DANFONIKA

The potential for implementation of athlete reaction time data into interpretive digital video systems used in VAR (Video Assistant Referee) analysis.

G.P. Brzezinski MA, BEng (Hons), AMIOA, PGD, PGCE

Chief Engineering Designer
Danfonika, RJ, Brasil

March 2025, Liverpool, UK

1. Abstract

This study investigates how the utilisation of an athlete's reaction time data could be implemented in digital video sports analysis software such as the Video Assistance Referee system used in football. It is clear that an athlete's reaction to the stimulus of a physical event is initially dependent upon their physiological response time to that event. This physical response is due both to the velocity of the event that triggers the stimulus, and the distance from the athlete where the event begins.

Using published physiological reaction time data from academic and professional sporting organisations, it was shown that there is a distance and velocity boundary where the real event time is lower than the physiological reaction times of the athlete. Therefore, the potential that the athlete has any physiological knowledge of the event is diminished. This information is currently not used in current software driven digital VAR systems, and yet could be easily upgraded to process situations such as a handball rule infringement.
In such a system, it would facilitate an immediate physical data metric for the VAR official, giving a greater information depth and an enhanced clarity when a decision is later relayed to the on-field official.

Contents

2. Glossary of Acronyms

fps - frames per second

VAR - Video Assistance Referee

RT - human reaction time

IAAF - International Association of Athletics Federations

UEFA - Union of European Football Associations

FA - (The) Football Association (ENG)

COD - Change of direction

HGRF - horizontal ground reaction forces

VGRF - vertical ground reaction forces

PGMOL - Professional Game Match Officials Limited

3. Introduction

Reaction time can be described as “the time interval between an external signal and your reaction to it”, (Kiikka, 2019), and can be modelled as three distinct factors - perception, processing and response.

In a sport such as football, this stimulus can be visual, auditory or tactile. When the signal is perceived through the athlete's sensory system, the brain both processes and responds with a nerve message via the spinal cord, and sent onwards to the required muscle area of the body. Kiikka (2019) reports that “then, and only then will an athlete respond with a physical transfer of motive kinetic energy”.

It is clear that this physiological process is not and can never be thought of as instantaneous. In sport, it is vital to understand this. Ghuntla & Mehta, et al. (2014) show that “Reaction is purposeful, and is a voluntary response to different stimuli as auditory or visual stimuli”.
Furthermore, that work of Nuri & Shadmehr, et al. (2013) states that “In sport - reaction time (RT) and anticipatory skill are critical aspects of perceptual abilities”, and are “considered advantageous to the player's successful performance”.

4. Discussion

(a) An overview of handball infringements in football - and the potential connection with physiological factors

The FA (2024) states that it is a handball offence (Fig. 1) if a player:

- *deliberately touches the ball with their hand/arm, for example moving the hand/arm towards the ball.*
- *touches the ball with their hand/arm when it has made their body unnaturally bigger. A player is considered to have made their body unnaturally bigger when the position of their hand/arm is not a consequence of, or justifiable by, the player's body movement for that specific situation. By having their hand/arm in such a position, the player takes a risk of their hand/arm being hit by the ball and being penalised.*

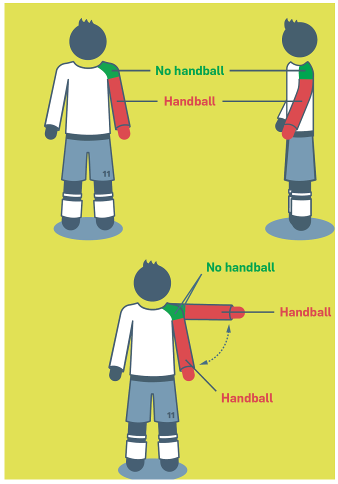

Fig. 1 - Image is reproduced with the courtesy of The Football Association ®

Whilst the semantic presentation of this rule is clear, the interpretation of the detail both by the officials is subjective, and the recent implementation of VAR in high level football competitions worldwide has increased this sense of abstraction.

An article by the BBC (2022) reported that "VAR was once again a talking point this weekend with a number of debatable decisions surrounding the handball rule". The BBC Sport football reporter Simon Stone highlighted that "the reality is, most of these calls involve a degree of subjectivity at some stage and that can lead to differences of opinion where there is no clear right or wrong answer."

The phrase, "*unnaturally bigger", as* referred to in the report by the FA (2024), has appeared to cause the most confusion amongst officials. However, the article by Bonn (2024) reported that this specific area of contention could be distilled into "intent" and “deflection”. The document by the FA (2024) explained that the intent and the possibilities of deflection from a player do not matter when judging handball offences.

However, there appears to be two major exceptions to this. Bonn (2024) suggested that:

> *“The handball law is written in such a way that it creates separate applications for penalising attacking players and defending players. Defending players are subject to all the previously discussed laws, attacking players are not. Instead, the rule is very simple for an attacking player — if the ball strikes a goal scorer's arm while in the midst of a goal scoring move, regardless of arm position, intent, or any other qualifiers, a goal shall be chalked off.”*

In an article by the BBC (2022) it states that “The PGMOL says for handball it is all about “*proximity* and *speed*”, but the PGMOL publishes no information as to how the data set relating to these variables is calculated.

