballs.

1 Introduction

The visco-elastic properties of a football influence its behaviour during and after impact. When determining the dynamic properties of footballs, high-speed camera footage is often used to quantify the ball deformation, the coefficient of restitution (COR) and the contact time [1, 2].

Force platforms can be used to measure the loading behaviour of a ball throughout impact [3]. They have been used in tennis and baseball research to compare the loading behaviour of different ball constructions, to improve the performance or safety of equipment and to inform standards of play [4–7]. To achieve a sufficiently high-frequency response, bespoke systems are often required [8]. However, studies examining impacts between a football and a planar rigid surface have used commercial force platforms designed for biomechanical applications such as gait analysis [9, 10], which can suffer from resonance due to the short contact time relative to the system's natural frequency [8]. Studies have used the force trace to validate mathematical or computational models [11–14], but few have used it to compare the loading behaviour of different models of footballs [3, 15]. These studies have reported a single value of mean peak impact force for each model of football, and do not present any evidence to suggest the repeatability of the system had been quantified before using it to make comparisons. To be able to compare different models of football, the repeatability of measurement of impact metrics from the force platform must be determined. The minimal detectable differences (MDD) of impact metrics are calculated from reliability statistics and allow differences in dynamic behaviour to be established to the required level of significance.

The aim of this paper was to determine the repeatability of measuring relevant impact metrics for a single, FIFA certified model of football using a commercial force platform.

This article is a part of Topical Collection in Sports Engineering on Football Research, edited by Dr. Marcus Dunn, Mr. Johsan Billingham, Prof. Paul Fleming, Prof. John Eric Goff and Prof. Sam Robertson.

✉ Katie L. Mills
k.mills@shu.ac.uk

[1] Sports Engineering Research Group, Faculty of Health and Wellbeing, AWRC, Sheffield Hallam University, Olympic Legacy Park, 2 Old Hall Road, Sheffield S9 3TU, UK

[2] Fédération Internationale de Football Association, Zurich, Switzerland

2 Methods

2.1 Experimental procedure

The study adhered to the ethical requirements of Sheffield Hallam University, meaning all procedures were approved by the corresponding Research Ethics Board (ER40333305). Four samples of a FIFA Quality Pro certified football (Adidas Tiro Pro; size 5, 32 panel, thermally bonded, mass = 434.0 ± 1.1 g) were inflated to an internal pressure of 0.80 ± 0.01 bar. Each football sample was conditioned (temperature 20 °C; humidity 65%) using a climate chamber (Climacell 404; MMM Medcenter Einrichtungen GmbH) for at least 24 h before impacting. Two samples were used at the velocity outlined by the FIFA Quality Programme test manual [16] (6.04 ± 0.04 m s^{-1}) and the other two samples were used at a higher velocity considered to better represent typical match play conditions (19.4 ± 0.4 m s^{-1}). Each sample was impacted 50 times at each velocity condition. At the lower velocity, the football was released 2 m above the force platform using a vacuum to minimise spin on release. At the higher velocity, the football was accelerated using a bespoke 4-wheel ball-launching device. The orientation of the football was controlled before release to avoid direct impacts on the valve. The football impacted a floor-mounted piezoelectric force platform (9281EA, Kistler Holding AG, dimensions; 600 × 400 mm, natural frequency; 1 kHz) without spin and above one of the corner sensors to reduce undesirable oscillations in the system. Two high-speed cameras (Phantom MIRO 311, Vision Research Ltd., USA; resolution 320 × 800 p; sample rate 10,000 fps) were synchronised with the force platform using a common trigger. One camera was positioned perpendicularly 1 m away from the edge of the force platform and calibrated using the diameter of the football, accounting for perspective errors. The second camera was positioned at a stereo angle of 45° to increase the field of view to ensure that at maximum deformation the football did not encroach the edge of the force platform. Impact tests were performed in a laboratory at room temperature 20.7 ± 0.8 °C at a relative humidity of 35.8 ± 5.5%. All impacts on one sample were carried out successively in one session with 2 min of rest between each impact. Each sample was tested in a different session with at least 24 h in-between, in which all test equipment was switched off.

