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Original Investigation

Quantifying Technical Actions in Professional Soccer Using Foot-Mounted Inertial Measurement Units

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Abstract

This study aimed to (i) establish the concurrent validity and intra-unit reliability of a foot-mounted inertial measurement unit for monitoring soccer technical actions, (ii) quantify the within-microcycle inter-positional differences in the technical actions of professional soccer training, and (iii) determine the influence of drill category on the technical actions of professional soccer training. Twenty-one professional soccer players' technical performance data (ball touches, releases, ball touches per minute, releases per minute), collected during training sessions (i.e. match-day (MD) minus day number) throughout twenty-four weekly microcycles, were analysed using general linear modelling. The inertial measurement unit exhibited good concurrent validity (P_A = 95.1% - 100.0%) and intra-unit reliability (P_A = 95.9% - 96.9%, CV = 1.4% - 2.9%) when compared with retrospective video analyses. The most ball touches ($\bar{X}$ = 218.0) and releases ($\bar{X}$ = 110.8) were observed on MD - 1, with MD - 5 eliciting the highest frequency of ball touches ($\bar{X}$ = 3.8) and releases ($\bar{X}$ = 1.7) per minute. Central midfielders performed the most ball touches ($\bar{X}$ = 221.9), releases ($\bar{X}$ = 108.3), ball touches per minute ($\bar{X}$ = 3.4) and releases per minute ($\bar{X}$ = 1.6). Small-sided games evoked more ball touches ($\bar{X}^{diff}$ = 1.5) and releases per minute ($\bar{X}^{diff}$ = 0.1) than previously reported in match-play. The fewest ball touches ($\bar{X}$ = 1.2) and releases per minute ($\bar{X}$ = 0.5) were observed during tactical drills. The results of this study provide a novel understanding of the within-microcycle, inter-positional and drill category differences in the technical actions performed by professional players during training.

Keywords: Professional Soccer Training, Technical Actions, Monitoring, Microcycle, Microtechnology

Introduction

The multifactorial demands of professional soccer require the implementation of training programmes that combine technical, tactical, physical and psychological components to enhance player performance (Stølen et al., 2005). Technical (i.e. ball touches, passes, crosses, shots) and tactical components are often prioritised by coaches during in-season training (Morgans et al., 2014), due to their association with competition success (Castellano et al., 2012; Carling, 2013). Farrow and Robertson's (2017) skill acquisition periodisation framework has enabled practitioners to systematically adjust players' technical performance in training throughout numerous sports. For instance, soccer specificity may be enhanced by comparing the extent that training mimics the technical demands of competition (Pinder et al., 2011), with progression expedited by prescribing an increased frequency of technical actions (Ericsson et al., 1993). However, technical actions are consistently neglected by practitioners during player monitoring processes (Akenhead & Nassis, 2016; Malone et al., 2020), despite contributing to players' overall external training load (Bradley & Ade, 2018).

The monitoring of technical actions is pertinent because the frequency of these actions executed by professional players during match-play has risen over time. Barnes et al. (2014) reported that the frequency of ball touches and passes executed by English Premier League players increased, by 10.5% and 39.9% respectively, over seven consecutive seasons. In the 2019/2020 season, Union of European Football Associations Champions League players typically performed 60.2 ± 20.7 ball touches and 50.1 ± 25.7 releases (i.e. passes, crosses, shots, clearances) per match (Yi et al., 2020). Despite such insights into match-play, examinations of technical actions during training scarcely appear within the literature (Liu et al., 2016; Bradley & Ade, 2018). Quantifying technical actions often requires complex and expensive infrastructure, such as semi-automated multiple camera tracking systems (e.g. ProZone®, Castellano et al., 2014) or local positioning systems (e.g. Inmotio, Frencken et al., 2010; Kinexon, Hoppe et al., 2018). Although these systems provide data that contextualises the multifaceted determinants of player performance (Bradley & Ade, 2018), the significant financial investment required hinders the transferability of such methods to the training environment (Akenhead & Nassis, 2016; Cardinale & Varley, 2017). In this setting, manual coding has been the prominent approach to assessing players' technical performance (Wright et al., 2013), which not only quantifies the specific technical actions performed (Wright et al., 2016), but also provides an understanding of players' pitch location (Taylor et al., 2010) and associated action success (Bateman & Jones, 2019). Yet, this process needs highly trained operators to limit measurement error (O'Donoghue, 2007) and to achieve sufficient validity and reliability (Francis et al., 2019; Gong et al., 2019). Moreover, the substantial human resources required has compelled practitioners to explore alternative approaches for quantifying technical actions during training (Carling et al., 2014; Robertson, 2020). As a solution to these problems, the implementation of wearable microtechnology, attached to players' boots (Edwards et al., 2019), may represent a time- and cost-efficient option for monitoring technical actions during weekly training microcycles (Chambers et al., 2015; Nedergaard et al., 2017). However, while the efficacy of such technology has been established from a time-motion perspective (Waldron et al., 2020), the validity, reliability, and applicability of this method for quantifying technical actions remains to be explored.

Quantifying technical actions during training would provide a broader understanding of the periodisation strategies used to prepare professional players for competition. Throughout a typical microcycle, external training load markers (e.g. total distance, mean speed) are consistently at their lowest on the day immediately before competition (Anderson et al., 2015; Malone et al., 2015; Stevens et al., 2017; Martín-García et al., 2018), with practitioners adopting this tapering approach to physically unload players and increase readiness for competition (Malone et al., 2015; Owen et al., 2017). Anecdotally, this unloading coincides with training becoming more technically and tactically oriented (Martín-García et al., 2018; Walker & Hawkins, 2018). However, empirical evidence to support this is lacking, necessitating an examination of the technical actions performed throughout professional soccer training microcycles.

The periodisation of technical actions provides a macro view of training. However, the within-session distribution of technical actions also warrants attention. Despite numerous studies examining technical actions during specific training drills (e.g. small-sided games) in isolation (Fradua et al., 2013; Aguiar et al., 2015), little consideration has been given to the effect of drill category on the technical actions executed by professional players (Barrett et al., 2020). Understanding these effects would allow practitioners to manipulate players' technical actions to satisfy the aforementioned principles of skill acquisition periodisation (Farrow & Robertson, 2017). Furthermore, to facilitate evidence-based decisions regarding the inclusion of drills to achieve training objectives (Jaspers et al., 2017), and to supplement coaches' feedback by providing objective insights into players' technical actions (Stodter & Cushion; 2019; Nosek et al., 2021), the aims of the current study were to: (i) establish the concurrent validity and intra-unit reliability of a foot-mounted inertial measurement unit for monitoring soccer technical actions, (ii) quantify the within-microcycle inter-positional differences in the technical actions of professional soccer training, and (iii) determine the influence of drill category on the technical actions of professional soccer training.

Methods

Validity and Reliability

Prior to the quantification of technical actions during training, the concurrent validity and intra-unit reliability of a foot-mounted inertial measurement unit (IMU) was established. Twelve amateur soccer players (mean ± standard deviation (SD) age: 23.8 ± 5.2 years; stature: 179.9 ± 5.3 cm; body mass: 85.1 ± 19.5 kg) collectively performed 8,640 ball touches and 5,760 releases, throughout a series of technical soccer tasks, repeated over two pre-determined distances (Supplementary Table 1). The 1000 Hz IMU microprocessor utilised zero-lag Butterworth and Kalman filters to transform raw accelerometer and gyroscope traces, via proprietary soccer-specific event detection algorithms (Waldron et al., 2020), prior to data being exported from the manufacturer's cloud-based software into Excel (v. 16.45; Microsoft®, Redmond, USA) for analysis.