It is also true that international leagues have varying interpretations of the handball rule, that according to Bonn - “some are more strict about this than others”, and the definition of *intent* and *deflection* appear to vary widely around the professional football world. This is highlighted in the following section.

(b) Recent contentious handball decisions in elite level football

(i) ***10 November 2019. Liverpool v Manchester City. English Premier League:*** The report by BBC (2019) describes an “unintentional ricochet” involving two Manchester City forward players. The deflected ball then strikes the arm of a Liverpool defender. The on field referee waved the play to continue. During a protest by the entire Manchester City coaching staff and players, Liverpool regained the ball, and proceeded to score a goal 21 seconds later.

(ii) ***28 November 2023. Paris St. Germain v Newcastle United. The Champions League Groups:*** A report by the BBC (2023) illustrated that in the eighth minute of stoppage time, A PSG forward’s cross appeared to strike a Newcastle United player’s body. The ball bounced up onto their arm. The initial ball was from foot to chest, and then from chest to elbow.

A long period of VAR scrutiny persuaded the on field referee to award a penalty, which PSG scored to secure a 1-1 draw.

(iii) 9 October 2022. West Ham United v Fulham: Grounds (2022) reported that the Fulham coaching staff remained furious after a restart of play in the 62nd minute. This passage of play resulted in a West Ham United goal. The goal was allowed to stand despite a lengthy VAR delay to check for a deflected handball by the West Ham United striker.

(iv) 09 Oct 2022. Arsenal V Liverpool: Evans (2022) reported that during a Liverpool attack, the Arsenal defender appeared to handle the ball to stop a Liverpool cross. Although the Arsenal player's hand was deemed to be in an unnatural position, VAR judged the distance of travel to be short, and so the penalty appeal was rejected..

(v) 9 Oct 2024. Everton v Manchester United: The report by Autty (2024) described how a Manchester United goal was disallowed following a VAR check, as the ball struck the Manchester United striker's arm whilst blocking an Everton defender's clearance in the build-up.

(c) The reaction time of a human and the connected athletic factors in high performance sport

Carson (2024) stated that the average RT with a specific population sample is approximately 0.250 s. However, an RT of 0.1 to 0.19 s is possible for professional athletes, Formula 1 racing drivers, and Jet fighter pilots.
The work of Pavlović (2021) reported that the "fastest starting RT in a sprint was recorded by Tim Montgomery in 2002, with a time of 0.104 s". Juhas & Matić et al. (2015) stated that the clear goal of any elite athlete is to "achieve the shortest starting RT.

Nevertheless, in athletics the RT criteria is limited by international rules. The governing body (IAAF) uses a RT of 0.1 s, for their false start decision making in races. World Athletics (2009) reported that this is "based on an assumed minimum auditory reaction time. If an athlete moves sooner than 100 ms after the start signal, then he/she is deemed to have false-started." According to the IAAF, the 0.1 second rule is based on "the science on standard reaction times", World Athletics (2009).

The work of Milloz (2022) contradicts this idea of the neurophysiological limit, where currently "we don't know what this neurophysiological limit is". Related studies have also shown that sprinters have been recorded faster than 0.085 seconds, Pain & Hibbs (2007). More recently, at the 2022 World Championships, Ziegler (2022) reported that both Julien Alfred and Devon Allen were disqualified for starting 0.095 and 0.099 seconds after the starting gun.

Nevertheless, the evidence for actually lowering this 0.1s threshold remains in question. The research by Mirsham Shahshahani & Lipps et al. (2017) has illustrated that "an apparent decrease in reaction times could be also due to a reduction in the proprietary force thresholds used to calculate the reaction times", and based upon "measurements from force sensors in the starting blocks, rather than the result of more specialized or effective training".
In addition, RT data for a large number of professional athletes has consistently shown times to far be higher than 0.1 s. At the 2008 Olympics, "male Olympic sprinters had an average reaction time of 162 milliseconds, and for women - a reaction time of 190 milliseconds", Juhas & Matić et al, (2015).
Therefore, it would appear that using 0.1 s as an RT benchmark threshold continues to have a high level of validity at present.

(d) Other physiological and biomechanical factors

The work of Pontzer & Herman et al. (2009) stated that "it has long been established that the arms do not swing as simple, unrestrained pendulums". The report also described the idea that any voluntary "arm motion is often considered to be a mechanism for counteracting free vertical moments (i.e. torque about the body's vertical axis)". This arm motion would also appear to be critical when the athlete changes direction.