2.2 Data collection

The first five impacts for every sample were discarded to account for the Mullins effects due to the visco-elastic properties of the football materials. The instantaneous in- and out-bound velocities were calculated by plotting the vertical positions obtained by manually digitising ball centres using a circular marker aligned to circumference of the football, on consecutive high-speed video frames (Check2D, Sports Engineering Research Group, Sheffield Hallam University, UK) and then applying the time at which the football impacts and leaves the surface to a 2nd order polynomial trendline. Unfiltered force–time data were acquired from the force platform using BioWare (5.4.3.0, Kistler Holding AG), and were imported into MATLAB (2020a, MathWorks, USA) to extract peak impact force and calculate impulse, rise time and loading rate. The rise time was defined as the time between 10 and 90% of the peak impact force, in line with previous published work [3]. The loading rate was defined as the gradient of the linear fit to the data used to calculate the rise time. To verify the accuracy of the magnitude and duration of the impact, the experimental impulse (I_t) (calculated from the velocity change measured by the high-speed camera) was compared to the theoretical impulse (I_e) (calculated from the force trace measured by the force platform) for impacts between the two samples using:

$$\text{RMSE} = \sqrt{\sum_{i-1}^{n} (I_{it} - I_{ie})^2} \quad (1)$$

2.3 Statistical analysis

Normality of each impact metric was assessed using Shapiro–Wilk tests, $P \geq 0.005$ (SPSS, 26.0.0.1, IBM Corporation). All but two metrics (impulse at low inbound velocity and peak impact force at high inbound velocity) were normally distributed. Metrics that were not normally distributed were log-transformed before analysis. Paired *t* tests ($\alpha = 0.05$) were used to detect statistical differences between the impact metrics of samples at each velocity. Percentiles and the intraclass correlation coefficient $(\text{ICC})_{(2,1)}$ were calculated to test the relative repeatability of each metric. Absolute repeatability was assessed using CV and MDD. ICC values ≥ 0.9 and CV values ≤ 10% were interpreted as high repeatability [17]. The MDD was calculated to establish the difference which must exist between two datasets to be considered significant and was calculated using the standard error of measurement (SEM) with 95% confidence intervals:

$$\text{SEM} = \text{SD}\sqrt{1 - \text{ICC}} \quad (2)$$

$$\text{MDD} = 1.96\text{SEM}\sqrt{2} \quad (3)$$

where data had been transformed, the MDD was converted to the scale of the original dataset using the back transformation and arithmetic mean of the transformed dataset [18]:

$$MDD_{raw} = \exp(mean_{ln}) - \exp(mean_{ln} - MDD_{ln}) \quad (4)$$

3 Results

No statistical differences were found for any metric between samples ($R = 0.76$–0.98, $P \leq 0.001$). All metrics indicated good agreement between samples at each velocity: 19.4 m s^{-1} ($ICC_{2,1} = 0.94$–0.98) and 6.04 m s^{-1} ($ICC_{2,1} = 0.96$–0.98) (Table 1). Figure 1 presents the raw output signals from the force platform at both impact conditions for all trials. The magnitude of error between the theoretical and experimental estimation of impulse accounted for less than 1% of the median value (19.4 m s^{-1}; 0.06 Ns, 6.04 m s^{-1}, 0.04 Ns). Figure 2 shows the distribution curves for all impact metrics at 6.04 m s^{-1}; the non-parametric distribution of impulse is visually apparent ($P = 0.000$). Likewise in Fig. 3, the non-parametric distribution of peak impact force is visually apparent at 19.4 m s^{-1} ($P = 0.000$). The MDD for peak force, impulse and loading rate are presented in Table 1. The calculation of rise time returned discrete values, constrained by the sampling frequency (19.4 m s^{-1} 2–2.5 ms; 6.04 m s^{-1} 2.6–2.8 ms). Zero variance was observed between the two samples. For all metrics, the MDD accounted for about 15% of the confidence interval between the 5% and 95% percentiles.

4 Discussion

This study examined the repeatability of measuring impact metrics for a single FIFA certified football model using a commercial piezoelectric force platform. The force platform used in this study was chosen for its appropriate technical specifications (measuring range, mass, rigidity, and natural

Table 1 Summary of statistics for impact metrics measured from a normal inbound football impact with a piezoelectric force platform at 6.04 m s^{-1} and 19.4 m s^{-1}