Concurrent validity was determined by calculating the proportion of agreement (P_A) between the IMU data and retrospective video analyses (SportsCode Elite, v. 11.2.23, SportsTec, Warriewood, Australia) (Cooper et al., 2007). Intra-operator reliability of the reference performance analyst, who conducted all analyses, was established by coding three randomly selected repetitions of each soccer task three times (P_A = 100.0%). Intra-unit reliability was established using the same method (Cooper et al., 2007), supplemented by a percentage coefficient of variation (CV), calculated as the standard deviation of the between trial difference divided by the mean between trial difference. P_A and CV values were appraised as good (< 5.0%), moderate (5.0% - 10.0%) or poor (> 10.0%) (Scott et al., 2016). The IMUs displayed good P_A (95.1% - 100%) and good CV (1.4% - 2.9%) values for measuring ball touches and releases throughout all experimental conditions (Table 1).

*****TABLE 1 ABOUT HERE*****

Experimental Design

Technical actions were quantified during training sessions throughout a twenty-four-week (September to February) mid-season period of the 2019/2020 English Football League Championship season (Supplementary Figure 1), prior to competition disruption (Football Association, 2020a). This phase ensured minimal changes to players' physiological fitness, such as those that typically occur during the transition from pre-season to in-season, where coaches emphasise the continuation of physical conditioning (Malone et al., 2015). Two microcycles were excluded as they fell within the Fédération Internationale de Football Association International Match Calendar (Malone et al., 2015; Stevens et al., 2017). Training sessions within one microcycle were categorised in relation to the number of days prior to a competitive fixture (i.e. match-day (MD) minus day number [MD - #]) (Malone et al., 2015). Microcycles encompassing one fixture (n = 13, 54.2%) typically contained four training sessions, with MD - 3 being a recovery day for all players. Fixtures were followed by a recovery day for all players. According to their primary objective, training drills were assigned one of the following categories: position specific; possession; small-sided games (SSG); tactical; technical; or warm-up (Supplementary Table 2).

Exclusion Criteria

Players were required to have completed three full pitch-based sessions on each training day, and three repetitions of each drill, to facilitate comparative analyses. This resulted in twenty-seven players (e.g. academy scholars, trialists, players transferred in/out) being removed from the dataset through their intermittent involvement during the training programme. For eligible players, the twenty-four-week data collection period yielded 8,535 drill observations. 9.3% (n = 796) of these were removed having imposed various exclusion criteria (Figure 1) derived from comparable longitudinal monitoring studies (Malone et al., 2015; Stevens et al., 2017).

*****FIGURE 1 ABOUT HERE*****

A total of sixty-six training sessions, comprising 7,739 individual player observations, were included for analysis. Players completed a mean of 47.7 ± 13.2 training sessions, with 7.4 ± 2.1 drill observations per session. Sessions had a ball-in-play time of 61.8 ± 5.5 minutes, with recovery periods removed to provide an accurate representation of training intensity (Wass et al., 2020). Each player completed 351.8 ± 98.1 drills during the study, which did not influence the training content delivered.

Participants

Twenty-one professional soccer players (mean ± SD age: 24.4 ± 3.1 years; stature: 183.0 ± 8.1 cm; mass: 80.6 ± 9.6 kg), from one English Football League Championship club, participated in this study. The sample size was constrained by the finite number of players with professional contracts, who were available to participate in training, that satisfied the aforementioned exclusion criteria. As categorised by the head coach, who typically employed a 4-2-3-1 formation, the sample of players comprised five central defenders (CD), five wide defenders (WD), six central midfielders (CM), three wide midfielders (WM) and two strikers (ST). The head coach and coaching staff remained consistent throughout, alleviating the potential influence of a change in head coach on the technical requirements of the training programme (Whitehead et al., 2018). This study obtained institutional ethical approval (FHS200), with data collected as part of daily player monitoring procedures.

Inertial Measurement Units

Technical actions were quantified using commercially available foot-mounted IMUs (PlayerMaker™, Tel Aviv, Israel). Each IMU incorporated two components from the MPU-9150 multi-chip motion tracking module (InvenSense, California, USA), being a 16 g triaxial accelerometer and a 2000°•sec^{-1} triaxial gyroscope. Housed in manufacturer-supplied tightly-fitting silicone straps, each player was equipped with two IMUs (one for each foot), which were located at the lateral malleoli over the player's boots. To diminish issues related to inter-unit reliability, players used the same IMUs throughout the data collection period (Buchheit et al., 2014; Malone et al., 2020).

Statistical Analysis

Having verified the assumption of normality using a Q-Q plot (Schielzeth et al., 2020), general linear modelling was conducted within SPSS (v. 26; IBM, Chicago, USA) to establish estimated marginal mean values for the four fixed variables of interest: ball touches, releases, ball touches per minute, releases per minute. Random variables (e.g. player age, calendar month) were screened for covariance (Hopkins & Wolfinger, 1998), with Wald Z statistics ($p > 0.05$) indicating that no random intercept was required. In the event of a statistically significant F ratio, Sidak adjusted post-hoc pairwise comparisons between the estimated marginal means were analysed. Cohen's *d* effect size (ES) statistics, using the pooled standard deviation as the denominator, was computed to ascertain the magnitude of the within-microcycle, inter-positional and drill category differences, with the following descriptors attached: trivial (< 0.20); small (> 0.21 - 0.60); moderate (> 0.61 - 1.20); large (> 1.21 - 2.00); very large (> 2.01) (Hopkins et al., 2009). Two-tailed statistical significance was established as $p < 0.05$.

Results

Fixture Proximity

There were main effects of fixture proximity on the frequency of technical actions ($F_{(4, 1019)}$ = 1705.05 - 2026.17, p < 0.001; ES = 0.01 - 0.89), inter-positional differences in the absolute frequency of ball touches and releases ($F_{(20, 1003)}$ = 347.19 - 416.34, p < 0.001; ES = 0.00 - 0.83) (Figure 2) and the relative frequency of ball touches and releases per minute ($F_{(20, 1003}$ = 361.10 - 446.99, p < 0.001; ES = 0.01 - 0.73) (Figure 3).

*****TABLE 2 ABOUT HERE*****

*****FIGURE 2 ABOUT HERE*****

*****FIGURE 3 ABOUT HERE*****

Playing Position

There were main effects of playing position ($F_{(5, 1018)}$ = 1301.82 - 1697.79, p < 0.001; ES = 0.01 - 0.64) on the frequency of ball touches, releases, ball touches per minute and releases per minute performed during a typical training session (Table 3).

*****TABLE 3 ABOUT HERE*****

Drill Category

There were main effects of drill category ($F_{(6, 7728)}$ = 3801.45 - 4314.05, p < 0.001; ES = 0.21 - 4.35) on the frequency of ball touches and releases (Table 4), on the relative frequency of ball touches and releases per minute ($F_{(6, 7728)}$ = 3709.50 - 4929.72, p < 0.001, ES = 0.04 - 3.04) (Figure 4), and on the inter-positional differences in the relative frequency of ball touches and releases per minute ($F_{(20, 1003)}$ = 361.10 - 446.99, p < 0.001; ES = 0.00 - 0.43) (Figure 5).