Brughelli & Cronin et al. (2008) illustrated that the application of levels of VGRF and HGRF to predict potential COD performance would seem intuitive - given that most human motion is a “combination of these two types of forces”. Alanen & Räisänen et al. (2021) showed that the ability to perform efficient and controlled COD movement requires advanced control of the application of VGRF and HGRF, a level of “raised technical abilities, adequate lower extremity muscle strength and speed. The report also explains that it “is relevant for both performance and injury prevention”.
This potential for athletic injury when turning is further elaborated by Edwards & Austin et. al (2017), where a COD “either involving the torso less, or greater trunk flexion, laterally flexing, or both rotating and laterally flexing away from the direction change places the athlete at greater risk of anterior cruciate ligament rupture via increasing knee joint moments”. This is later also reported by Dos’ Santos & Thomas et. al (2018), where “sharper CODs increase the relative lower body loading”.

This “raised technical ability”, described by Alanen & Räisänen et al. (2021) also increases the possibility of a successful COD. Edwards & Austin et. al (2017) illustrated this in their work regarding COD positioning. They showed that by rotating their body “more toward the direction of travel - they became more upright and decreased their lateral flexion”. Therefore, the rotational forces exerted upon them. This is also true during elevation.
Hewit & Cronin (2012) showed that during the takeoff of an athlete, the arms are driven upwards towards the raised ball. The work showed that “a high arm drive assists in raising the body’s center of mass, thereby increasing the height reached when jumping and also positioning the hands in a better position to grab the ball, and align the body for a bilateral, parallel landing”.

In addition, it has been shown by Badau & Baydil et. al (2018) that left and right hand and arm react differently - and is dependent upon what the dominant side of the athlete actually is - “the more complex the application is, the more efficient the dominant hand is”.
In all cases, the trained athlete’s muscles are already preloaded biomechanically, and only the “extension of the arms” is then needed to “complete the motion”, Hewit & Cronin (2012).

This physiological and biomechanical positioning appears wholly natural - the motion of an athlete's arms is clearly designed and facilitated to permit excellent movement, reduce rotational forces, and thereby reduce the possibility of injury.

This is clearly in direct conflict with the concept of "*unnaturally bigger", as* reported by the FA (2024).

5. Method

Using the RT work of Carson (2024) as a starting point, and the understanding that current VAR implementations worldwide only account the effect of athlete RT as a subjective element of the decision making process - it was decided to focus upon investigating the possibility of generating and processing simple RT data sets for a live potential handball infringement.

The use of this data (if available) could then be used as part of a deeper decision making process for a VAR referee to reduce subjectivity, and increase the possibility of a more accurate decision outcome.

Due to the expense of installation, maintenance, and operation, VAR is currently only used only at the elite level of football, and relies upon the manipulation of video image data. It is hypothesised that using this video technology to generate RT data will allow further data analysis to be undertaken.

This realistic possibility is not difficult to imagine. Early work by Mudric & Cuk et. al (2015) clearly illustrated the use of a “video-based method for the measurement of reaction time in specific sport situation”, using a high definition, externally triggered camera running at a frame rate of 60fps. VAR currently generates digital video data at only 50 fps, and generates precise time data with measured intervals of 1/50 s, or 0.02 s. It is therefore important to evaluate how useful this interval data is in a realistic match situation. It was decided to evaluate this using an upper limit of match ball velocity.

(a) Relationship to potential maximum velocity of a football struck by an elite level football athlete and recorded frames per second by a digital video system

A report by Omuya (2024) collected the top 20 shot velocities recorded in elite level football. A summarised table of this data is presented in Appendix (i), page XX.

The mean (average) velocity of these examples was found to be 50.4 ms^{-1}, and is illustrated in Fig. 2.

Utilisation of the formula: **velocity (ms^{-1}) = distance (m) / time (s)**

It can be shown that if the video system is designed to be used at **50 fps**, then the match ball at the maximum recorded average velocity of **50.4 ms^{-1}** will travel approximately **1m** - i.e. from one recorded frame to the next.

A more common match ball velocity would be slower - such as during a close proximity handball incident. Therefore, it can be seen that the precision of the distance measurement remains high, relative to the physical dimensions that will be referenced, such as player to player distances, player height / width et al.

Shot speed (ms^{-1})	distance that the ball travelled in 1 video frame, m
1	0.020
2	0.040
5	0.100
10	0.200
15	0.300
50.4	1.008

Fig. 2 - Shot speed (ms^{-1}) v ball journey in 1 video frame.

To calculate RT from video data, a set of measurement parameters (Fig. 3) are required. These are:

- The start height of the ball (m) at Player 1 - $\mathbf{h_1}$.
- The finish height of the ball (m) at Player 2 - $\mathbf{h_2}$.
- The difference in magnitude of height, $\mathbf{h = | h_2 - h_1 |}$.
- The horizontal distance (m) from Player 1 to Player 2, **s**.
- The diagonal distance (m) from Player 1 to Player 2, **d**.
- The number of frames elapsed (fps) from when the match ball leaves Player 1 and strikes Player 2 - then converted into time data (s), **t**.
- Using the data, d and t - the match ball velocity (ms^{-1}), **v** can be calculated.