Inbound velocity (m s^{-1})	Metric	Median	5% percentile	95% percentile	Range	Sd	ICC	MDD	CV (%)
6.04	Peak impact force (N)	1011.2	1003.9	1019.5	15.6	4.56	0.98	1.96	0.45
	Impulse (Ns)	4.81	4.79	4.83	0.05	0.01	0.96	0.01	0.18
	Rise time (ms)	2.8	2.7	2.8	0.1	0.06	–	–	2.02
	Loading rate (MN/s)	0.31	0.30	0.32	0.02	0.01	0.96	0.003	1.60
19.4	Peak impact force (N)	3693.6	3445.4	3786.3	340.90	73.46	0.98	28.5	0.25
	Impulse (Ns)	14.80	14.71	14.91	0.20	0.06	0.95	0.04	0.39
	Rise time (ms)	2.4	2.1	2.5	0.4	0.12	–	–	4.31
	Loading rate (MN/s)	1.2	1.05	1.40	0.35	0.08	0.94	0.06	7.09

sd standard deviation, *ICC* intraclass correlation coefficient, *MDD* minimum detectable difference, *CV* coefficient of variation in percentage

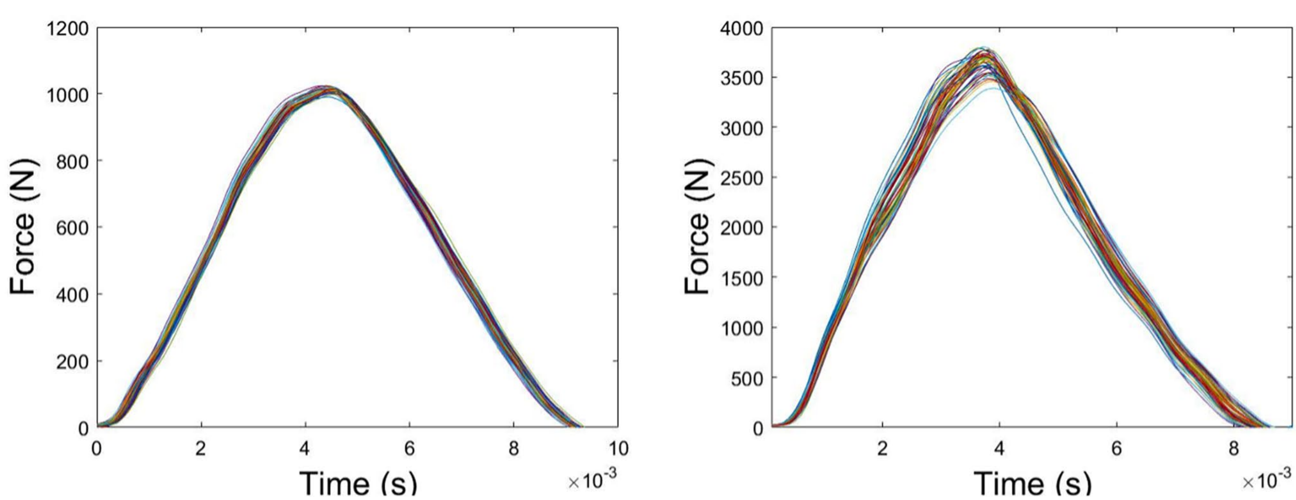

Fig. 1 Raw force–time output signal at 6.04 m s^{-1} [left] and 19.4 m s^{-1} [right]