*****TABLE 4 ABOUT HERE*****

*****FIGURE 4 ABOUT HERE*****

231 ***FIGURE 5 ABOUT HERE***

Discussion

The primary findings of this study were: (i) the foot-mounted IMU displayed consistently good concurrent validity and intra-unit reliability for measuring ball touches and releases, (ii) players typically performed the most ball touches and releases on MD - 1, (iii) training sessions on MD - 5 elicited the most ball touches and releases per minute, (vi) central midfielders generally performed the highest frequency of ball touches, releases, ball touches per minute and releases per minute, (v) the specificity of small-sided games for replicating the positional technical demands of match-play may be limited, and (vi) regardless of playing position, the fewest ball touches per minute and releases per minute were observed during tactical drills.

The foot-mounted IMU examined during this study displayed good concurrent validity and intra-unit reliability for measuring ball touches and releases (Table 1). Such technological advancements that quantify sport-specific non-locomotor activities may benefit practitioners (Lutz et al., 2020), by supplementing player monitoring procedures with the integration of technical data (Malone et al., 2020). The relative ease of implementation of foot-mounted IMUs (Starling & Lambert, 2018) provided a time-efficient automated alternative to laborious manual coding (Carling et al., 2014; Robertson 2020), with the efficacy of the IMUs negating concerns regarding human measurement error (O'Donoghue, 2007).

Previous research has demonstrated that players exhibit the lowest external training load on the day immediately preceding competition (Anderson et al., 2015; Malone et al., 2015; Stevens et al., 2017; Martín-García et al., 2018). Conversely, the current study noted that the frequency of technical actions performed during a typical microcycle peaked on MD - 1 (Table 2), which supports the notion that, to physically unload players as competition approaches (Malone et al., 2015; Owen et al., 2017), training objectives become more technical and tactical in nature (Martín-García et al., 2018; Walker & Hawkins, 2018). It would appear that the coaches sought to facilitate this pre-competition physical unloading by prescribing a greater proportion of position specific, tactical and warm-up drills on this day (Supplementary Table 4), with such drills demonstrating significantly lower external training load markers than small-sided games (Barrett et al., 2020). However, training sessions on MD - 1 resulted in the average player performing almost four times the frequency of ball touches, and more than double the frequency of releases, compared to previously reported match-play data from semi-automated multiple camera tracking systems (Yi et al., 2020). Although previous research has emphasised caution when comparing data from different monitoring systems (Buchheit et al., 2014; Taberner et al., 2020), the foot-mounted IMU is not currently permitted during match-play under the Laws of the Game (Law 4.4; International Football Association Board, 2020). Therefore, albeit tentatively, the current study begins to question whether players' readiness for the impending fixture may have been inadvertently compromised (Anderson et al., 2016; Kelly et al., 2020), given the potential for neuromuscular fatigue attributed to the heightened frequency of technical actions performed (Guex & Millet, 2013, Silva et al., 2018). Nevertheless, the IMU could not differentiate between the types of release performed, nor did the current study examine players' shank angular velocity during kicking (Lees et al., 2010), which has demonstrated fatigue-related decrements (Ferraz et al., 2012; 2019). Future research considering the magnitude of players' releases may, therefore, provide an insight into the metabolic cost implications of performing specific technical actions (Osgnach et al., 2010; Russell et al., 2011; Walker et al., 2016). By understanding the resulting biomechanical load imposed on the musculoskeletal system pre-competition (Vanrenterghem et al., 2017), and associated mechanobiological response (Wisdom et al., 2015), practitioners would be better placed to gauge players' holistic readiness to perform in conjunction with current monitoring systems (Bradley & Ade, 2018; Verheul et al., 2020).

Relative to ball-in-play time, training sessions on MD - 5 elicited the most ball touches and releases per minute. The greatest proportion of technical drills was also observed on MD - 5 (Supplementary Table 4), perhaps delivered in an attempt to compensate players for the lack of technical stimuli through not participating in competition (Morgans et al., 2018). Although this study did not account for levels of match participation, which has demonstrated large effects on external training load markers (Anderson et al., 2015), the training group on MD - 5 often comprised non-starting and fringe players, with those who started the previous fixture performing recovery activities (Morgans et al., 2014; Anderson et al., 2016). Practitioners frequently prescribe 'top-up' training immediately after a fixture to atone for the insufficient external training load encountered by partial-match and unused substitute players (Hills et al., 2018; Buchheit, 2019; Buckthorpe et al., 2019). However, such training is solely physical in nature, with players rarely exposed to supplementary technical activities (Hills et al., 2020a). This may be due to governing body pitch-usage restrictions permitting only fifteen minutes of post-match activity (Rule 23.11i, Football Association, 2020b), team travel requirements (Hills et al., 2020b) or a lack of available coaching staff (Hills et al., 2020b). As such, it would appear that coaches attempt to limit the consequences of reversibility (Farrow & Robertson, 2017), by utilising technical drills on MD - 5 to provide non-starting and fringe players with sufficient perceptual-cognitive stimuli that is crucial for technical performance (Reilly et al., 2000; Williams & Hodges, 2005). Nonetheless, the alternative tactical systems (Whitehead et al., 2018) and within-microcycle schedules (Malone et al., 2015) employed by coaches may influence technical performance during specific training programmes, limiting the generalisability of these results (Dalton-Barron et al., 2020).

Inter-positional differences in the technical actions of match-play are well documented within the literature (Ade et al., 2016; Baptista et al., 2018). However, prior to the current investigation, research examining these differences in the training environment were scarce. This study reported trivial-to-moderate (ES = 0.01 - 0.64) inter-positional differences in the technical actions of professional soccer training, with central midfielders performing the most absolute and relative ball touches and releases during a typical training session (Table 3). This suggests that the technical actions performed by CM during training are somewhat specific to those experienced during competition (Farrow & Robertson, 2017), with this position typically performing the most ball touches and releases per match (Yi et al., 2020). This is likely related to the tactical responsibilities of CM (Dellal et al., 2011), which primarily involves coordinating attacking play and creating goal scoring opportunities (Gonçalves et al., 2014; Bush et al., 2015). For instance, regardless of match status, 61.0% of passes originate from the midfield third of the pitch (Taylor et al., 2010), likely contributing to central midfielders demonstrating trivial differences in frequency of technical actions between playing at home versus playing away, and trivial differences when playing against a higher quality of opposition (Yi et al., 2020). This highlights the importance of training specificity for CM (Farrow & Robertson, 2017), given the apparent stability of the technical actions performed by this position during match-play.

Small-sided games are routinely employed in professional soccer training (Hill-Hass et al., 2011), simultaneously providing players with technical, tactical, physical and psychological stimuli similar to that encountered during competition (Halouani et al., 2014; Bujalance-Moreno et al., 2019).