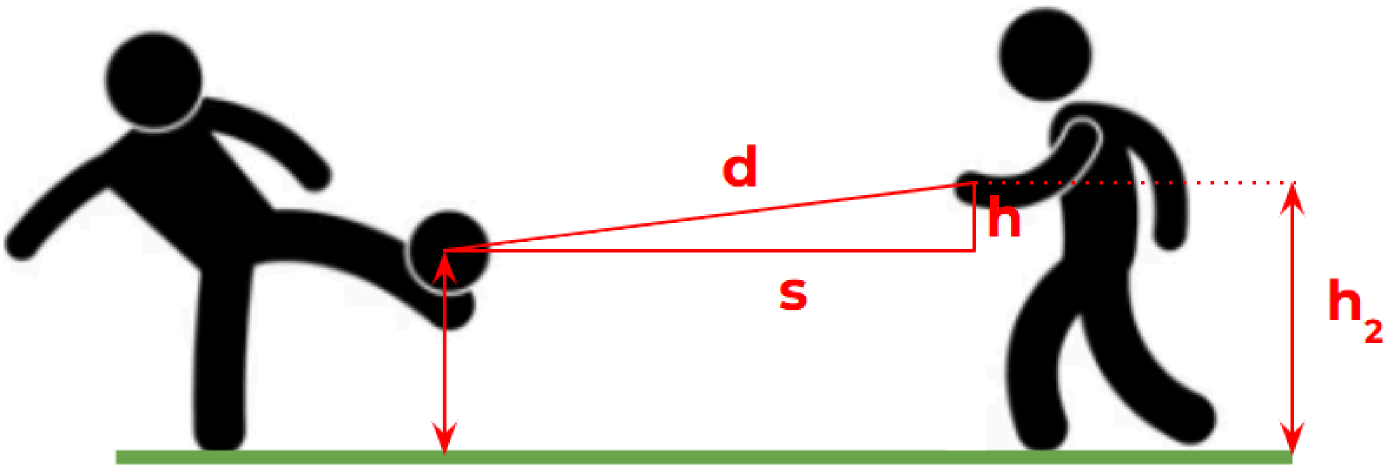

Fig. 3 - Explanation of geometry used in RT calculation

The calculation of the frames elapsed in the handball event, and the diagonal distance travelled in the handball event, will permit a template to be created utilizing a default data set. Using a default of h= 0.2 m and a range of horizontal distances, s (m) - a set of values for d (m) can be generated.

This is presented in Appendix (ii), page XX.

A range of colour coded values for RT (s) are also returned (Fig. 4) together with match ball velocity data and equivalent fps data:

0.391	**RT > 0.2**
0.195	**0.1 < RT < 0.2**
0.098	**RT < 0.1s - The Olympic standard minimum**

Fig. 4 - RT range

These RT ranges can be altered, depending upon the decision of the elite competition governing body.

If this example data could be summarised (Fig. 5) to assist in the finalisation of a hypothetical handball incident - it could presented as follows:

0.391	*"Player 2 definitely exhibits a deliberate physiological response to the event" - decision:* ***handball.***
0.195	*"Player 2 is likely exhibiting a deliberate physiological response to the event" - upper limit of range - decision:* ***potential handball.***
0.098	Player 2 is likely to be unaware of the match ball striking arm *- decision:* ***no handball.***

Fig. 5 - possible VAR decisions based upon the incident RT returned

In the following section, the RT template is configured to use live match data from one of the handball situations shown earlier in Section 4, page 5.

6. Results and observations

(a) The use of the RT template in a live handball incident. Flow diagram.