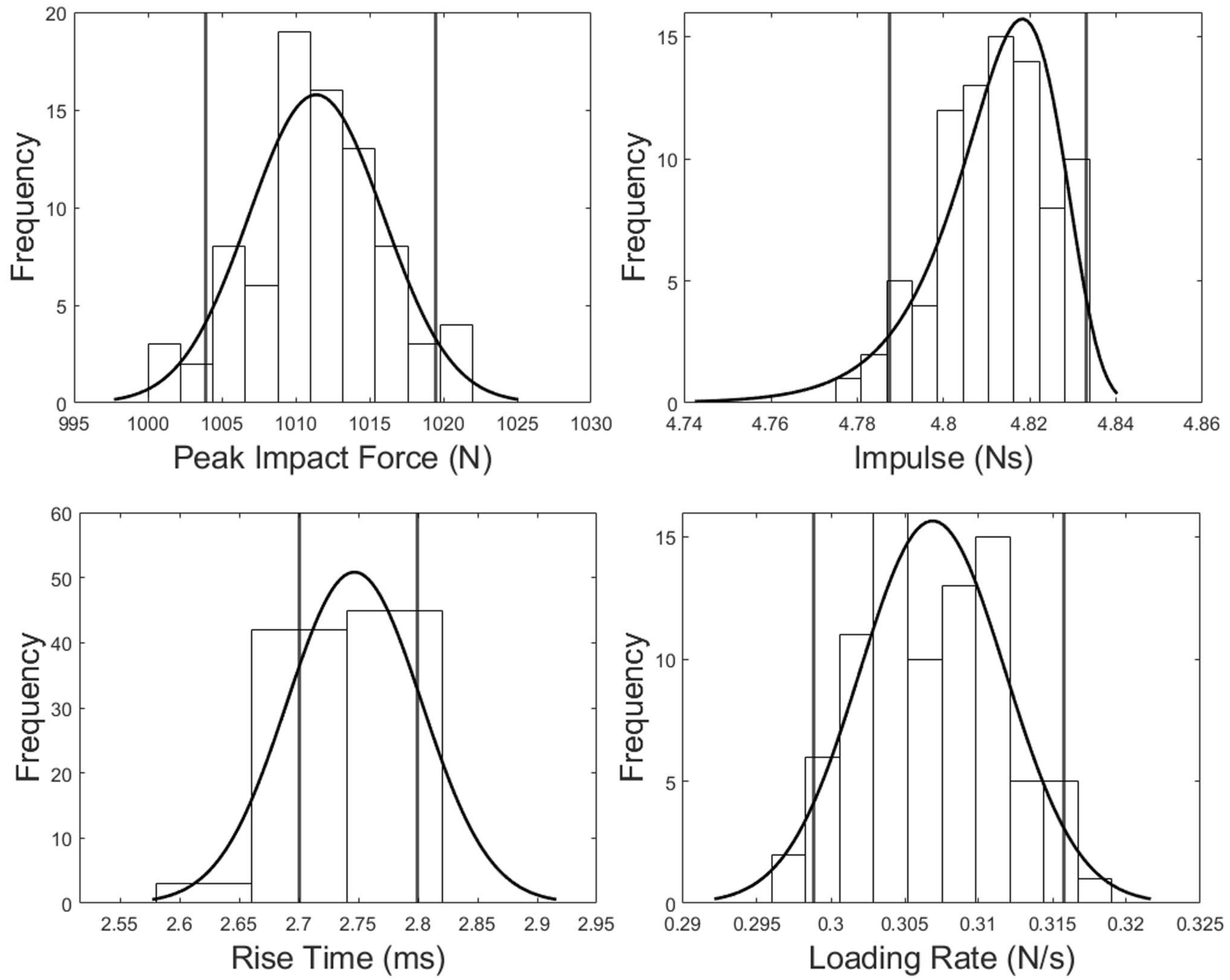

Fig. 2 Histograms with distribution fit for peak impact force, impulse, rise time and loading rate at 6.04 m s^{-1}

frequency [20]) to avoid the amplitude of the natural frequency vibrations corrupting the output signal during short duration impacts [19]. The results suggest the commercial force platform used in this study can be used as an alternative to a bespoke system to measure the loading behaviour of a normal inbound football impact.

Peak impact force, impulse, rise time and loading rate were measured as these metrics characterise the shape of the force–time curve. High absolute (CV ≤ 10%) and relative (ICC ≥ 0.94) repeatability was observed for repeated impacts at both inbound velocities. High repeatability in these metrics demonstrates the force platform, primarily designed for biomechanical analysis, can consistently measure the dynamic response of a football when impacted in the corner, directly above one of the sensors [14]. Larger confidence intervals and slightly lower repeatability statistics were observed at 19.4 m s^{-1}. The motorised launch device introduces greater variation in the impact orientation and location on the force platform. The larger variation in impact metrics could be due to the impact orientation, as suggested by Price et al. [21].

The MDDs' of peak impact force and impulse at both velocities and loading rate at 6.04 m s^{-1} accounted for less than 1% of the mean value of each metric. The MDD for loading rate at 19.4 m s^{-1} was higher at 5%; this is due to the lower repeatability as mentioned above. Providing the differences in impact metrics exceed the MDD's, the force platform can be used to detect differences in loading behaviour between different models of footballs. Future work will use this methodology to compare impact metrics for various FIFA certified footballs from different manufacturers. The MDDs' presented in this study will be used to inform the interpretation of the results, to enable meaningful comparisons of dynamic behaviour between footballs. It must be noted, the experiment set-up used several bespoke systems (launch devices and mounting platform) which may not