Indeed, SSG accounted for 49.5% of individual drill observations during the current investigation, with the highest proportion being observed on MD - 1 (Supplementary Table 4). The trivial-to-small (ES = 0.00 - 0.35) inter-positional differences in the frequency of ball touches and releases per minute observed during SSG would imply that the specificity of these drills for replicating the inter-positional technical actions of match-play may be limited (Farrow & Robertson, 2017). For example, the only small differences during SSG were observed within CM, who performed more ball touches than CD and ST. For all playing positions, SSG during training evoked more ball touches and releases per minute than match-play (Yi et al., 2020), suggesting that SSG may facilitate progression through the elevated frequency of technical actions performed (Farrow & Robertson, 2017), alongside the concurrent decision-making and perceptual demands of these drills (Sampaio & Maçãs, 2012; Aguiar et al., 2015). However, comparisons between training and match-play should be interpreted with caution, given the problematic nature of quantifying performance with different systems in different environments (Buchheit et al., 2014). Future research should explore the agreement between the foot-mounted IMUs and semi-automated multiple camera tracking systems, to determine whether these approaches can be used interchangeably throughout training and match-play (Taberner et al., 2020).

Drill category displayed trivial-to-very large (ES = 0.04 - 3.04) effects on the relative frequency of technical actions performed during training (Table 4). Tactical drills (e.g. team shape, set pieces) are arguably the most important training modality in professional soccer, with players' tactical roles being a powerful determinant of match performance (Bradley & Ade, 2018). This study observed that, for all positions, the fewest ball touches and releases per minute were observed during tactical drills. These drills are intermittent in nature (Siegle & Lames, 2012), with coaches frequently interrupting to provide instruction and management-related information (Ford et al., 2010). Although instruction and management are crucial for delivering tactical messages (Cushion & Jones, 2001), previous research has demonstrated the potential issues related to interrupting practice too frequently (Williams & Hodges, 2005), which perhaps contributed to the lowest relative technical stimuli being provided by tactical drills. Therefore, practitioners should seek alternative exercise modalities, such as incorporating technical actions within warm-up drills, should a high technical output be required from a particular session.

The application of foot-mounted IMUs is not unproblematic. Firstly, foot-mounted IMUs lack the contextual information provided by manual coding (i.e. player location, action success/failure). Practitioners will need to weigh up the time-saving ability of the IMUs, against the reduced contextual information provided, when considering the implementation of this solution. Secondly, soccer players often perform technical actions with alternative body parts (e.g. thigh, head) (Bloomfield et al., 2007), which a foot-mounted device is unlikely to detect. Given that underreporting the frequency of technical actions performed may have implications for skill acquisition periodisation (Farrow & Roberton, 2017), practitioners should account for the disparity between the frequency of technical actions measured by foot-mounted IMUs and those performed with alternative body parts when programming players' technical actions during training. The inability of the IMU to quantify specific types of release performed, which likely possess distinct metabolic requirements (Osgnach et al., 2010; Walker et al., 2016), may limit the subsequent usefulness of the monitoring system (Taberner et al., 2020). Researchers might seek to develop a cumulative vector magnitude index of technical 'load', incorporating players' shank angular velocity alongside the specific types of release performed (Lees et al., 2010), to provide practitioners with an arbitrary value representative of the metabolic cost of players' technical performance (Boyd et al., 2013; Barrett et al., 2015; Dalen et al., 2016). While the current study provided an examination of the capabilities of the foot-mounted IMUs during controlled, discrete, technical soccer tasks that are commonly observed during training, the validity and reliability of the IMUs is yet to be comprehensively examined during match-play. The increasingly complex scenarios observed during competition may involve instances of foot-to-foot contact between players, potentially resulting in additional false positive ball touches and releases being recorded (Rossi et al., 2018). Further research establishing the efficacy of the foot-mounted IMU during competitive match-play scenarios, such as when physically contesting for possession of the ball (Drust et al., 2007), is required.

This investigation has provided a novel understanding of within-microcycle, inter-positional and drill category differences in the technical actions of professional soccer training, which may be especially relevant to researchers and practitioners alike. Although the magnitude of players' releases was not quantified, which may yield a broader understanding of the metabolic and mechanobiological implications of performing technical actions (Walker et al., 2016; Vanrenterghem et al., 2017), the insights provided by this investigation have the potential to inform pre-competition recovery strategies to negate the neuromuscular fatigue possibly induced through increased technical activity on MD - 1 (Rey et al., 2012a; 2012b; Nédélec et al., 2015). Lastly, coaches could manipulate the frequency (e.g. CM performing additional releases during possession drills), and complexity (ST required to hit certain zones during position-specific drills) of technical actions during training, to provide an optimal challenge point that enhances the positional specificity and promotes progression according to the principles of skill acquisition periodisation (Guadagnoli & Lee, 2004; Farrow & Robertson, 2017; Mujika et al., 2018).

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Declaration of Interest Statement

The second author of this study is now employed by the company who provided the foot-mounted IMUs used to collect players' technical performance data. However, throughout the data collection and writing up periods, the second author had the same affiliation as the first author and was not involved with the company in any way. Despite this, and to remove the potential for bias, the second author was not involved in any statistical analyses or data interpretation conducted during the investigation.

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Tables with Captions

Table 1: A summary of the concurrent validity and intra-unit reliability of the foot-mounted IMUs for quantifying ball touches and releases throughout all experimental conditions.

Variable	Concurrent Validity					Intra-Unit Reliability				
	SportsCode Mean ± SD	PlayerMaker™ Mean ± SD	P_A (%)	SE (%)	P_A (%) 95% CI	PlayerMaker™ Between Trial Mean ± SD Difference	P_A (%)	SE (%)	P_A (%) 95% CI	CV (%)
Ball Touches	30.0 ± 0.0	29.9 ± 0.5	95.1	0.1	95.0 - 95.3	0.0 ± 0.4	96.9	0.0	96.8 - 96.9	1.8
Releases	20.0 ± 0.0	20.0 ± 0.5	97.6	0.0	97.5 - 97.7	0.0 ± 0.4	95.9	0.2	95.5 - 96.2	2.3

N.B. SD = standard deviation. P_A = proportion of agreement. SE = standard error. CI = confidence intervals. CV = coefficient of variation.

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Table 2: Estimated marginal mean (± SE) values representative of the absolute frequency of ball touches and releases, and the relative frequency of ball touches and releases per minute of ball-in-play time, performed by professional soccer players on each training day within a typical weekly microcycle.