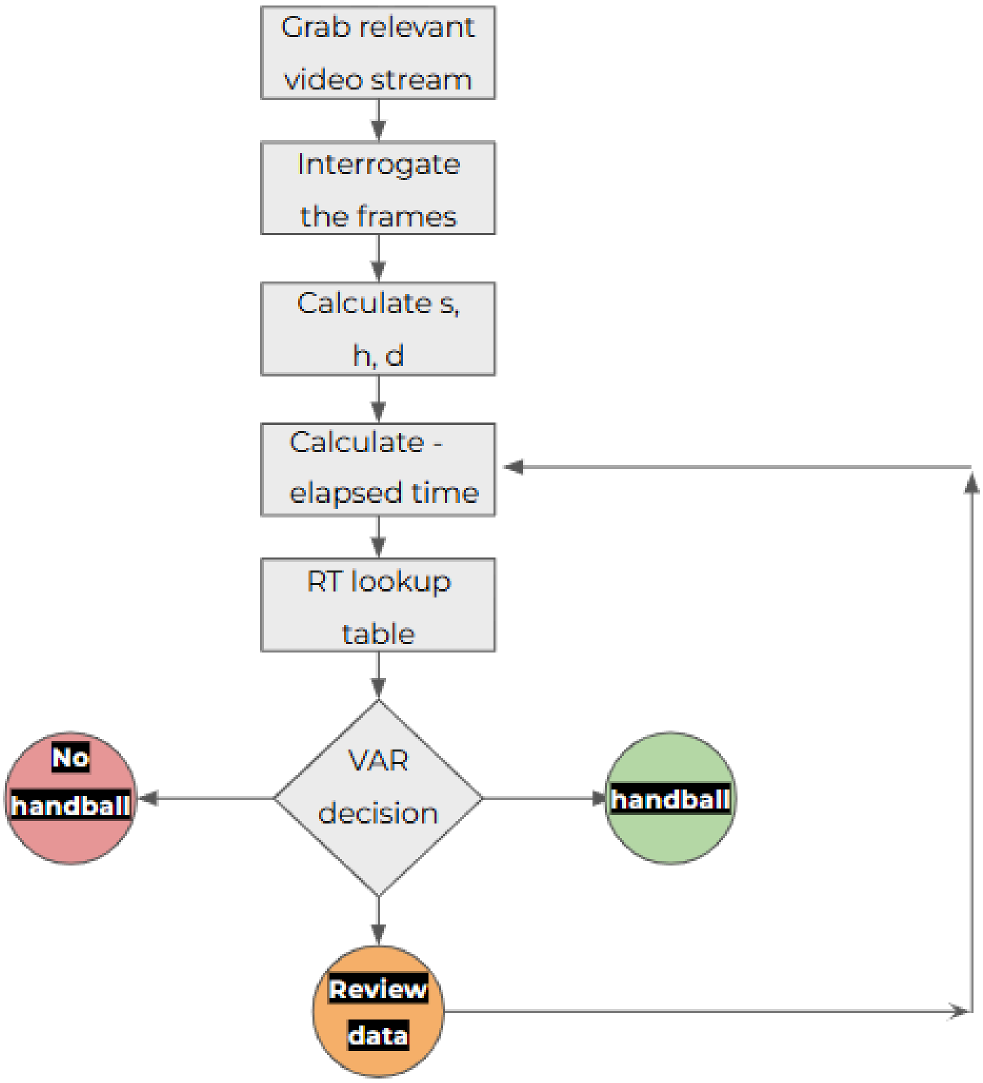

Fig. 6 - Flow diagram of VAR methodology using RT template and digital video resource

In addition to the information shown in Fig. 6,, if the RT template is implemented digitally - it would be implemented as a dynamic live database.

The software would then refer to this and would output a set of values based upon the incident.

(b) The use of the RT template in a case study

This case study example was introduced earlier in Section4, page 5 - "*28 November 2023. Paris St. Germain v Newcastle United. The Champions League Group stages*". *

Step 1: Grab the relevant video streams.

The incident was recorded in a video stream that lasted 6 seconds.

- Player 1 (PSG)
- Player 2 (Newcastle United)

The relevant action:

Stage 1: matchball leaves Player 1 - strikes the torso of Player 2

Stage 2: matchball leaves the torso of player 2 and strikes the arm of Player 2

Step 2: Interrogate the frames.

- The 'frame timestamp' for the beginning and end of the incident was noted.
- A frame was found which showed Player 1 and Player2 clearly in a single, static frame.

Step 3: Calculate s, h, d.

- This frame was sent to a CAD system (AutoDesk Fusion 360®) which can analyse scale and proportion from a 2D image input.
- leave Player 1 - strike the torso of Player 2, $\mathbf{v_1 = 1.68\ m}$
- leave the torso of player 2 and strike the arm of Player 2, $\mathbf{v_2 = 0.2\ m}$

Step 4: Calculate - elapsed time.

Elapsed time is time taken for the matchball to:

- leave Player 1 - strike the torso of Player 2, **approx. 13 frames +/- 50 subframes**
- leave the torso of Player 2 and strike the arm of Player 2, **approx. 2 frames +/- 50 subframes**

Step 5: RT lookup table.

(a) Stage 1: matchball leaves Player 1 - strikes the torso of Player 2

Stage 1: range of values		
0.26	**0.28**	RT
12.87	*14.00*	*fps*

Note: If Player 2 had their arm in the way of the trajectory when the matchball travelled from Player 1 to Player 2, instead of their torso - the result would be a “green” positive for the on field decision - **PENALTY.**

(b) Stage 2: matchball leaves the torso of player 2 and strikes the arm of Player 2

Stage 2: range of values		
0.03	**0.05**	RT
1.67	*2.67*	*fps*

Step 6: Final VAR decision using the RT data.

The implication is that Stage 2 is the important part of the action. And so:

RT < Player 1 minimum window - NO HANDBALL - NO PENALTY

(c) Data Precision

The limiting factor in the measurement will be the recording of frames per second data. As VAR uses a frame rate of exactly 50 frames per second.

As 1 frame = 1/50 = 0.02s, the time data can therefore be no more precise than +/- 0.02 s.

Using the digital image manipulation software available to the author, then the distances (m) of s,d, and v can be recorded with a precision of +/- 0.01 mm. However, this has been limited by the Author to be +/- 0.01 m.

---

* Note: The author has forwarded a request to TNT Sports International® to use the video footage of the incident in this game. This permission is currently pending, and so will not be presented here.