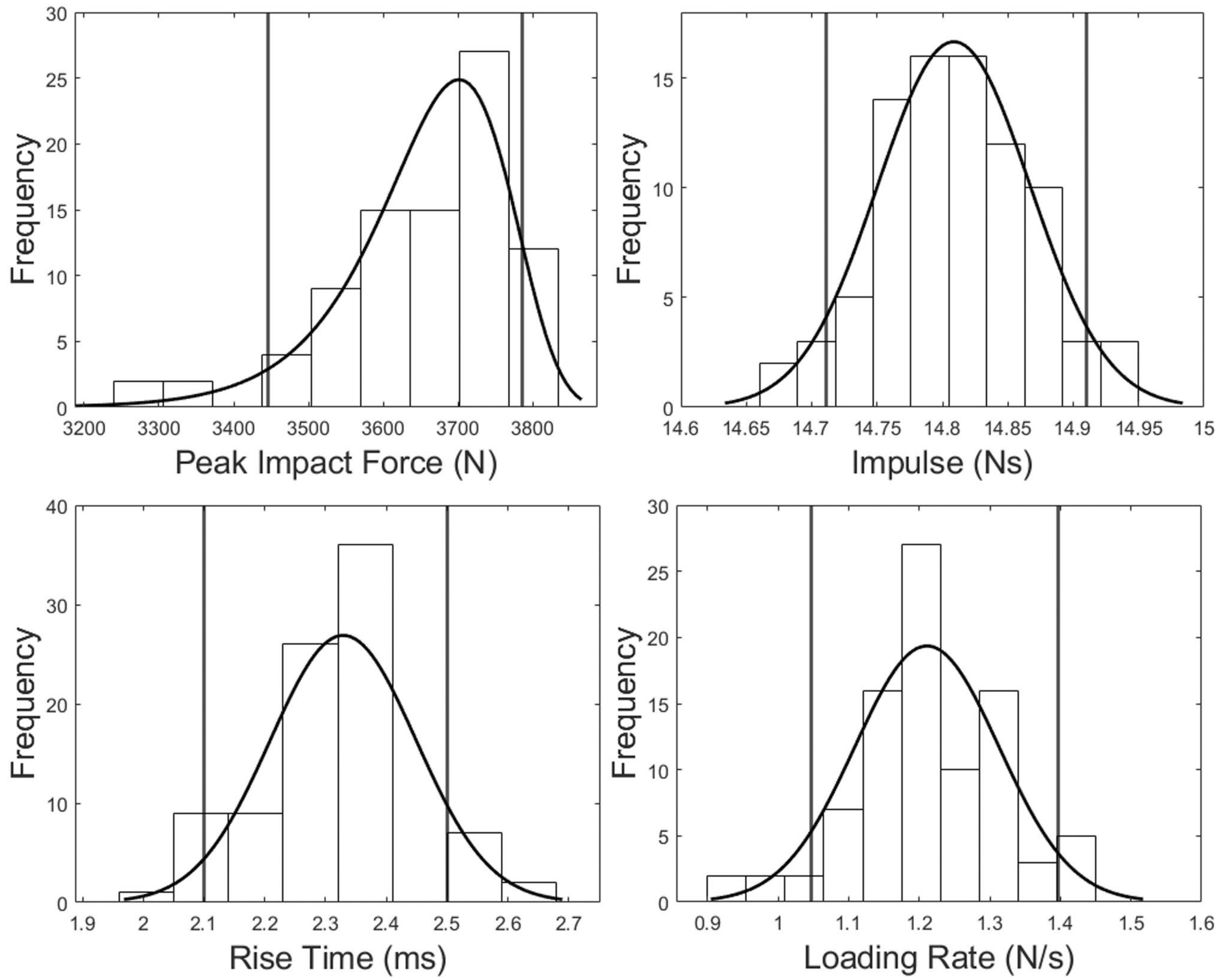

Fig. 3 Histograms with distribution fit for peak impact force, impulse, rise time and loading rate at 19. 4 m s^{-1}

reflect the inter-reliability to other force platforms; alternative systems would require additional validation.

5 Conclusion

This study determined the repeatability of measuring impact metrics for a single model of football using a commercial piezoelectric force platform. The force platform reliably measured the loading behaviour for normal inbound football impact at 6.04 and 19.4 m s^{-1}. The MDDs' for peak impact force, impulse and loading rate were calculated and it can be concluded that this methodology can be used to measure and detect differences in physical impact metrics between football models.

Acknowledgements The authors would like to express thanks to colleagues at the Sports Engineering Research Group at Sheffield Hallam University for their helpful advice and to FIFA for support of the project.

Funding The work is sponsored by FIFA, however, the football used in this study was independently selected by the university. Authors Dr Marcus Dunn and Mr Johsan Billingham are guest editors for the Topical Collection on Football Research and were blinded from the peer-review process. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any AuthorAccepted Manuscript version arising from this submission.

Declarations

Conflict of interest There are no other competing interests to declare.

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