Variable	OVERALL			MD - 5			MD - 4			MD - 2			MD - 1		
	EM Mean	SE	95% CI	EM Mean	SE	95% CI	EM Mean	SE	95% CI	EM Mean	SE	95% CI	EM Mean	SE	95% CI
Duration (mins)	62.5	0.8	61.0 - 64.1	41.5 $_{4}^{L}{}_{2}^{L}{}_{1}^{M}$	2.1	37.3 - 45.7	76.6 $_{5}^{L}{}_{1}^{M}$	1.8	73.1 - 80.1	70.8 $_{5}^{L}{}_{1}^{S}$	1.4	68.1 - 73.5	57.8 $_{5}^{M}{}_{4}^{M}{}_{2}^{S}$	1.1	55.7 - 59.9
Ball Touches (f)	209.9	2.4	205.3 - 214.6	181.9 $_{4}^{S}{}_{2}^{S}{}_{1}^{S}$	7.0	168.2 - 195.7	209.0 $_{5}^{S}$	5.9	197.4 - 220.5	208.4 $_{5}^{S}$	4.4	199.7 - 217.1	218.0 $_{5}^{S}$	3.5	211.2 - 224.8
Releases (f)	103.0	1.3	100.4 - 105.5	80.9 $_{4}^{S}{}_{2}^{S}{}_{1}^{M}$	3.8	73.6 - 88.3	99.7 $_{5}^{S}{}_{1}^{S}$	3.2	93.5 - 105.9	100.6 $_{5}^{S}{}_{1}^{S}$	2.4	95.9 - 105.2	110.8 $_{5}^{M}{}_{4}^{S}{}_{2}^{S}$	1.9	107.2 - 114.5
Ball Touches ($f \cdot min^{-1}$)	3.1	0.0	3.1 - 3.2	3.8 $_{4}^{M}{}_{2}^{M}{}_{1}^{M}$	0.1	3.6 - 4.0	2.8 $_{5}^{M}{}_{2}^{S}{}_{1}^{S}$	0.1	2.6 - 2.9	3.1 $_{5}^{M}{}_{4}^{S}$	0.1	3.0 - 3.2	3.1 $_{5}^{M}{}_{4}^{S}$	0.1	3.0 - 3.2
Releases ($f \cdot min^{-1}$)	1.5	0.0	1.4 - 1.5	1.7 $_{4}^{M}{}_{1}^{S}$	0.1	1.5 - 1.8	1.3 $_{5}^{M}{}_{2}^{S}{}_{1}^{S}$	0.0	1.2 - 1.4	1.5 $_{4}^{S}$	0.0	1.4 - 1.6	1.5 $_{5}^{S}{}_{4}^{S}$	0.0	1.4 - 1.5

N.B. EM = estimated marginal. SE = standard error. CI = confidence intervals. MD = match day. Statistically significant differences ($p < 0.05$) are depicted in bold: **5** = MD **-** 5, **4** = MD **-** 4, **2** = MD **-** 2, and **1** = MD **-** 1. Observed magnitude of effects are denoted as [$^{\mathbf{T}}$] = trivial, [$^{\mathbf{S}}$] = small, [$^{\mathbf{M}}$] = moderate, [$^{\mathbf{L}}$] = large, and [$^{\mathbf{V}}$] = very large.

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Table 3: Estimated marginal mean (± SE) values representative of the inter-positional differences in the absolute frequency of ball touches and releases, and the relative frequency of ball touches and releases per minute of ball-in-play time, performed by professional soccer players during a typical training session.

Variable	CENTRAL DEFENDERS			WIDE DEFENDERS			CENTRAL MIDFIELDERS			WIDE MIDFIELDERS			STRIKERS		
	EM Mean	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**
Ball Touches (f)	206.1	4.8	196.7 - 215.4	200.9 **CM**^{S}	4.8	191.5 - 210.2	221.9 **WD**^{S} **ST**^{S}	4.4	213.3 - 230.4	218.3	6.4	205.6 - 230.9	195.4 **CM**^{S}	7.5	180.7 - 210.2
Releases (f)	102.2	2.6	97.1 - 107.3	97.5 **CM**^{S}	2.6	92.4 - 102.6	108.3 **WD**^{S}	2.4	103.6 - 112.9	106.9	3.5	100.0 - 113.8	97.2	4.1	89.2 - 105.3
Ball Touches $(f \cdot min^{-1})$	2.9 **WD**^{S} **CM**^{S}	0.1	2.7 - 3.0	3.2 **CD**^{S} **ST**^{S}	0.1	3.0 - 3.3	3.4 **CD**^{S} **ST**^{M}	0.1	3.3 - 3.5	3.2 **ST**^{S}	0.1	3.0 - 3.4	2.7 **WD**^{S} **CM**^{M} **WM**^{S}	0.1	2.5 - 2.9
Releases $(f \cdot min^{-1})$	1.4 **CM**^{S}	0.0	1.3 - 1.5	1.5 **ST**^{S}	0.0	1.4 - 1.6	1.6 **CD**^{S} **ST**^{S}	0.0	1.5 - 1.7	1.4	0.0	1.3 - 1.5	1.3 **WD**^{S} **CM**^{S}	0.1	1.2 - 1.4

N.B. EM = estimated marginal. SE = standard error. CI = confidence intervals. Statistically significant differences ($p < 0.05$) are depicted in bold: **CD** = central defenders, **WD** = wide defenders, **CM** = central midfielders, **WM** = wide midfielders, and **ST** = strikers. Observed magnitude of effects are denoted as [^{T}] = trivial, [^{S}] = small, [^{M}] = moderate, [^{L}] = large, and [^{V}] = very large.

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Table 4: Estimated marginal mean (± SE) values representative of the differences in the absolute frequency of ball touches and releases, and the relative frequency of ball touches and releases per minute of ball-in-play time, performed by professional soccer players throughout each category of training drill.

Variable	**POSITION SPECIFIC**			**POSSESSION**			**SMALL-SIDED GAMES**			**TACTICAL**			**TECHNICAL**			**WARM-UP**		
	EM Mean	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**	**EM Mean**	**SE**	**95% CI**
Duration (mins)	27.0 POS^{V} SSG^{V} TAC^{V} TEC^{V} WU^{V}	0.2	26.6 - 27.5	12.7 PS^{V} SSG^{L} TAC^{S} TEC^{M} WU^{S}	0.2	12.3 - 13.2	2.7 PS^{V} POS^{L} TAC^{L} TEC^{L} WU^{V}	0.1	2.5 - 2.8	10.3 PS^{V} POS^{S} SSG^{L} TEC^{T} WU^{M}	0.2	10.0 - 10.6	9.4 PS^{V} POS^{S} SSG^{L} TAC^{T} WU^{M}	0.2	9.1 - 9.7	15.2 PS^{V} POS^{S} SSG^{V} TAC^{M} TEC^{M}	0.2	14.7 - 15.6
Ball Touches (f)	56.4 POS^{M} SSG^{V} TAC^{L} TEC^{S} WU^{V}	0.9	54.6 - 58.2	30.9 PS^{M} SSG^{M} TAC^{M} TEC^{L} WU^{V}	1.0	28.9 - 32.8	6.9 PS^{V} POS^{M} TAC^{S} TEC^{V} WU^{V}	0.4	6.2 - 7.6	12.4 PS^{L} POS^{M} SSG^{S} TEC^{V} WU^{V}	0.7	11.1 - 13.6	61.2 PS^{S} POS^{L} SSG^{V} TAC^{V} WU^{L}	0.7	59.7 - 62.6	104.2 PS^{V} POS^{V} SSG^{V} TAC^{V} TEC^{L}	0.9	102.4 - 106.0
Releases (f)	28.3 POS^{L} SSG^{V} TAC^{L} TEC^{S} WU^{V}	0.5	27.3 - 29.3	13.3 PS^{L} SSG^{M} TAC^{M} TEC^{L} WU^{V}	0.5	12.3 - 14.4	2.8 PS^{V} POS^{M} TAC^{S} TEC^{V} WU^{V}	0.2	2.4 - 3.2	5.4 PS^{L} POS^{M} SSG^{S} TEC^{V} WU^{V}	0.4	4.7 - 6.1	31.0 PS^{S} POS^{L} SSG^{V} TAC^{V} WU^{L}	0.4	30.2 - 31.8	55.2 PS^{V} POS^{V} SSG^{V} TAC^{V} TEC^{L}	0.5	54.2 - 56.1
Ball Touches ($f \cdot min^{-1}$)	2.4 TAC^{S} TEC^{L} WU^{V}	0.1	2.2 - 2.5	2.5 SSG^{T} TAC^{M} TEC^{V} WU^{V}	0.1	2.3 - 2.6	2.2 POS^{T} TAC^{S} TEC^{V} WU^{V}	0.0	2.1 - 2.2	1.2 PS^{M} POS^{M} SSG^{S} TEC^{V} WU^{V}	0.1	1.1 - 1.3	6.2 PS^{V} POS^{V} SSG^{V} TAC^{V} WU^{S}	0.1	6.1 - 6.3	6.8 PS^{V} POS^{V} SSG^{V} TAC^{V} TEC^{S}	0.1	6.6 - 6.9
Releases ($f \cdot min^{-1}$)	1.2 SSG^{S} TAC^{M} TEC^{L} WU^{V}	0.0	1.2 - 1.3	1.1 SSG^{T} TAC^{S} TEC^{V} WU^{V}	0.0	1.0 - 1.2	0.9 PS^{S} POS^{S} TAC^{S} TEC^{V} WU^{V}	0.0	0.9 - 0.9	0.5 PS^{M} POS^{S} SSG^{S} TEC^{V} WU^{V}	0.0	0.5 - 0.6	3.1 PS^{V} POS^{L} SSG^{V} TAC^{V} WU^{S}	0.0	3.1 - 3.2	3.6 PS^{V} POS^{V} SSG^{V} TAC^{V} TEC^{S}	0.0	3.6 - 3.7