7. Conclusions

While subjective interpretation of handball decisions in football continues to prevail, it has been illustrated that biomechanical studies of elite athletes have a bearing on the intent to handball - or not. The examples illustrated in this report clearly point to physiological RT data that (if known) could have had more of an effect on VAR decision outcomes than was previously considered.

It is also easy to conclude that much of this negative evidence should be directed at the current use of VAR. However, if this iteration of the implementation is wrong - in which manner is it incorrectly utilised ? Furthermore, any advance in the future needs to be implemented into the digital landscape of VAR seamlessly.

Kristiansson & Rapp (2024, page 10) have shown that rapid technological change in a traditional sport can be controversial, where there exists “a significant tension between the push for technological advancement and the cherished emotional spontaneity” defining the sport.

The work of Brown (2024) recently suggested that the “implementation of VAR requires referees to adapt to the new technology”, and also be informed on its proper use and current limitations. It is debatable whether this is happening consistently, as contentious decisions such as those outlined in this report continue to occur. It is also likely that the levels of stress that officials are experiencing are also higher.

A report by Samuel (2024) described the implementation of VAR, and its effects upon levels of anxiety and reduced processing efficiency, leading to the possibility of “adjusting the referee’s tactical approach to a match”. Harwood (2023) also suggested that “these differences in perception and knowledge affect problem solving and decision making”.

In addition, VAR technology is yet to solve the problem of fair play as players continue to simulate actions “to gain the favour of a referee”, (Musa et al., 2022). The RT data, if made available, would give the official more time data to analyse, and decide whether that player action was intentional - or not. If the visual data and physical dynamics of the event can be utilised and combined in a more effective manner, using verified data and less subjective analysis - this can only help in this process.

Therefore, the continued investigation into the use of quantitative RT data in VAR decisions at elite level football would appear a worthy journey to undertake.

8. References

Autt, Y., (2024). Why Marcus Rashford's Manchester United goal against Everton was disallowed. https://m.allfootballapp.com/news/Headline/Why-Marcus-Rashfords-Manchester-United-goal-against-Everton-was-disallowed/2927559. [Last accessed 27/2/2025]

Alanen, A.M., Räisänen, A.M., Benson, L.C. and Pasanen, K., (2021). The use of inertial measurement units for analyzing change of direction movement in sports: A scoping review. *International Journal of Sports Science & Coaching*, *16*(6), pp.1332-1353.

Badau, D., Baydil, B. and Badau, A., (2018). Differences among three measures of reaction time based on hand laterality in individual sports. Sports, 6(2), p.45.

BBC (2019). Liverpool v Man City handball: "Was this 2019-20 season's 11mm moment?" https://www.bbc.co.uk/sport/football/50368255. [Last accessed 27/2/2025].

BBC (2022). "Astonishing" handball decisions. https://www.bbc.co.uk/sport/football/63197543. [Last accessed 22/1/2025]

BBC (2023). "PSG 1-1 Newcastle: Why was a controversial late penalty given?" https://www.bbc.co.uk/sport/football/67562308#:~:text=But%2C%20in%20the%20eighth%20minute,secure%20a%201%2D1%20draw. [Last accessed 26/2/2025]

Bonn, K. (2024). Handball rules in football explained, including latest changes by FIFA, Premier League to hand ball in soccer. https://www.sportingnews.com/uk/football/news/handball-football-rules-changes-fifa-uefa-hand-ball-soccer/tdnqkct6nzocrbfvscrxvtzl. [Last accessed 27/2/2025]

Brown, J.K., (2024). *The Impact of Video Assistant Referee (VAR) on the English Premier League* (Master's thesis, California Polytechnic State University).

Brughelli, M., Cronin, J., Levin, G. and Chaouachi, A., (2008). Understanding change of direction ability in sport: a review of resistance training studies. *Sports medicine*, *38*, pp.1045-1063.

Carson, O. (2024). How Fast is Human Reaction Time? https://www.pubnub.com/blog/how-fast-is-realtime-human-perception-and-technology/. [Last accessed 22/1/2025]

Dos' Santos, T., Thomas, C., Comfort, P. and Jones, P.A., (2018). The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports medicine*, *48*, pp.2235-2253.

Edwards, S., Austin, A.P. and Bird, S.P., (2017). The role of the trunk control in athletic performance of a reactive change-of-direction task. *The Journal of Strength & Conditioning Research*, *31*(1), pp.126-139.

Evans, C., (2022). EXPLAINED: Why Liverpool were denied penalty vs Arsenal after Gabriel handball. https://www.goal.com/en-gb/news/explained-why-liverpool-did-not-recieve-penalty-for-gabriel-handball/blt4ea457ad94f98360. [Last accessed 27/2/2025]

The FA (2024). HANDLING THE BALL. https://www.thefa.com/football-rules-governance/lawsandrules/laws/football-11-11/law-12---fouls-and-misconduct. [Last accessed 18/01/2025].

Ghuntla, T.P., Mehta, H.B., Gokhale, P.A. and Shah, C.J., (2014). A comparison and importance of auditory and visual reaction time in basketball players. Saudi Journal of Sports Medicine, 14(1), pp.35-38.

Grounds (2022). West Ham 3-1 Fulham: Contentious Gianluca Scamacca strike helps Hammers record back-to-back wins https://www.skysports.com/football/news/11095/12713682/west-ham-3-1-fulham-contentious-gianluca-scamacca-strike-helps-hammers-record-back-to-back-wins. [Last accessed 27/2/2025]

Harwood, H., (2024). *Investigating Video Assistant Referees (VARs): Does contextual information influence VAR decision-accuracy and decision-severity in football* (Doctoral dissertation, University of Essex).

Hewit, J.K., Cronin, J.B. and Hume, P.A., (2012). Understanding change of direction performance: a technical analysis of a 180 aerial catch and turn task. *International Journal of Sports Science & Coaching*, *7*(3), pp.503-514.

Juhas, I., Matić, M. and Janković, N., (2015). Comparative analysis of reaction time of elite sprinters at the world championships in 2013 and 2015. *Godišnjak Fakulteta sporta i fizičkog vaspitanja*, (21), pp.43-52.

Kiikka, D. ,(2019). Reaction time in sports. https://thesportsedu.com/reaction-time-definition/. [Last accessed 18/01/2025].

Kristiansson, K. and Rapp, A., (2024). The VAR Effect: Balancing Tradition and Innovation in Swedish Football. School of Business, Economics and Law at the University of Gothenburg, Sweden.

Milloz, M. J Holmes, E Crotty, AJ Harrison, (2022). VISUAL DETECTION OF RESPONSE TIME IN ATHLETICS: A “GOLD STANDARD”?. ISBS Proceedings Archive.

Mirshams Shahshahani P, Lipps DB, Galecki AT, Ashton-Miller JA., (2018). On the apparent decrease in Olympic sprinter reaction times. PLoS One.

Mudric, M., Cuk, I., Nedeljkovic, A., Jovanovic, S. and Jaric, S., (2015). Evaluation of Video-based method for the measurement of reaction time in specific sport situation. International Journal of Performance Analysis in Sport, 15(3), pp.1077-1089.

Nuri, L., Shadmehr, A., Ghotbi, N. and Attarbashi Moghadam, B., (2013). Reaction time and anticipatory skill of athletes in open and closed skill-dominated sport. European journal of sport science, 13(5), pp.431-436.

Omuya, K. (2024). https://sportsbrief.com/football/58247-the-fastest-soccer-shots-history-sport/. [Last accessed 27/2/2025]

Pain MT, Hibbs A., (2007). Sprint starts and the minimum auditory reaction time. J Sports Sci. 2007 Jan 1;25(1):79-86. doi: 10.1080/02640410600718004. PMID: 17127583.

Pavlović, R., (2021). The importance of reaction time in athletics: Influence on the results of sprint runs of World Championships finalists. Central European Journal of Sport Sciences and Medicine, 34, pp.53-65.

Pontzer, Herman, John H. Holloway III, David A. Raichlen, and Daniel E. Lieberman,. (2009). Control and function of arm swing in human walking and running. Journal of Experimental Biology

Samuel, R.D., Filho, E. and Galily, Y., (2024). Attention allocation in elite football refereeing: conceptual, empirical, and applied considerations. *Journal of Cognitive Psychology*, *36*(4), pp.474-492.

World Athletics, (2009). IAAF Sprint Start Research Project. https://worldathletics.org/news/news/iaaf-sprint-start-research-project-is-the-100. [Last accessed 22/1/2025]

Ziegler, M., (2022). Marque attraction at World Championships Dq'ed after a questionable false start. https://www.sandiegouniontribune.com/2022/07/18/marquee-attraction-at-world-championships-dqed-after-a-questionable-false-start/. [Last accessed 18/01/2025].

9. Appendices

(i) Fastest shot speeds recorded in elite level football

Players' name	Shot speed (ms^{-1})	distance travelled in 1 video frame, m
Luis Suarez	45.6	0.911
Pierre-Emerick Aubameyang	46.1	0.922
Gareth Bale	46.4	0.928
Thierry Henry	46.9	0.939
Radamel Falcao	47.5	0.950
Wayne Rooney	47.8	0.956
Allan Shearer	48.3	0.967
Matt Le Tissier	48.6	0.972
Frank Lampard	49.2	0.983
Cristiano Ronaldo	50.6	1.011
Arjen Robben	50.6	1.011
Ritchie Humphreys	50.6	1.011
David Hirst	50.8	1.017
Tony Yeboah	50.8	1.017
Pavel Pardo	51.1	1.022
David Beckham	52.8	1.056
Roberto Carlos	55.0	1.100
Steven Reid	55.6	1.111
Zlatan Ibrahimovic	55.6	1.111
Ronny Heberson	58.6	1.172
MEAN	**50.4**	**1.008**