N.B. EM = estimated marginal. SE = standard error. CI = confidence intervals. Statistically significant differences ($p < 0.05$) are depicted in bold: **PS** = position specific, **POS** = possession, **SSG** = small-sided games, **TAC** = tactical, **TEC** = technical, and **WU** = warm-up. Observed magnitude of effects are denoted as [^{T}] = trivial, [^{S}] = small, [^{M}] = moderate, [^{L}] = large, and [^{V}] = very large.

Figures

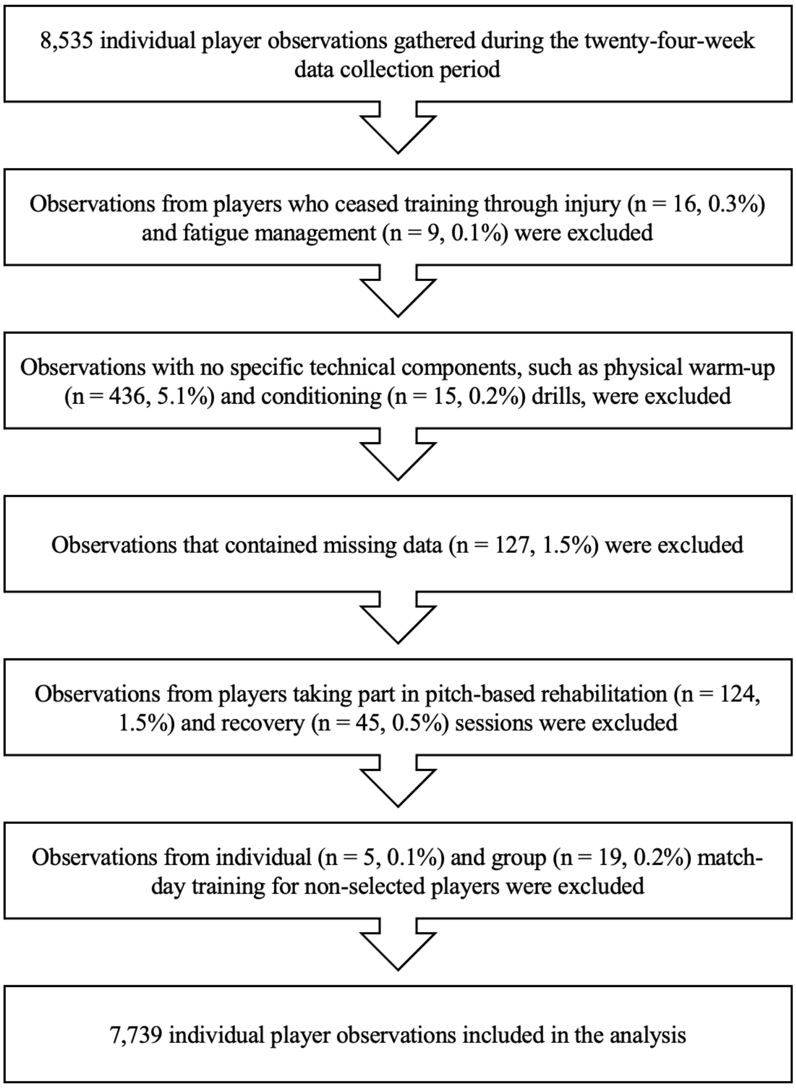

Figure 1: A schematic of the data exclusion process derived from comparable longitudinal monitoring studies (Malone et al., 2015; Stevens et al., 2017).

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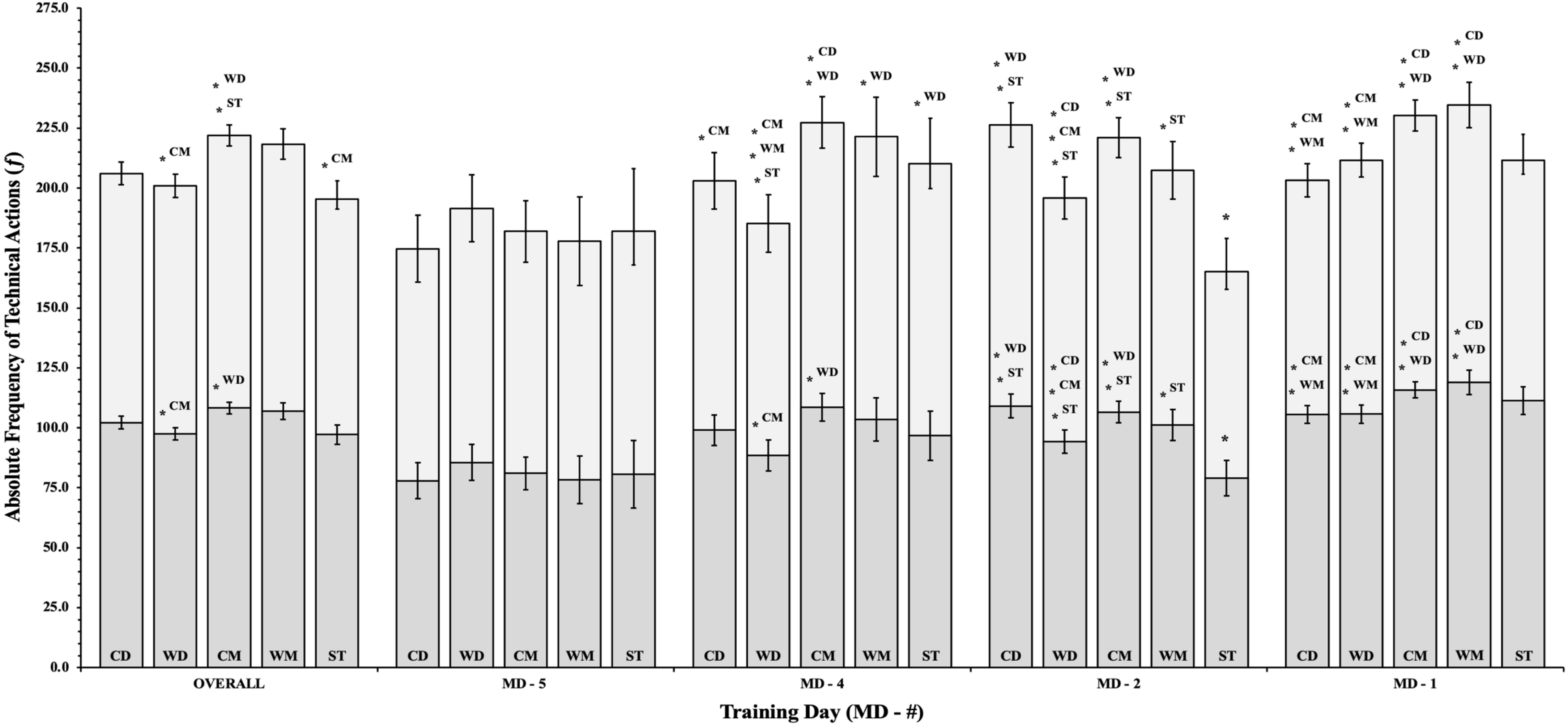

Figure 2: Estimated marginal mean (± SE) inter-positional differences in the absolute frequency of ball touches and releases performed by professional soccer players on each training day within a typical weekly microcycle. **N.B.** Each bar represents one playing position. Lighter shaded areas represent ball touches. Darker shaded areas represent releases. Statistically significant differences ($p < 0.05$) are displayed above SE bars. MD = match day. ***** = statistically significant difference to all other training days. $*^{CD}$ = statistically significant difference to central defenders. $*^{WD}$ = statistically significant difference to wide defenders. $*^{CM}$ = statistically significant difference to central midfielders. $*^{WM}$ = statistically significant difference to wide midfielders. $*^{ST}$ = statistically significant difference to strikers.

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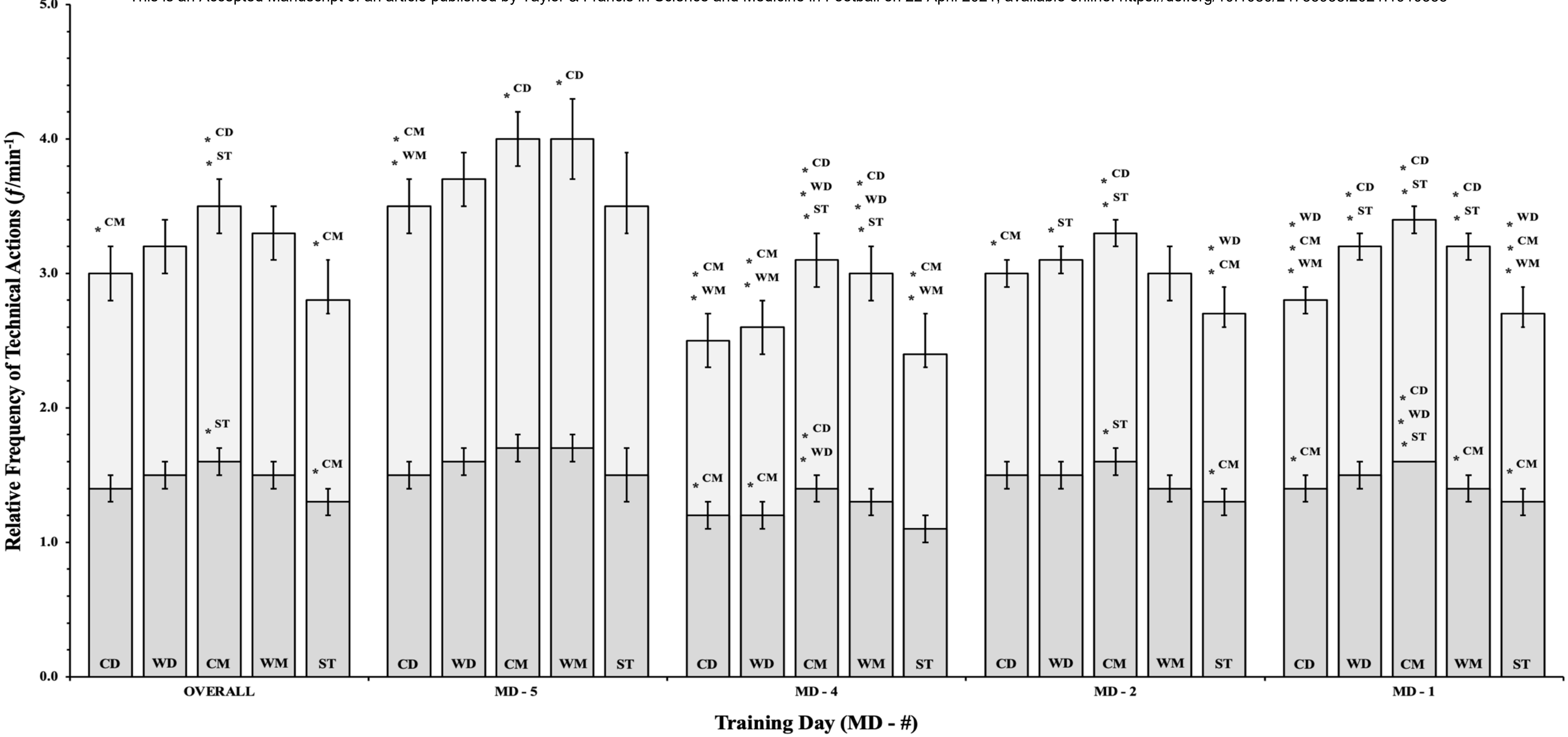

Figure 3: Estimated marginal mean (± SE) inter-positional differences in the relative frequency of ball touches and releases, per minute of ball-in-play time, performed by professional soccer players on each training day within a typical weekly microcycle. **N.B.** Each bar represents one playing position. Lighter shaded areas represent ball touches per minute. Darker shaded areas represent releases per minute. Statistically significant differences (p < 0.05) are displayed above SE bars. MD = match day. ***** = statistically significant difference to all other training days. $*^{CD}$ = statistically significant difference to central defenders. $*^{WD}$ = statistically significant difference to wide defenders. $*^{CM}$ = statistically significant difference to central midfielders. $*^{WM}$ = statistically significant difference to wide midfielders. $*^{ST}$ = statistically significant difference to strikers.