(ii) RT template - example, showing initial strike height to arm, h = 0.2m

initial strike height to arm (max), h (m)	approx. linear distance, s (m)																
	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00
	approx. diagonal distance ball travels (player 1 foot/head - player 2 arm), d (m)																
0.20	**0.20**	**0.32**	**0.54**	**0.78**	**1.02**	**1.27**	**1.51**	**1.76**	**2.01**	**2.26**	**2.51**	**2.76**	**3.01**	**3.26**	**3.51**	**3.76**	**4.00**
potential ball velocity, v (m/s)	**impact time, t (s)**					**upper value in seconds**					**lower value in *fps***						
1.00	**0.20**	**0.32**	**0.54**	**0.78**	**1.02**	**1.27**	**1.51**	**1.76**	**2.01**	**2.26**	**2.51**	**2.76**	**3.01**	**3.26**	**3.51**	**3.76**	**4.00**
	10.00	*16.01*	*26.93*	*38.81*	*50.99*	*63.29*	*75.66*	*88.07*	*100.50*	*112.94*	*125.40*	*137.86*	*150.33*	*162.81*	*175.29*	*187.77*	*200.25*
2.00	**0.10**	**0.16**	**0.27**	**0.39**	**0.51**	**0.63**	**0.76**	**0.88**	**1.00**	**1.13**	**1.25**	**1.38**	**1.50**	**1.63**	**1.75**	**1.88**	**2.00**
	5.00	*8.00*	*13.46*	*19.41*	*25.50*	*31.65*	*37.83*	*44.03*	*50.25*	*56.47*	*62.70*	*68.93*	*75.17*	*81.40*	*87.64*	*93.88*	*100.12*
4.00	**0.05**	**0.08**	**0.13**	**0.19**	**0.25**	**0.32**	**0.38**	**0.44**	**0.50**	**0.56**	**0.63**	**0.69**	**0.75**	**0.81**	**0.88**	**0.94**	**1.00**
	2.50	*4.00*	*6.73*	*9.70*	*12.75*	*15.82*	*18.92*	*22.02*	*25.12*	*28.24*	*31.35*	*34.47*	*37.58*	*40.70*	*43.82*	*46.94*	*50.06*
6.00	**0.03**	**0.05**	**0.09**	**0.13**	**0.17**	**0.21**	**0.25**	**0.29**	**0.33**	**0.38**	**0.42**	**0.46**	**0.50**	**0.54**	**0.58**	**0.63**	**0.67**
	1.67	*2.67*	*4.49*	*6.47*	*8.50*	*10.55*	*12.61*	*14.68*	*16.75*	*18.82*	*20.90*	*22.98*	*25.06*	*27.13*	*29.21*	*31.29*	*33.37*
8.00	**0.03**	**0.04**	**0.07**	**0.10**	**0.13**	**0.16**	**0.19**	**0.22**	**0.25**	**0.28**	**0.31**	**0.34**	**0.38**	**0.41**	**0.44**	**0.47**	**0.50**
	1.25	*2.00*	*3.37*	*4.85*	*6.37*	*7.91*	*9.46*	*11.01*	*12.56*	*14.12*	*15.67*	*17.23*	*18.79*	*20.35*	*21.91*	*23.47*	*25.03*
10.00	**0.02**	**0.03**	**0.05**	**0.08**	**0.10**	**0.13**	**0.15**	**0.18**	**0.20**	**0.23**	**0.25**	**0.28**	**0.30**	**0.33**	**0.35**	**0.38**	**0.40**
	1.00	*1.60*	*2.69*	*3.88*	*5.10*	*6.33*	*7.57*	*8.81*	*10.05*	*11.29*	*12.54*	*13.79*	*15.03*	*16.28*	*17.53*	*18.78*	*20.02*
12.00	**0.02**	**0.03**	**0.04**	**0.06**	**0.08**	**0.11**	**0.13**	**0.15**	**0.17**	**0.19**	**0.21**	**0.23**	**0.25**	**0.27**	**0.29**	**0.31**	**0.33**
	0.83	*1.33*	*2.24*	*3.23*	*4.25*	*5.27*	*6.31*	*7.34*	*8.37*	*9.41*	*10.45*	*11.49*	*12.53*	*13.57*	*14.61*	*15.65*	*16.69*
14.00	**0.01**	**0.02**	**0.04**	**0.06**	**0.07**	**0.09**	**0.11**	**0.13**	**0.14**	**0.16**	**0.18**	**0.20**	**0.21**	**0.23**	**0.25**	**0.27**	**0.29**
	0.71	*1.14*	*1.92*	*2.77*	*3.64*	*4.52*	*5.40*	*6.29*	*7.18*	*8.07*	*8.96*	*9.85*	*10.74*	*11.63*	*12.52*	*13.41*	*14.30*
15.00	**0.01**	**0.02**	**0.04**	**0.05**	**0.07**	**0.08**	**0.10**	**0.12**	**0.13**	**0.15**	**0.17**	**0.18**	**0.20**	**0.22**	**0.23**	**0.25**	**0.27**
	0.67	*1.07*	*1.80*	*2.59*	*3.40*	*4.22*	*5.04*	*5.87*	*6.70*	*7.53*	*8.36*	*9.19*	*10.02*	*10.85*	*11.69*	*12.52*	*13.35*