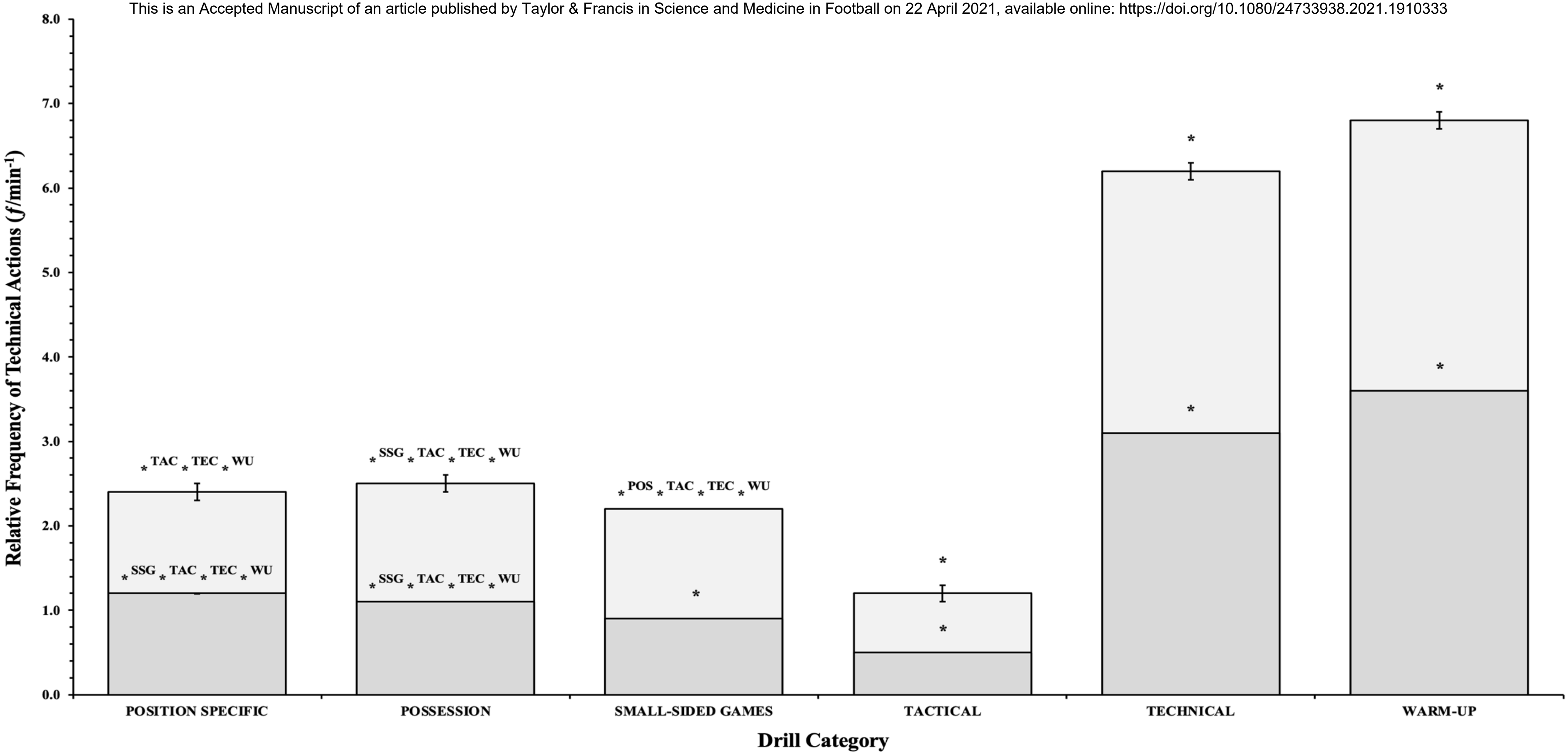

Figure 4: Estimated marginal mean (± SE) differences in the relative frequency of ball touches and releases, per minute of ball-in-play time, performed by professional soccer players throughout each category of training drill. **N.B.** Lighter shaded areas represent ball touches per minute. Darker shaded areas represent releases per minute. Statistically significant differences (p < 0.05) are displayed above SE bars. ***** = statistically significant difference to all other drill categories. *PS = statistically significant difference to position specific. *POS = statistically significant difference to possession. *SSG = statistically significant difference to small-sided games. *TAC = statistically significant difference to tactical. *TEC = statistically significant difference to technical. *WU = statistically significant difference to warm-up.

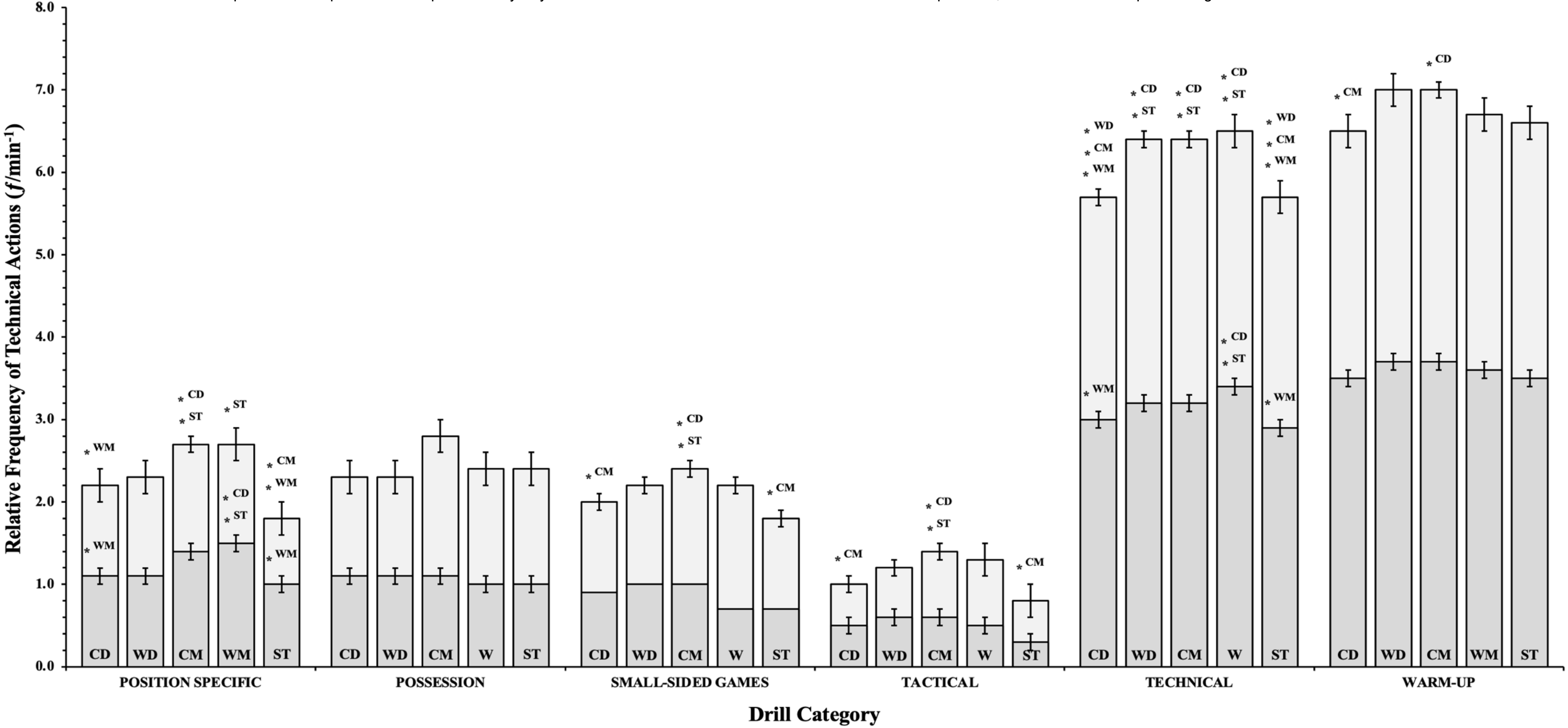

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Figure Captions

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